Engineering Innovation

Pipebots for Rising Mains

Research & Feasibility Study – OFWAT Catalyst Project

Overview Report FINAL

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Executive Summary

The Pipebots for Rising Mains Research & Feasibility Study has been the first Ofwat Innovation fund project undertaken and completed by the partners, namely Thames Water Utilities Ltd, Wessex Water Services Ltd, Dwr Cymru Cyfyngedig (Welsh Water), The University of Sheffield and Synthotech Ltd. The project has been successful and has delivered the required outputs to the agreed programme.

The application for funding was based on the aim of developing a rising main inspection tool by harnessing the expertise of academia and industry beyond the water sector. The scope of the project was ambitious within an original 10 month plan, to design, build and test a robotic platform to house novel sensor inspection systems. During the project, field visits and desktop studies have been undertaken to support the mechanical and electrical design work packages.

A target of 300mm diameter metallic pipe was chosen for the initial project focus. Metallic pipe in all forms constitutes the largest proportion of the asset base and operational failures due to material deterioration. Existing access points into mains are extremely limited. Any live inspection systems are likely to require engineering works to drill and fit a tee onto the main, with an isolation valve for working under pressure.

The use of fluid-borne triaxial accelerometers and low frequency acoustics as a pipeline condition assessment tool has been investigated and the results from the tests are encouraging. The trials have shown that variance in pipe wall thickness can be determined, and defects successfully identified with sensors mounted on a robot system. The original project objective to fulfil proof of concept for the technology has been achieved and the Technology Readiness Level (TRL) has increased from 1 to 3*. Further work is needed on the interpretation and calibration of data, the mounting of the accelerometers and the influence of the robot body on the results. These factors combine with the next challenge of operating in a live rising main, with high pressure, fast moving rag laden flow.

The physics behind the use of accelerometers to assess pipe condition is complex and a high level of technical expertise has been demonstrated by the suppliers. Excellent working relationships have been maintained with all the partners throughout the project which has been successfully delivered.

There is a continuing industry need for tools to undertake internal inspections of live rising mains. Further research and development of the Pipebots for Rising Mains work should continue to target TRL 6* with an Ofwat Innovation Fund application for Phase 2. If successful, the development can continue to build on the work to date and ultimately provide the industry with a viable rising main inspection tool. Such a tool would enable operators to assess the condition of mains, identify defects and plan rehabilitation works. This capability would reduce the risk of failure leading to pollution, reduce the risk of flooding to customers and reduce the inconvenience and expense of emergency repair works.

*TRL 1 = Basic principles, TRL 3 = Proof of Concept, TRL 6 = demonstration in live environment

Contents

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1. Introduction

1.1 Ofwat Innovation Fund

The Ofwat Innovation Fund was launched in 2020 to support innovative initiatives to deliver benefits for customers, society and the environment. The Water Breakthrough Challenge, Round 2 was launched as part of the Fund in October 2021, which invited applications for projects under the Catalyst and Transform Stream. Entries to the Catalyst Stream closed in December 2021, with the winners being announced in March 2022.

Thames Water Utilities Ltd submitted the Pipebots for Rising Mains Research & Feasibility Study entry during Round 2 of the Challenge. The proposed project was in partnership with Wessex Water Services Ltd, Dwr Cymru Cyfyngedig (Welsh Water), The University of Sheffield and Synthotech Ltd. The entry was adapted from an earlier unsuccessful application to the Fund during Round 1 by Wessex Water Services Ltd. A funding request of £230.9k was submitted with £112.3k being contributed in kind by the partners resulting in a total project value of £343.3k. The project was to be led by Thames Water and delivered over a 10 month period. Notification of the successful bid was received by Thames Water in March 2022 and the project commenced from April 2022. The original Water Breakthrough Challenge submission document is included in **Appendix 1.**

1.2 Pipebots

Pipebots is an umbrella term, being both the name of an academic research partnership developing robots for the inspection of buried pipe infrastructure and a generic name for a wide range of robots used for pipe inspection purposes (www.pipebots.ac.uk). The Pipebots partnership comprises: The University of Sheffield, University of Birmingham, University of Bristol and University of Leeds. Each University has specialist areas of expertise and they have been working closely with industry to develop inspection tools as part of an Engineering and Physical Sciences Research Council (EPSRC) project. The Pipebots for Rising Mains project aimed to build on expertise developed by The University of Sheffield during their Pipebots work, to instigate the use of acoustics as an inspection tool for live rising mains.

1.3 Partners

One of the benefits of the Ofwat Innovation fund is to encourage the transfer of technology from other industries into the water sector, particularly from the petrochemical industry which uses a wide range of pipe inspection techniques. Synthotech Ltd have extensive experience in pipeline inspection for the gas industry and are widely recognised for their innovation skills, products and systems development. Synthotech Ltd were therefore an ideal partner for the Pipebots for Rising Mains project, bringing engineering, site and systems capabilities to enable lab-based technologies developed by The University of Sheffield, to be adapted into practical tools for use in the water industry.

1.4 Project Management

Winning an Ofwat Innovation Fund bid was new to all the project partners, so the processes and agreements necessary to undertake the work needed to be established. Initially, Thames Water were required to sign a Winners Agreement with Ofwat (via Nesta). This outlined the process for the funds to be paid (by Ofwat) to Thames Water and the obligations for Thames Water to manage the project, payments and reporting. This agreement was signed in May 2022.

Following the Winners Agreement, a Collaboration Agreement was needed between all the partners. This detailed the contributions and deliverables from the suppliers in terms of outputs and the contribution of the water companies in terms of resources. This was a complex legal document and required detailed discussions with legal teams from all parties. After significant work by all the partners, the Collaboration Agreement was signed in late December 2022.

Lastly, individual Delivery Agreements were required between the suppliers, namely The University of Sheffield, Synthotech Ltd and Thames Water. This agreement defined contractual delivery commitments and legal responsibilities. Again, following lengthy legal discussions, the Delivery Agreements were signed in late January 2023.

Without experience of previous projects, the extent of the legal process was not anticipated by the partners during the application process. As such, the initial 10 month delivery programme became impossible to achieve, as Purchase Orders for the work could not be raised until all the agreements had been signed (preventing the purchase of hardware etc. by the suppliers). Thames Water therefore requested a 5 month project extension from Ofwat, from May 2023 to October 2023 which was granted in December 2022.

The project timeline was ambitious, even with the 5 month extension. The scope to undertake field tests, the design and build of a robotic transport system, sensor development, rig tests and data interpretation were challenging. The project was defined as a Research & Feasibility Study with the aim of demonstrating proof of concept from a low technology readiness level (TRL).

To manage the project, a Steering Group was established and chaired by Thames Water. Representatives from all the partners attended the meetings which were held on a monthly basis. The Steering Group reviewed outputs and approved payments in line with the agreed schedules. In parallel with this, a Technical Working Group was also formed, chaired by Thames Water to lead on the technical aspects of the project. These meetings were held fortnightly.

1.5 Rising Mains – The Challenge

Rising mains are pressurised pipelines that convey flow from pumping stations, where sewage is pumped from a low level to a higher level for gravity discharge or treatment. A rising main burst can lead to severe environmental impact, as pressurised sewage flow from a large-scale burst or leak is likely to result in pollution via uncontrolled sewage discharge. The pipeline materials vary, but they are predominantly cast or ductile iron and typically range from around 100mm to 1000mm diameter. Managing sewer flows in the event of a burst can have a widespread impact on customers. If a pumping station and rising main need to be isolated to undertake a repair, upstream flows need to be managed. This is normally achieved using road tanker lorries which is an expensive and disruptive short-term solution. There is generally no redundancy, such as twin mains for diversion of flows. The temporary reduced capacity at the pumping station during a repair can lead to increased risk of flooding for customers upstream. The challenges of dealing with flows for emergency pipe repairs equally apply to temporary shutdowns for pipe condition inspections. As such, routine internal condition surveys are rarely undertaken.

The development and availability of 'in-pipe', live inspection tools are desperately needed for rising mains, an asset which is unique to the water sector. Such tools would enable operators to assess the condition of mains, identify defects and plan rehabilitation works. This capability would reduce the risk of failure leading to pollution, reduce the risk of flooding to customers and reduce the inconvenience and expense of emergency repair works.

2. Project Scope & Deliverables

The project scope and deliverables included in the original submission were refined during the compilation of the schedules for the Collaboration and Delivery agreements. The project was split into two work packages, namely:

Phase 1 – External inspection and Sensor Optimisation
- 1a Field work
- 1b Lab work
- 1c Desktop study

Phase 2 – Proof of concept
- 2a Sensor insertion (access system)
- 2b Robot platform
- 2c Sensor package
- 2d Field tests
- Reporting

Deliverables in terms of report outputs for the phases were defined for Synthotech and The University of Sheffield. These were detailed in Schedule 1 of the Collaboration Agreement and Schedule 3 of the Delivery Agreements. A staged payment schedule was linked to the deliverables from the supplier. The deliverable components are detailed in tables 1 & 2 below

Table 1. Synthotech outputs

D1	Site Findings Report (access locations)	Measurements taken during site visits (by The University of Sheffield) Access location review & observations to inform specification and concepts.
D2	Sensing requirements capture	Review of pipeline materials, environment and sensing requirements to benchmark.
D3	Specification	Specification and key design parameters for Proof of Concept, commercial solutions and operational needs.
D4	Lab tests report	Test reports on Proof of Concept
D5	Test rig trial reports	Test reports on Proof of Concept
D6	FMEA	Documented process for value capture from pipeline inspection
D7	End to end process	Documented process for value capture from pipeline inspection
D8	Project close out report	Close out report

Table 2. The University of Sheffield outputs

U1	Computational Model	Documenting field, lab and simulations – including potential of sensors, sensitivity, frequency & range can operate and deployment needs.
U2	Lab Report	Documenting field, lab and simulations – including potential of sensors, sensitivity, frequency & range can operate and deployment needs.
U3	Delivery of final report	Sections / appendices as agreed with Steering Group – updated simulations of how will work on robot and experience from lab/field conditions.

2.1 Reporting

The outputs from Synthotech Ltd and The University of Sheffield were submitted to the Steering Group as standalone documents. This Overview Report serves as a summary of the various aspects of the project and references the outputs as appendices. This Overview Report can be published with or without the appendices as required.

3. Project Outputs & Results

3.1 Site Investigations & Scoping

Phase 1 of the project initially focused on field work and data gathering. The aim of this work was to enable The University of Sheffield to mount accelerometers on live rising mains, to record the movements and vibrations during pumping cycles. This was the first step towards assessing the feasibility of using accelerometers as a condition assessment tool. Three sites were made available for inspection, a Welsh Water site at Bretton and two Wessex Water sites at Christchurch and Weymouth. The Bretton site provided three excavated external access points onto a live 300mm diameter cast iron pipe which was soon to be replaced. The Christchurch site provided external access to a live 400mm diameter ductile iron pipe via a flow meter chamber. The Weymouth site provided external access to a live 800mm and 1100mm diameter cast iron pipe via a valve chamber which required confined space entry. A summary of the findings completed by The University of Sheffield is included in: U2 – Field & Lab Testing Report, Appendix 2.

Following the initial site visits, The University of Sheffield pursued lab and computer modelling work to further explore the concept of using accelerometers for condition assessment. A 1.5m length of 300mm diameter ductile pipe with invert corrosion holes was provided to The University of Sheffield by Thames Water for lab testing purposes. A summary of the findings completed by The University of Sheffield is included in: U1 – Computational Modelling, Appendix 3.

The physics behind the use of fluid-borne accelerometers to determine pipe condition is based on the measurement of microscopic movements of the fluid in the vicinity of the pipe wall. The pipe material minutely flexes during internal pressure changes due to pumping transients or induced sound pressure waves. This creates a complex scattering pattern of acoustic velocity near an area of wall damage. The 'vibro-acoustics' technique seeks to measure the differing movements in the pipe wall, depending on the thickness and structural integrity due to corrosion or other defects.

While The University of Sheffield were undertaking their measurements at the Christchurch site, a team from Synthotech Ltd also visited the site and surrounding area to assess the general layout of pumping stations and potential rising main access options. A summary of the findings completed by Synthotech Ltd from this element of the project is included in: D1 Site Findings Report, Appendix 4.

Statistical data on rising main assets including diameter, lengths, age, materials and burst history was provided by the partner water companies to Synthotech Ltd. Using this data, the initial scope for an inspection tool for the project was developed. A target of 300mm diameter metallic pipe was subsequently chosen as the initial project focus. Metallic pipe in all forms constitutes the largest proportion of the asset base and operational failures due to material deterioration. The vibro-acoustic technique may not be limited to the survey of metallic pipe. It offers potential to survey a variety of other materials, although this has not been investigated during the scope of this project.

3.2 Sensor Options & Specification

While defining the scope for the inspection tool, alternative sensor systems were considered for potential use. The vibro-acoustics technique was being pursued for development, but conventional condition assessment technologies could be operated in parallel to provide supporting data. Synthotech Ltd therefore undertook a review of existing technologies, namely ultrasonic and electromagnetic systems and outlined the advantages and disadvantages of each. Synthotech Ltd produced an output from this stage of the project, which is included in: D2 Sensing Requirements Capture, **Appendix 5.**

As the target pipe size and material detail evolved, the specification for the robot platform and testing environment developed. In conjunction with The University of Sheffield, Synthotech Ltd had undertaken outline conceptual designs for the proof of concept robot platform and accelerometer mountings. A specification was refined to test and assess the various elements of the system, such as the sensor performance and robot platform operability. An additional requirement of the vibro-acoustics sensing technique is a sound pressure generator. An 'in pipe' speaker system had been proposed, laboratory tested by The University of Sheffield and included in the specification for field development and trials. The specification is included in: D3 Specification, **Appendix 6.**

It was agreed that future live installation techniques would be considered in terms of a desktop review, but not fully fabricated and tested. Access into rising mains is generally extremely limited and there are few suitable access points. Any live inspection systems are likely to require engineering works to drill and fit a tee onto the main, with an isolation valve for working under pressure. The internal diameter of a drilled tee onto a host pipe for access purposes could vary depending on the material and condition of the main. Although noted for future development, elements relating to insertion were not fully explored for proof of concept testing.

3.3 Lab Tests & Mechanical Development

Phase 2 of the project commenced in January 2023 with the detailed design of the robot platform, data interface, sensor package and sound generator. Close working arrangements were maintained between The University of Sheffield and Synthotech Ltd to optimise the layout and mounting of the accelerometers. A halo ring at the back of the robot crawler evolved as the preferred layout, with six accelerometers mounted around the circumference. Pictures of the robot crawler are shown in figures 1. & 2. Below.

Figure 1. Design image of robot crawler, forward and rear facing cameras mounted on the body

Figure 2. Completed build with accelerometers mounted on the halo to the rear

Steady progress on the build of the robot system was maintained by Synthotech Ltd during the early months of 2023. The accelerometers procured for the robot by Synthotech Ltd were tested within the rig at The University of Sheffield. Discussions continued regarding the mountings, the mechanical isolation and housings for the accelerometers. Details of the lab testing by Synthotech Ltd for the robot, data acquisition systems and accelerometer sensors is included in: D4 Lab Tests Report, Appendix 7.

In parallel with the build of the robot, options for the rig testing were considered. Original plans for testing in an abandoned main at Wessex Water were changed, as the site was no longer available and quantifying the test results would not be possible. Rising mains are a challenging, hostile environment, particularly for potential live surveys. Corrosive sewage containing rag, silt and solids is intermittently pumped at velocities up to 2.4m/s, with surge pressures potentially over 10bar. It was accepted that it would not be feasible to replicate this scenario in a rig and not needed for initial proof of concept testing.

A bespoke rig at the Synthotech Ltd test site at Ripon was therefore proposed that could be operated under pressure with flow velocity, but use clean water as opposed to sewage. The rig would be buried in a trench with sand and gravel backfill to replicate site conditions. A variety of machined defects were discussed and agreed by the partners to simulate defects in the field. During subsequent testing, the exact position and extent of a simulated defect would be known, which could be precisely referenced with data from the sensors.

A rig comprising 4 x 2m sections of new 300mm diameter ductile iron pipe, 2 x equal tees and 2 x 1m upstand pipe was agreed. The pipework was procured by Thames Water and delivered to the Ripon test site in April 2023. Blank flanges, valves and a clean water circulation system were supplied and installed by Synthotech Ltd. Sketches of the test rig are shown in figures 3. & 4. Below.

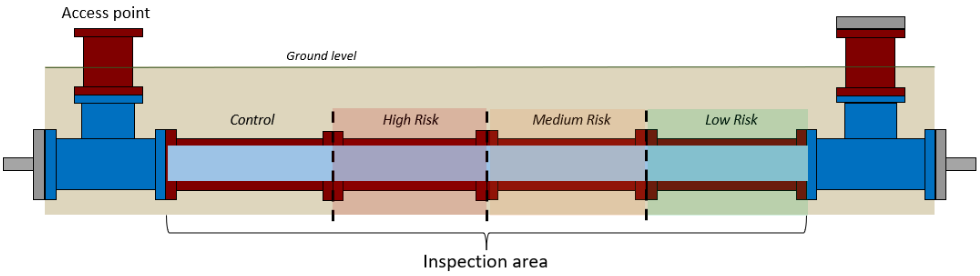


Figure 3. Test rig pipework

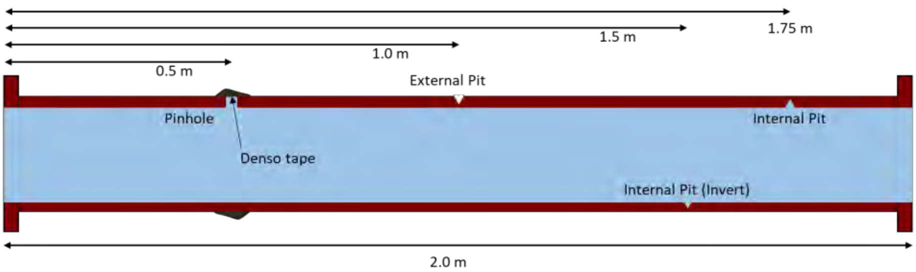


Figure 4. Pipe section with machined defects

3.4 Rig Testing

The following rig test details and summary (shown in italics) have been imported directly from the Synthotech Ltd outputs: D8 Closure Report, Appendix 8 and D5 Test Rig Trial Report, Appendix 9.

Simulated Testing at Ripon

The initial objective of the simulated testing was to validate the suitability of the crawler and halo's design for vertical insertion into the test pipe. This assessment included a dry run to evaluate the insertion process from a vertical, open riser, followed by a wet deployment into the test rig using the same approach. On each occasion, the deployment and retrieval of the robot were executed successfully, and the overall functionality remained intact throughout the entire process. A schematic of the test rig, robot insertion and speaker is shown in figure 5. Deployment of the robot into the launch pipe and the control system is shown in figure 6.

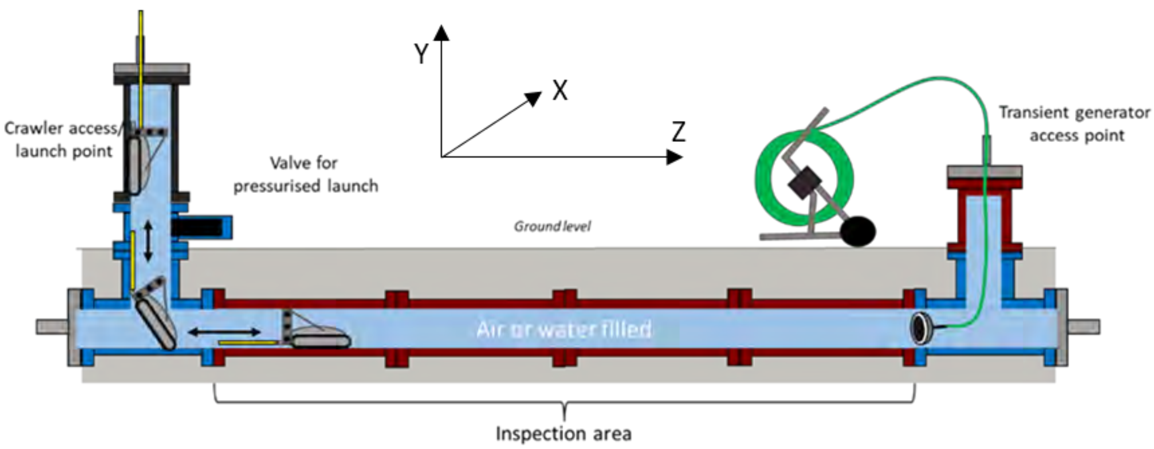


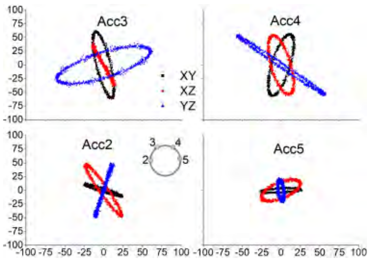
Figure 5. Schematic of the test rig, test configurations and sensor orientation

a)

b)

Figure 6. Wet deployment of crawler into test rig:
a) crawler in wet riser, b) control and display unit showing crawler visuals from within pipe.

Scans were captured within the test rig under static conditions, with the robot at rest, to evaluate both data quality and the consistency of repeated measurements. The variance among these repeated measurements was minimal, signifying that a single scan would be adequate for data collection during subsequent testing and operational procedures. Consequently, a complete circumferential scan would take approximately 36 seconds using the current data acquisition method within the proof of concept. It's worth noting that this duration could be reduced to 6 seconds if data were simultaneously collected from all accelerometers which can be completed within the next stage. Examples of repeat scans from the rig tests are shown in figure 7. and accelerometer mounting positions shown in figure 8.



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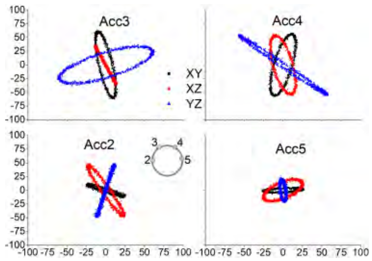

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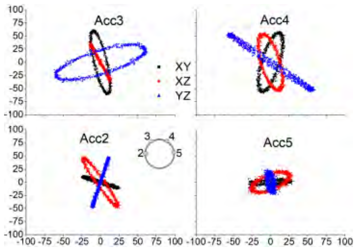


c)

Figure 7. Example of repeat scans with triaxial accelerometers within the test rig.

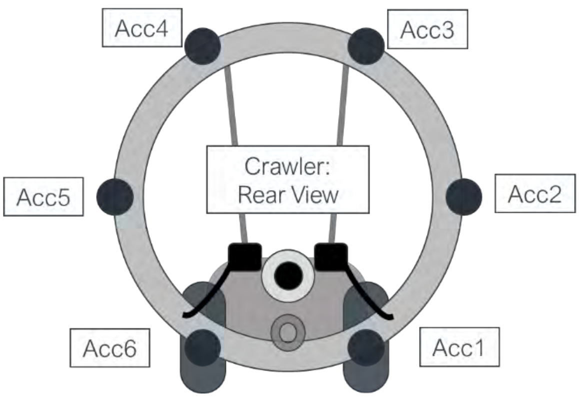


Figure 8. Accelerometer mounting positions

Joints were scanned to understand changes in the amplitude and position data compared to that of the pipe barrel. The crawler was aligned before a joint and moved forward, taking scans at different positions to track accelerometer data changes across the joint. These results are shown in Figure 9.

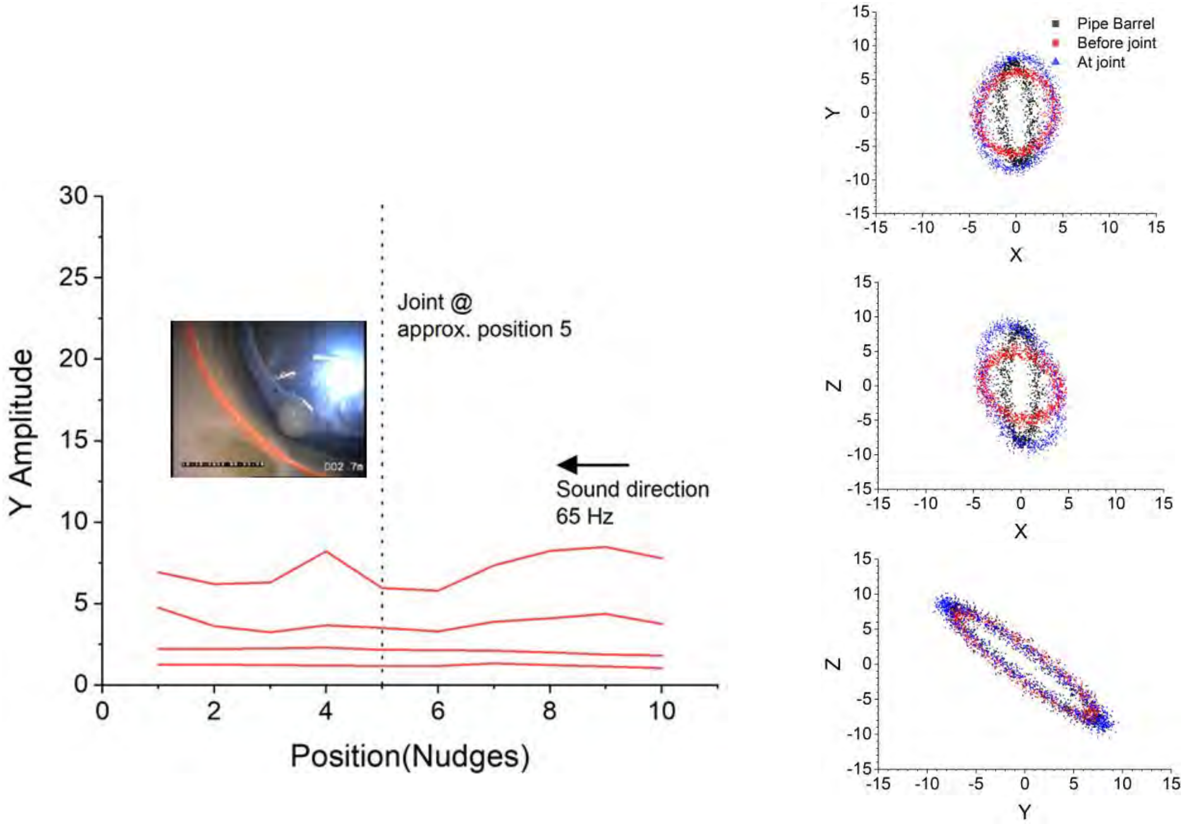


Figure 9. Joint detection with accelerometer data, showing changes in the amplitude of the three acceleration components (XYZ) in the pipe barrel (black), pipe section before the joint (red), and the joint itself (blue).

To test the system's ability to detect significant pipe structure changes, defects were created in the test rig. A 1" hole was machined, threaded, and partially sealed to simulate internal material loss. The data was captured in the same way as a joint. Figure 10. Demonstrates that this approach is capable of sensing the defect, as shown by the increased amplitude in Y around the defect, and also the angle change in the position data when compared to the pipe barrel. Further work to pinpoint the future orientation of sensors will ensure these changes in the position data are more obvious.

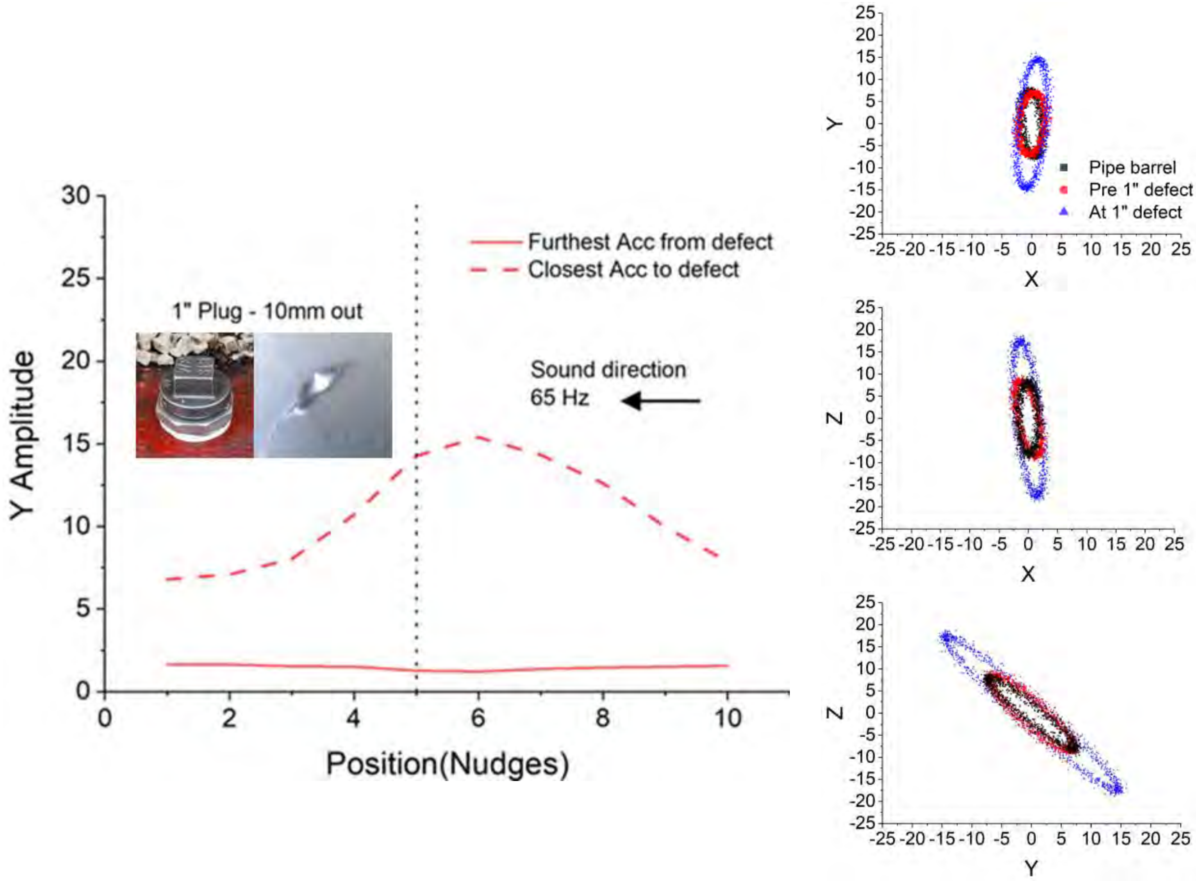


Figure 10. Defect detection with triaxial accelerometer data, showing amplitude changes over the robot's position and comparing XYZ position data of the pipe barrel (black), pipe section before the defect (red), and the defect itself (blue).

The comparison between a joint sweep and a defect sweep has revealed significant distinctions in feature characteristics, particularly in the XY and XZ dimensions. Notably, joints exhibit a tendency to become more circular with minor amplitude changes, whereas the 1" defect displays subtle angle adjustments and increased Y-axis amplitude. While further testing and in-depth data analysis are required to validate these observations across a broader range of internal pipe features, this provides a foundation to develop a portfolio of feature characteristics that can be used by operators on site.

A further technical summary of the accelerometer sensor testing, results and theory behind the concept is included in the final report from The University of Sheffield, namely: U3 Final Report, Appendix 10.

3.5 End to End Process

The final element of the testing programme was to assess the launch and recovery procedure for the inspection system. As outlined in section 3.2, the diameter of drilled tees onto host mains for access purposes was not fully explored. For the proof of concept tests, the access tees into the rig were equivalent to the main pipe diameter, namely 300mm. A launch tube was fabricated and pressure tested for insertion simulations. The outline for a potential future survey process is included in: D7 End to End Process, Appendix 11. A failure mode and effect analysis (FMEA) was also undertaken by Synthotech to capture potential failure scenarios and risks, primarily for the testing process. This output is included in: D6 FMEA, Appendix 12.

Details of the End to End Process are included below, imported directly from the D7 report: (shown in italics)

To facilitate the deployment of the system into a live rising main, an end-to-end process was devised on how the current system could be deployed on a network rising main. Based on existing live access deployment of CCTV robotic inspection systems, the process involves isolating the crawler within a launch vessel that directly connects to a valve, see figure 11.

Figure 11. Insertion trialling at the StaRs site, Ripon

The operator would control the crawler from a position near the access point, whilst managing the crawler's tether which would pass through a glanding system – a methodology that allows a tether to pass in and out of a pressurised pipe without leakage of the fluid from within the pipe. The tether is directly connected to the crawler, situated in the launch vessel. To purge the launch vessel before launch, chlorinated water is pumped in to remove the air. Any submerged system checks can then take place, in addition to leak tests of the vessel and connections prior to opening the gate valve for access to the live rising main.

To open the valve, the launch vessel must reach operational pressures. Higher pressures might require a bypass or bleed valve. Once the valve is open, the system enters the pipe and begins taking measurements. In the proof-of-concept phase, the development of the data acquisition has been the focus rather than the speed of inspection, with measurements taken incrementally. In the future with improved data capture and post-processing, data will be collected faster while the robot continually drives forward.

To retrieve the robot from the pipe, the robot is driven back to the launch point and pulled up into the launch vessel. Upon re-entry into the launch vessel, the valve is closed to isolate the rising main. Pressure in the launch vessel is relieved, and foul water is purged with chlorinated water. The system is left to sit for disinfection, and then air is pumped in to remove the water. Any launch *tube pressure is again released. The launch tube can then be unbolted from the valve, equipment removed from the network and broken down for further cleaning and disinfection on-site. To manage foul water, it's advisable to employ a hazardous waste tank for collecting wastewater from purging and cleaning. A suitable portable bowser would enhance site manoeuvrability. Disposal should align with water company practices and regulations, possibly reintroducing the wastewater into the rising main system through disposal in a wet well or other accessible foul water drains.*

This concludes the development and testing work undertaken by Synthotech Ltd and The University of Sheffield for the Pipebots for Rising Mains – Research & Feasibility Study.

4. Conclusions

The scope of this project was ambitious from the outset. The original 10 month programme required the partners to undertake field tests, design and build a robotic transport system, develop, test and interpret new sensor systems and complete rig tests. Even with the 5 month extension (due to delays with the legal agreements) the timeline was extremely challenging. All the partners, particularly the suppliers, Synthotech Ltd and The University of Sheffield have completed the work with significant outputs in terms of hardware built and testing for the proof of concept feasibility. Excellent working relationships have been maintained with all the partners throughout the project.

The use of fluid-borne triaxial accelerometers as a pipeline condition assessment tool has been investigated and the results from the tests are encouraging. The trials have shown that variance in pipe wall thickness can be determined and defects successfully identified with sensors mounted on a robot system. In this respect, the proof of concept has been achieved and the TRL has increased from 1 to 3. Further work is needed on the interpretation and calibration of data, the mounting of the accelerometers (in terms of orientation), the viability of the halo and the influence of the robot body on the results. These factors combine with the next challenge of operating in a live rising main with high pressure, fast moving, rag laden flow. Initial work focused on 300mm diameter, metallic pipe, but varying size pipe and materials will need to be considered for future development. The tracked crawler system was chosen to overcome potential silt deposits within the pipe. Existing access points into mains are extremely limited and bespoke fittings and chambers are likely to be required as part of a future end to end survey process.

There is a continuing industry need for tools to undertake internal inspections of live rising mains. Further research and development of the Pipebots for Rising Mains work should continue with an Ofwat Innovation Fund application for Phase 2. If successful, the development can continue, to build on the work to date and ultimately provide the industry with a viable rising main inspection tool. Such a tool would enable operators to assess the condition of mains, identify defects and plan rehabilitation works. This capability would reduce the risk of failure leading to pollution, reduce the risk of flooding to customers and reduce the inconvenience and expense of emergency repair works.

5. Recommendations

- The development of Pipebots for Rising Mains should continue with an application to the Ofwat Innovation Fund for a Phase 2 project. This will enable the system to be tested in live rising mains and to optimise the robot design to cope with rag and silt laden flow. This will progress the Technology Readiness Level from 3 to 6.

- The results from the project should be published and communicated to the water sector and wider industry through UKWIR, other national research communities and specialist interest groups. Wider awareness of the need for inspection tools, the challenges to overcome and the work completed to date can hopefully kickstart further development in this field.

Appendix 1. Water Breakthrough Challenge Submission

Title	**0012** by **Andrea Gysin** in **Water Breakthrough Challenge 2: Catalyst Stream Entry Form** andrea.gysin@thameswater.co.uk	12/01/2021 id. 21930876

Original Submission

12/08/2021

Welcome to the entry form for the Catalyst Stream of the Water Breakthrough Challenge 2. Please refer to the Entrant Handbook when creating your entry, which details the assessment criteria and assessors guidance for each question. This form will close at 12 noon (GMT) on 8 December 2021. There are three types of questions in the entry form: Unassessed questions - these questions are not scored but will be used to manage your entry, determine eligibility, and create announcement materials if your entry is successful. Assessed general questions – these questions are not be scored but will be used to aid the understanding of our judges and assessors when scoring your entry. Assessed criteria questions – these questions are scored against the assessment criteria. If you wish to work on more than one draft on the online entry form during the entry period, please contact waterinnovation@nesta.org.uk for assistance. If you have any questions relating to the form or the Challenge, please feel free to email waterinnovation@nesta.org.uk. Please note that we will aim to get back to you in 1-2 working days; we recommend emailing with questions as soon as you can and no later than 7 December 2021.

Eligibility Criteria

Is the lead entrant a water company (including NAVs) in England and Wales?	**Yes**
Are all entry partners abiding to the terms and conditions of the Water Breakthrough Challenge 2?	**Yes**
Do the entry partners commit to making a minimum 10% total financial contribution to this entry if it is awarded funding?	**Yes**

Is the amount of funding requested between £100,000 and £1,000,000?	**Yes**
	Unassessed Questions
	A. Entrant Details
i) Which organisation is leading this entry?	**Thames Water**
ii) Please provide the mailing address of the lead organisation.	**Clearwater Court Vastern Road Reading Berkshire RG1 8DB GB**
iii) Name(s) of Partner Organisation(s)	**Wessex Water Services Ltd: Dan Green; dan.green@wessexwater.co.uk Dwr Cymru Cyfyngedig (Welsh Water): Gemma Hall; Gemma.Hall@dwrcymru.com The University of Sheffield: Kirill Horoshenkov; k.horoshenkov@sheffield.ac.uk Synthotech Ltd: Simon Langdale; Simon.Langdale@synthotech.co.uk**
	B. Main Contact Details
i) Name of main contact	**Andrea Gysin**
ii) Main contact job title	**Head of Innovation Partnerships**
iii) Main contact's work email address(es)	**andrea.gysin@thameswater.co.uk**
iv) Main contact's work telephone number	**+447747647755**
	C. Funding
i) What is the amount you are requesting from the Fund?	**£230,930**
ii) What is the value of your 10% mandatory financial contribution?	**£34,400**

iii) What is the value of any in-kind or financial contributions excluding the 10% mandatory financial contribution relevant to the project?	**Synthotech: £47,970 equivalent covering a range of inputs. University of Sheffield (Pipebots): £30,000 equivalent covering academic & technician time (attendance at progress meetings, field measurements, laboratory work), access charges. Water companies: additional resource/cost including travel costs/expenses, overheads, lab/field visits, preparing samples, support to report writing/publicity etc.**
iv) What is the total cost of your project?	**£343,300**
	D. Intellectual Property Rights
i) Which IPR option are you choosing?	**1a. Default IPR**
ii) Default IPR	**Background IPR may be brought from the development partner, Synthotech, for the purposes of this project, however, many other companies serving the petrochemical industry have similar NDT/pipe entry technology which could be adapted using the foreground IP.** **Any foreground IPR created will be made publicly available, e.g. publication of insertion drawings, results from all trials etc., with the objective of creating a competitive market. It will not be dependent on the specific background IPR. This project is an enabler, to overcome hurdles which currently prevent surveys using existing technologies from happening; it will serve as a demonstration of the challenges and what is currently possible to the industry with the objective of stimulating further development.** **This project will rely on insight and IPR from the Pibebots project which is EPSRC funded and therefore any findings must be in the public domain.**
	E. Confidentiality
i) Confidentiality of your entry	**The entry does not contain any confidential information**
ii) Details of confidentiality of your entry	**Not applicable**
	F. Monitoring & Evaluation Questions
i) What is the duration (in months) of your project?	**10 months**
ii) Anticipated start date	**5/1/2022**

iii) Anticipated end date	**5/31/2023**
iv) Entry stage at start of project	**Level 1 - Initial research**
v) Entry stage anticipated at project completion	**Level 2 - Concept and feasibility**
vi) Are you resubmitting this entry following a previous submission to an Ofwat Innovation Fund competition round?	**Yes**
vii) Have the entry partners worked together with the lead entrant before?	**Yes, but we're partnering in a different capacity for the entry**
viii) Please explain your answer to question Fvii above.	**The partners have worked together on a range of research and innovation projects. We are coming together in this capacity for the first time for the purpose of developing a new solution to a challenge encountered by water companies; rising mains inspection.**
	Assessed Questions
	0. General Questions These questions will not be scored but will be used to aid the understanding of our judges and assessors when scoring your entry.
0.1 Entry Title	**Pipebots for rising mains – research and feasibility study**

0.2 Entry description	**Our long-term objective is to use robots to assess the condition of operational sewer rising mains from inside, greatly reducing the cost of surveying these critical assets. This project will be a world first in testing the feasibility of technologies and a catalyst to transform the way we work. Rising mains convey sewage under pressure up a gradient. Commonly made of cast iron or ductile iron, pipe walls deteriorate gradually, eventually leading to bursts which can cause major pollutions. Deterioration can be due to hydrogen sulphide attack, abrasion, and corrosion linked to ground conditions. These variables are localised and hard to predict. We want to carry out preventative inspection and maintenance to stop bursts from happening. Currently this is difficult and expensive because there is uncertainty/risk regarding which sections need surveying and mains are hard to access and shut off. We use in-pipe robotic survey methods in tunnels and gravity sewers, however, these are easier to survey as they are not under pressure. We want to build on this, testing the feasibility of technology from petrochemical sectors to address this difficult context and develop methods for full-length internal inspections. The project will be delivered in two phases. Firstly, we will take measures from the outside of selected rising mains (vibration patterns and pipe wall thickness) and we will assess old pipe sections for corrosion in the laboratory. Secondly, we will develop and test methods for inserting inspection devices into a pressurised sewer, and trial these in decommissioned rising mains.**
	1. Positive impact for water customers, society and the environment Under this assessment category, we will be looking to understand the benefits your entry seeks to deliver for customers, society, and the environment. Strong entries will be seeking to address a well evidenced, important need or opportunity in the water sector in England and Wales for water customers, society and/or the environment that aligns with one or more of Ofwat's five strategic innovation themes.

1.1.1 What is the problem that the proposed entry is seeking to address for the water sector?	**Rising mains are pressurised pipelines that convey flow from pumping stations, where sewage is pumped from a low level to a higher level for gravity discharge or treatment. A rising main burst can lead to severe environmental impact, as pressurised sewage flow from a large-scale burst or leak is likely to result in pollution via uncontrolled sewage discharge. The pipeline materials are predominantly cast or ductile iron and typically range from around 100mm to 1000mm diameter. Managing sewer flows in the event of a burst can have a widespread impact on customers and society. If a pumping station and rising main need to be isolated to complete a repair, upstream flows need to be dealt with, normally via road tankers which is an expensive, short-term solution. The reduced capacity at the pumping station can lead to increased risk of flooding for customers upstream. Increased vehicle movements (tanker movements in the vicinity of the pumping station) can be disruptive and temporary traffic management may be needed. Increased vehicle movements also have an additional environmental impact. The development and availability of 'in-pipe', live inspection tools are desperately needed for rising mains, an asset which is unique to the water sector. Such tools would enable operators to gauge the condition of mains, to identify defects and plan rehabilitation works. This capability would subsequently reduce the risk of failure leading to pollution and the secondary impact of increased risk of flooding to customers and inconvenience to society during repair works.**
1.1.2 What, if anything, has already been done to understand and address this problem, either by the entry partners or others?	**To date: Thames Water (TW) has undertaken research with University of Surrey to improve understanding of deterioration of cast iron. Previously focussed on clean water, wastewater has recently been included, however, not to rising mains and aspects are different e.g. H_2S. This research has shown pipe condition is very variable and needs full length in-pipe assessment. TW have invested in a test facility to stimulate the market for clean water and this project is intended as a catalyst for waste. TW has captured failed rising main samples and forensic studies to improve the understanding of failure. An archive over 20 years has been established. This information has been used to target investment however, local asset condition is needed to be more pro-active. Other water companies also express this need. The partners have supported development of potential rising main survey techniques with WRc. Tests including gross metal loss, Sahara and conductivity leakage have been conducted on live mains with limited success. Review and testing of Non Destructive Techniques, from suppliers within and outside the water industry. Including communication and joint projects with industry leaders worldwide (e.g. Sydney Water and UKWIR). However, no solutions are available to the water industry that completely meets our needs at an affordable price. For example, operating in wastewater environments, unknown bends, partial blockages and limited pipe wall contact due to sediment/deposits. Also addressing the technical challenges of entering/surveying live mains over long distances. It is hoped this project will be a catalyst to the industry's development.**

1.2.1 How will this entry directly deliver better short and long-term outcomes against one (or more) of Ofwat's five strategic innovation themes?	**This project can be measured against 4 of Ofwat's 5 strategic innovation themes: Restoring and improving the ecological status of our water environments, protecting current and future customers from the impacts of extreme weather and pollution: All water and sewerage companies need to reduce pollution incidents to improve water environments for customers. Improved asset performance is key to this. This project seeks to develop tools/techniques to reduce the risk of significant pollution events caused by burst rising mains. Understanding long-term operational resilience and infrastructure risks to customers and the environment, finding solutions to mitigate these in sustainable and efficient ways: Water companies need to maintain and enhance an extensive, ageing sewerage network. The availability of reliable, cost-effective inspection tools, would improve understanding of the assets to enable efficient, planned rehabilitation works to reduce environmental risk. Responding and adapting to climate change, including how to meet the sector's ambition of net-zero emissions: To improve customer service, water companies need to increase the resilience of their infrastructure to cope with current and future demand due to climate change. Widespread use of in-pipe survey methods, we would reduce the need for excavation for external testing, reducing the associated operational emissions involved. Testing new ways of conducting core activities to deliver wider public value: Planned inspection and maintenance would reduce the risk of disruption caused by sudden asset failure. Planned work would enable the protection of nature and amenities enjoyed by local communities. Costs of surveys would reduce by increasing competition amongst suppliers.**
1.2.2 Select which theme(s) your entry is impacting:	**Please select the Ofwat theme(s) which are directly impacted through this entry.**
Theme most impacted:	**2: Restoring and improving the ecological status of our water environments, protecting current and future customers from the impacts of extreme weather and pollution**
Theme second most impacted:	**3: Understanding long-term operational resilience and infrastructure risks to customers and the environment, finding solutions to mitigate these in sustainable and efficient ways**
Theme third most impacted:	**1: Responding and adapting to climate change, including how to meet the sector's ambition of net-zero emissions**
Theme fourth most impacted:	**4: Testing new ways of conducting core activities to deliver wider public value**
Theme fifth most impacted:	**Not applicable**

1.3.1 What are the entry's intended outcomes?	**This entry intends to accelerate development of rising mains in-pipe condition assessment and proactive rehabilitation technologies to meet water industry needs and stimulate other supplier products to the market, increasing competition and consequently providing cost-effective solutions. This will also reduce repair/replacement costs by enabling more targeted solutions through better condition assessment hence benefitting customer bills and protection of the environment. This aims to be a catalyst for the industry: This project will define water industry needs for rising mains condition assessment technologies to support suppliers to develop suitable innovative solutions . Demonstrate the transferability of condition assessment inspection techniques e.g. from petrochemicals, to rising mains. This will hopefully stimulate development of solutions onto the market to meet water industry needs at a competitive price for the benefit of all customers in England and Wales. Technical studies completed within this project will be documented and shared with universities, water and oil/gas industry by the retrospective partners. It is intended this will demonstrate the constraints and opportunities for development at different Technology Readiness Levels (TRLs) stimulating innovation in the market to meet the need. Overall positive outcomes will be to; Improve the performance and resilience of rising mains by enabling 'in-pipe' inspection of defects, planning rehabilitation work, reducing the risk of failure and pollution, enhancing the amenity value of watercourses, rivers and lakes. Improve customer service by reducing the risk of bursts and pollutions, leading to reputational benefits to the industry. Demonstrate to customers that the industry can innovate and develop novel technologies to improve the performance of assets. Determine the constraints and opportunities for future market stimulation for innovative development and applicability to rising main inspections. Develop tools to enable improved asset management and targeted investment to reduce customer bills and improve environmental performance.**

1.3.2 Provide an explanation of how this initiative will achieve the entry's intended outcomes.	**The proposed work will aim to achieve the entry's intended outcomes by taking a practical approach to the challenge. A two-stage programme will enable initial viability of the concepts to be tested and evaluated prior to larger scale trials. Phase 1 will field tests sensors and tools on the external surface of at least two rising mains. The data collected will be analysed to interpret the recorded results for practical condition assessment purposes. In parallel with this, similar work will be done on exhumed rising main pipes samples and verified by shot blasting to determine the extent of corrosion. This initial work will provide a good basis for a range of conditions likely to be encountered across the industry. Phase 2 will then move onto the practical challenge of under pressure insertion of robots and equipment (as a vehicle for the sensors) into live rising mains. The equipment will be tethered to ensure it can be safely retrieved. Data analysis will be undertaken to interpret results and assess the viability of the technique for condition assessment. Technical studies will be documented and shared with universities, water and oil/gas industry by the retrospective partners. This will demonstrate the constraints and opportunities for technology development stimulating the market. The water industry needs will be defined, and challenges demonstrated including: the performance of sensors on rising mains, if these can be mounted on autonomous robots and transferred to live rising mains overcoming insertion issues and the environment e.g. silt, rag and bends This practical approach to the testing, development and publication is necessary as the first steps towards achieving the longer-term goal of internal condition assessment for live rising mains. With reliable inspection tools, the benefits of planned works and targeted repairs to reduce the risk of failure can be realised.**
1.3.3 What longer-term impacts and benefits will the entry provide for the water sector in England and Wales, once the project has been completed?	**By creating a unified process for rising main condition assessment and sharing these openly with the supply chain, a competitive and level playing field for innovators will be established in the UK. This will stimulate the market and SME investment. Direct benefits will see the availability of proven and tested pipe condition assessment tools, providing capability to identify defects and undertake rehabilitation works. This will reduce the risk of failure/pollution and indirectly benefit society and the environment with reduced reactive repairs. Innovative 'no dig' inspection technologies are essential for the water sector of England and Wales. Customer tolerance reduces for repeated repair and the associated disruption caused by reactive works. Costs to the environment and customers can be reduced by improved asset performance. Cost effective inspection tools are key the step change in performance required. In Thames Water, during 2019, two of the 15 serious pollution events were linked to rising mains (approximately 15%). From a total of 373 Category 1-3 pollution incidents in 2019, 18 incidents were due to rising mains, approximately 5% of the failures. If a monetary value is considered for each event, and multiplied across the industry, cost savings and performance improvement are significant.**

1.4.1 What are the most significant external risks of your entry and how have they been considered and addressed in the development of this entry?	**This initiative proposes an ambitious, innovative technological challenge to develop tools for the internal condition assessment of rising main pipes. As such, there are many direct and indirect risks associated with the work. Linked to the direct risk of technical feasibility, there are fundamental unknowns on the performance of materials, their mechanisms of deterioration and tools to measure this. Much academic study has been undertaken over the years to build knowledge around this subject and more is needed. As such, there is uncertainty that the basic science and principles selected to provide the required insight into the condition of the pipes, may not give the level of confidence required. However, research so far does indicate that for metallic mains, metal loss can be very variable along the pipe length/circumference and actual inspection will provide better data than trying to infer from other (e.g. environmental) data. Inspections will generate a lot of data which brings another potential risk as this will need to be interpreted, however, improved data storage, handling and analysis capabilities in recent years largely mitigate this risk. Again, linked to the direct risk of technical feasibility, the overall viability of the concept of inserting robot inspection devices into live rising mains is unknown at this stage. However, by drawing on experience from synergistic sectors and applications, the project plans to overcome this barrier. The wider goal of demonstrating the potential to the sector, to stimulate the market and reduce costs, may not be achievable and/or may require more fundamental research/development than currently envisaged. However, having partnering with Pipebots and Synthotech will mitigate this significantly. There is a risk the market may not be stimulated to take up the challenge following this project. The team are intending to articulate and communicate a clear water industry need to engage potential suppliers, this should be a two-way process and feedback regarding hurdles is essential to future success. A follow-on project may be a consideration if required. Longer term regulatory policy changes could influence and change the market in the future. For example, to reduce the risk of future pollution, water companies could be obliged to entirely relay/rehabilitate any mains that fail, so the need for specific condition assessment tools would diminish. Alternatively, the current very strong drive public and regulatory driver to reduce pollutions may diminish. We feel these scenarios are unlikely owing to respective cost and social/environmental pressures. The initiative proposes to focus on the development of inspection tools for rising mains in larger size range, typically 450mm diameter and above. The larger mains pose a higher risk of pollution in the event of a burst or leak. There are, however, a significant proportion of rising mains of smaller diameter that would benefit from inspection. There is a risk that technology developed and tested in larger mains, may not be adaptable or suitably miniaturised for use in smaller pipework, however, Synthotech has capability in the development of inspection systems as small as 10mm. This could limit the overall market.**

1.4.2 How do the benefits of this entry justify acceptance of the external risks?	**The potential development of a system for the internal condition assessment of rising main pipework will yield several benefits. It can enable the identification of faults in pipework , thereby enabling targeted rehabilitation works to be planned to reduce the risk of leaks or bursts. The reduced risk of failure will, in turn, reduce the potential pollution incidents that often result from failures. For example, during 2019 in Thames Water, two of the 15 serious pollution events were linked to rising mains, approximately 15%. Eliminating rising mains failures and the resulting pollutions is therefore vital to achieving the industry's stated aim of zero uncontrolled discharges from sewers. The monetary cost and environmental impact of pollution events vary depending on scale, although all are unacceptable. Fines and reputational damage for pollution incidents, specific to rising mains, cost the industry millions of pounds each year. The potential benefits, however, need to be balanced against the risks. The ambitious objectives of the initiative may not be achievable, however, we believe the risks and mitigation measures set out in our answer to question 1.4.1 maximise our changes of success. Investment to develop, test and trial techniques is ultimately speculative, although based on sound engineering principles and expertise. Similar technologies for similar applications are available to the petrochemical industry and need tailoring to water industry needs and affordability. The ultimate objective of the work is to improve the performance of assets to reduce the risk of failure leading to pollution. There is risk that the funds invested in the initiative may not yield immediate monetary benefits, however, the cost of fines and reputational damage to water companies is extremely high and we therefore believe this relatively small speculative investment to develop tools that could lead to improved performance is justified.**
	2. Innovation enablers and innovative solutions Under this assessment category, we will be looking to understand what is novel about the proposed approach and solution, and how it could deliver a positive sector-wide innovation legacy. Strong entries will demonstrate how the proposed entry goes beyond the entrant's business-as-usual approach to innovation and how it may draw inspiration and/or talent from other sectors. This is both in terms of what the entrant proposes to deliver (innovative solutions) and how they propose to deliver it (innovation enablers). Innovation enablers are the innovative approaches the entry is proposing, which may include how entrants are working internally and externally with collaborators within and outside of the water sector for the benefit of water customers in England and Wales. Entries could include testing new ideas; adapting ideas or practices that have established themselves in other sectors; or adopting proven approaches that haven't been tried at scale.

2.1.1 What solutions, technologies, methodologies, and/or insights are you intending to use?	**The Pipebots team led by the University of Sheffield will initially undertake in-situ, external tests on live cast and ductile iron pipework using accelerometers, ultrasonic probes and electromagnetic (EM) induction sensors. This will enable the measurement of vibration patterns and an assessment of wave propagation through the pipe wall to be taken for a range of pipe conditions and pumping regimes. This work will help inform decisions for the subsequent 'in-pipe' tests. In parallel with this, Synthotech will undertake an internal CCTV survey of an appropriate rising main to analyse the internal surface and flow conditions. Synthotech have extensive expertise in the inspection of pipelines in the gas and water industries and will adapt existing equipment as required. Following this work, phase 2 of the project will see the Pipebots and Synthotech teams working together to mount suitable sensors on a tethered 'in-pipe' crawler unit. A system to install safely and economically the crawler into a pressurised main will also be developed by Synthotech. With all the elements complete, the viability of 'in-pipe' surveys for live rising mains can be tested and evaluated on a range of pipe sections of representative area and length. Pipe wall thickness measurements will enable the structural integrity of the material to be assessed. The range of the surveys and hence the number of access points on a main to facilitate overall inspection will be established.**

2.1.2 What is innovative about your entry? How are the solutions, technologies, methodologies, and/or insights better than what has been developed and/or deployed in the past? Why would it not reasonably be expected to be funded as part of business as usual?	**To define what is innovative about this project, it is necessary to outline current practice and limitations of existing inspection tools. Difficulties of accessing rising mains, costs and inconvenience to customers for temporary shutdowns mean that most maintenance/inspections are reactive. Opportunistic access is available after a burst. Certain high risk/high consequence mains may be targeted for proactive inspection, but options are limited and expensive. Rising mains are occasionally shut down to allow CCTV surveys to be undertaken, but this is only visual inspection, not measuring metal loss. Existing methods of external pipe analysis, for example, using ultrasound, only allow a ‘snapshot’ at specific points along a main. Varying ground conditions can affect the rate of external corrosion so spot samples are not always representative of overall condition. Capability is needed to internally assess the condition of a live main over the full length, pinpointing locations where work is needed, thus optimising planning and investment. This capability does not currently exist. We have no methods for inserting inspection devices into pressurised sewage pipes, and no devices that can scan the pipe wall to detect loss of material. The nearest technology available is the WRc Sahara system which is used to detect leak noise in clean water supply pipes. Unfortunately, the system is not suited to identifying defects in rising mains. Free swimming devices have been developed and tested for clean water mains, but rarely used due to cost and complexity. Technology from the petrochemical industry need to be adapted for the water industry so is at low TRL in this context. The robotic devices proposed will potentially, for the first time, record at reasonable cost the diminution of wall thickness over an entire rising main. Once correlated to local geology, this would greatly increase our predictive capabilities and ability to carry out pre-emptive repairs. The proposed project aims to demonstrate the feasibility of the concepts and is likely to require further development. The potential to share development costs and benefits across the industry is key and would be beyond the ‘business as usual’ (BAU) investment options for an individual company.**

2.2.1 What approaches, ways of working and other enablers of innovation are you intending to use?	**This three-way collaboration between water companies, academia and specialist suppliers with experience in petrochemical sector is a new approach to sewer management for the industry. In the past, sewer maintenance innovation has resulted from one-to-one relationships between water companies and solution developers or supply chain companies. For this project, the water company partners have initiated the work as a collaborative consortium, rather than being approached to join a group convened by another organisation. Pooling resources and data are likely to be crucial in the future as the industry will need to develop deterioration models that are built on proven cases studies. This will provide the confidence needed to for decision making going forward. By including Synthotech the partners have looked beyond the typical suppliers of solutions for the water sector, involving a technology partner with transferable capabilities developed for gas networks. Pipebots provide highly technical expertise with a long-term vision of innovation for pipe networks. This is coupled with a background understanding of metal pipe measurement and deterioration. The project takes the opportunity to use the Water Breakthrough Challenge to catalyse innovation in an area that is under-served, looking beyond immediate, readily-available solutions which do not adequately meet industry needs.**

2.2.2 What is innovative about your approach? How are the approaches and ways of working better than what has been developed and/or deployed in the past? Why isn't this approach developed as part of business-as-usual practice?	**The innovative, combined and collaborative approach from the project partners will accelerate development and testing capability in a way that would otherwise be unachievable. Each partner brings value in terms of experience, expertise, and facilities. The innovative way of working is an improvement from the past, where water companies have acted alone or with one specific supplier to develop new technologies. Collaboration enables resources to be pooled and knowledge sharing in an open working environment, with no barriers or individual ambitions to secure or protect intellectual property. This way of working will provide benefits to the partners and wider industry. Individual companies undertaking investment in the pursuit of new tools as part of their 'business as usual' will inevitably be protective of their investment. As such, the likelihood of a broad collaborative approach is reduced. The unified approach will improve working relationships across the sector and establish beneficial future ways of working. The project phases will be progressed in parallel by the different partners which will accelerate the project progress, enabling outputs to be delivered in a relatively short timeframe. It is also envisaged that discoveries during this project will demonstrate different aspects of the capability required are at different TRL's and through the consortia, can be communicated and addressed by the most appropriate partner (e.g. low TRL would be more university-based research). For this reason, there will be regular interaction between teams working on individual phases and with the project steering group, to ensure that learning/insight is shared as it arises. Looking ahead, if this project succeeds, it is likely that it will enable further collaborations that will also go beyond business as usual. The first could be increased transfer of experience and knowledge of in-pipe survey techniques between wastewater and clean water supply networks. Secondly, next generation pipe robotic systems as new entrants to a market, will benefit as the concept has been shown to be feasible (thereby increasing appetite of clients/accelerating uptake). The whole sector will benefit as this drives up quality, increases the range of potential solutions, and drives down cost.**

2.3.1 Following the successful delivery of this entry, how could it be implemented at scale across the water sector in England and Wales and what steps will you take in your entry to enable this? What challenges and/or barriers to further implementation have you identified?	**By demonstrating the potential benefits of this early-stage technology and sharing with the supply chain, this entry will drive innovation and facilitate development of technology solutions that meet a market need shared by water companies. Asset condition data leading to improved operation/reduced pollutions is an industry-wide need. Implementation will be facilitated by publishing the results from the project and trials, promoting these through UKWIR, other national research communities and specialist interest groups, such as SWIG. The project partners will also leverage their existing networks; Pipebots alone includes over 40 partners spanning academia, supply chain, infrastructure companies and regulators in the UK and overseas. Successful wider implementation at scale will be reliant on suppliers of such technologies identifying the market and developing their products. This may require intermediate funding and collaboration with suppliers. As a partner, Synthotech will bring practical and commercial skills to develop the technology for wider implementation at scale. There is a risk that technology developed and tested in larger mains, may not be adaptable or suitably miniaturised for use in smaller pipework. As explained in our response to 1.4.1, we believe we have mitigated this as far as is reasonable through our selection of partners.**
	3. Capacity, capability and commitment to deliver Under this assessment category, we will be looking for a clear narrative demonstrating strong evidence that the proposed entry is feasible and that appropriate resources and governance will be in place for its delivery.

3.1.1 Who are the senior sponsors and leaders involved in the entry, from the lead water company and partner organisations, and how are they engaged and invested in it?	**Thames Water: Senior sponsor, Martin Perrin, Director of Waste Asset Strategy and Planning. Over AMP7, Thames Water has committed to reduce pollutions by 30% from 2019/20 levels, with the long-term aspiration to achieve zero pollutions. Martin is accountable for investment strategy, ensuring that we meet both AMP7 and long-term objectives. Wessex Water: Senior sponsor, John Thompson Executive Director of Engineering and Sustainable Delivery, supports this application for Ofwat innovation funding to progress robotics for gross metal loss assessment. Welsh Water: Senior sponsor, Robert Jones, North Asset Manager (Below Ground Assets), supported by the Research and Innovation Manager, Faye Ward. Welsh Water have a strong commitment and ambitious targets to reduce pollutions. Synthotech: Senior sponsors Mark Tindley (CEO) and Simon Langdale (Engineering). Both are responsible for the development and implementation of cross sectoral technology development and its transfer. Simon is responsible for the technology development and brings experience for the development of live access inspection robotics from pressurised gas pipelines and Mark brings water market experience/knowledge. Sheffield University: Pipebots is a research grant funded by the Engineering and Physical Sciences Research Council (EPSRC). This grant is led by the University of Sheffield and involves the Universities of Birmingham, Bristol and Leeds. Its ambition is to create the new science, knowledge, technical capabilities to develop and deploy swarms of small robots to operate in underground pipe network with no or minimal human intervention. This project aligns with this entry so demonstrates their commitment.**
3.1.2 Are any additional contributions, above the mandatory 10% contribution, committed to the entry from entry partners (including financial and non-financial)?	**Synthotech are contributing in-kind 30% of their resources to this project, equivalent to £47,970. This covers a range of inputs to the project. They bring wider technology development expertise from the water and gas industry, access to their R&D facility and committed to presenting the work to the oil and gas industry to help stimulate the market. Pipebots team led by Sheffield University are supplying in kind academic, technician time and access to their bespoke experimental facilities. This includes attendance at progress meetings, field measurements, laboratory work and access charges. This is equivalent to £30,000 of resources. Thames Water, Wessex Water and Welsh Water are also providing additional in-kind resource/costs above the value calculated specifically for facilitating the project. This will include provision of data, travel costs/expenses, overheads, lab/field visits, preparing samples, support to report writing /publicity etc. Thames Water will also provide access to our archive of failed rising mains, comprised of failed rising main samples and forensic studies to improve the understanding of failure, gathered over 20 years.**

3.2.1 Please provide a description of the entry delivery team. Include team structure, roles, responsibilities, skills and experience.	**The project team has partners with distinct capabilities: water company engineers, researchers specialising in sensors, and a manufacturer of robots for difficult environments. Each partner has a clear role, which will aid collaboration throughout the project. We will uphold principles of collaborative project management, e.g. ensuring all are involved from the start in planning and control processes; central point for documents/data; and encouraging transparency about aims and emerging issues. For governance we will use two main groups: A steering group to meet monthly to oversee progress (timetable, milestones, deliverables). This will include the water companies involved but also an extended invite to other water companies to help steer the project. Academics from Pipebots team and other universities will also be invited. Synthotech will be represented as a supplier. Others will be invited as/when appropriate. A delivery team that meets fortnightly on project implementation details e.g. technical challenges, specifications, logistics. This group will meet more frequently when work on site is imminent or underway. It will ensure that operational colleagues in the water companies are fully involved to ensure that this project is inclusive. Thames Water will act as the project lead and the following team has been assembled for this project: Project director – Rachel Cunningham, Thames Water – over 25 years of experience in the delivery of R&D programmes – responsible for the overall direction of the programme. Project manager – Dejan Vernon, Thames Water, Wastewater Networks Research Manager– over 15 years of experience on wastewater R&D - responsible for ensuring the project delivers on time and budget, co-ordinating resources, leading stakeholder engagement. Technical lead - David Walters, Thames Water, Principal Research Engineer over 25 years of experience in R&D testing/technology development in wastewater networks – responsible for technical direction of the project, leading engagement with the steering group, primary interface with the development partner. Wessex Water will lead on the field trials. Technical and testing lead - Julian Britton – Programme Manager, Sewer Rehab- over 25 years of wastewater engineering experience and a leader in the UK field of rehabilitation and maintenance – responsible for the delivery of Wessex based field trials. Research lead, Pipebots - will provide the access to the sensing, robotics and communication science expertise, research and academic staff and facilities. Leading on the testing and development of the sensor solution. The team will also carry out the analysis of the data collected in the laboratory and field. The main individuals involved are: Professor Kirill Horoshenkov (University of Sheffield) Professor Simon Tait (University of Sheffield) Professor Bruce Drinkwater (University of Bristol) Development lead, Synthotech - Synthotech is an innovative engineering company with a proven history of design, development, manufacture and supply services to the utility and infrastructure industries worldwide. For this project, Synthotech will lead on design and development of proof of concept devices and on site support for testing in decommissioned pipes. The main individuals are: Simon Langdale Mark Tindley**

Please upload an organogram detailing the structure of the entry delivery team (JPEG, PNG or PDF).

Pipebots_Rising_Mains_Breakthrough-Catalyst-FINAL.png

3.3.1 Please set out the major milestones and activities for the entry.	**PHASE 1: External inspection and sensor optimisation Phase 1 tasks: 1a External pipe assessment: data collection from devices deployed on at least two rising mains; followed by completed data analysis. 1b Lab-analysis: conclusions regarding the deterioration seen in exhumed pipe section. 1c Desktop study Phase 1 milestones: Initial sensor data collected from the field New data on sensor performance collected and analysed Optimal sensor arrangement Operating conditions and sensor requirements defined. Phase 1 success measure: Conclusions regarding deterioration, its detection and user needs defined - Report signed off PHASE 2: Developing Proofs of Concept (POC) for accessing rising mains Phase 2 tasks: 2a. Sensor insertion POC for tethered inspection robot in a live rising main. 2b: Development of POC robot platform to transport sensors through the pipe, and tested in a simulated pressurised tank / pipe, using Synthotech andPipebots facilities. 2c: Develop sensor package including additional testsand wiring to the control system. Phase 2 milestones: Access POC available for simulated testing Robot POC platform available for simulated testing at 2-10Bar Draft operational RAMS and training Sensor housing available for simulated testing at 2-10Bar Phase 2 success measures: Robot insertion successful - attachment of insertion devices; conclusive comparison of potential access points; successful insertion and retrieval. In-pipe sensing: successful data collection from robot-mounted sensors; minimising problems posed by sewage; proven methods for negotiating silt and other problematic surfaces Full report and conclusions signed off**

3.3.2 What project controls will be implemented and what is the monitoring plan for the delivery of the entry and its outcomes?	**The project governance structure has been designed with openness and adaptability in mind, ensuring that decisions, risks, uncertainties and disputes can be managed efficiently and effectively without stifling innovation. Our response to question 3.2.1 outlines the delivery team structure, which shows the lines of communication and escalation, should it be required. It strikes a balance between accountability within Thames Water, as the lead organisation, and partner organisations (recognising that partners will steer and deliver discreet phases of the project). A RACI framework has been developed which links to the project governance, ensuring clarity of the roles and responsibilities of team members, and aiding in risk management as well as the decision-making and dispute resolution. A stage gated governance process will be followed for all decisions; this is based on Thames Water's established governance and has been adapted to provide the agility required to manage the uncertainty inherent in innovation projects. At each stage gate (validation, solutioning, delivery and benefits realisation), decision making will be aligned to the RACI. As well as meeting monthly to support the delivery, the steering group will also be a key consultee for stage gate decisions, ensuring that the project reflects the needs and desired outcomes of all project partners and stakeholders. Deliverables and outcomes will be kept under continuous review throughout the project; the Delivery Team will ensure alignment with the strategic and technical objectives whilst the Project Manager will ensure that the delivery is on time and budget. The Project Director is ultimately accountable for delivery, including any change control that is required. Risks and uncertainties will be centrally managed and captured in a standard Thames Water risk register. This utilises heat maps to assign risk levels and allows contingency and mitigation plans to be made when a risk is initially identified, and if a risk is escalated. This register and review process allows for early warning/indication of potential risk escalation, and so contingency plans can be developed ahead of an issue arising.**
3.4.1 What is the breakdown of the entry costs, including the assumptions made?	**Please complete Tabs A, B and C of the Entry Template. Download the Entry Template here.**
3.4.2 Other than that, provided by any of the entry partners, what other sources of funding or in-kind contributions will be needed to support this entry?	**Not applicable**

3.5.1 What are the risks and opportunities that have been identified for the entry and how will they be managed or mitigated?	**For a highly innovative project such as this, we cannot foresee all possible risks. However, we will have at the disposal of the project a team of engineers that have encountered complex situations previously and are adept at rapidly improvising solutions. Technical issues are the biggest challenge to this project and key risks are listed in tab D of the entry template. These issues will be mitigated by using test samples and environments including a decommissioned main and using rigorous H&S procedures. We have chosen to focus on larger diameter mains as the consequence of failure is higher and greater chance of technology success. The main opportunities are as set out in section 1a, e.g. the opportunity to develop a much lower cost, lower carbon means of maintaining a critical asset type, that can be highly disruptive when they fail. Furthermore, with the ubiquity of rising mains around the world, there is a great opportunity to develop a world first technology that could be highly marketable globally.**

Please upload your completed Entry Template.

Pipebots_Rising_Mains_Breakthrough-Catalyst-FINAL.xlsx

Appendix 2. U2 – Field & Lab Testing Report

Rising Mains Measurement Report - UoS

Introduction

This report presents the results of Phase 1 of the Rising Mains project. Phase 1 was to measure the pipe wall vibration on selected sections of rising main at field sites in Bretton village (Wales) (figure 1.) and Christchurch & Weymouth (Dorset). The site visit in Bretton was on 4th August 2022, organised by Welsh Water. The Christchurch site visit was on 13th September 2022, and the Weymouth site visit 30th January 2023, both organised by Wessex Water. The purpose of these site visits was to study the displacement of the pipe wall whilst the pump(s) generated flow through the pipe. The frequency domain properties will inform the design of the sensor array to be deployed on a robot for the inspection of rising mains.

Location

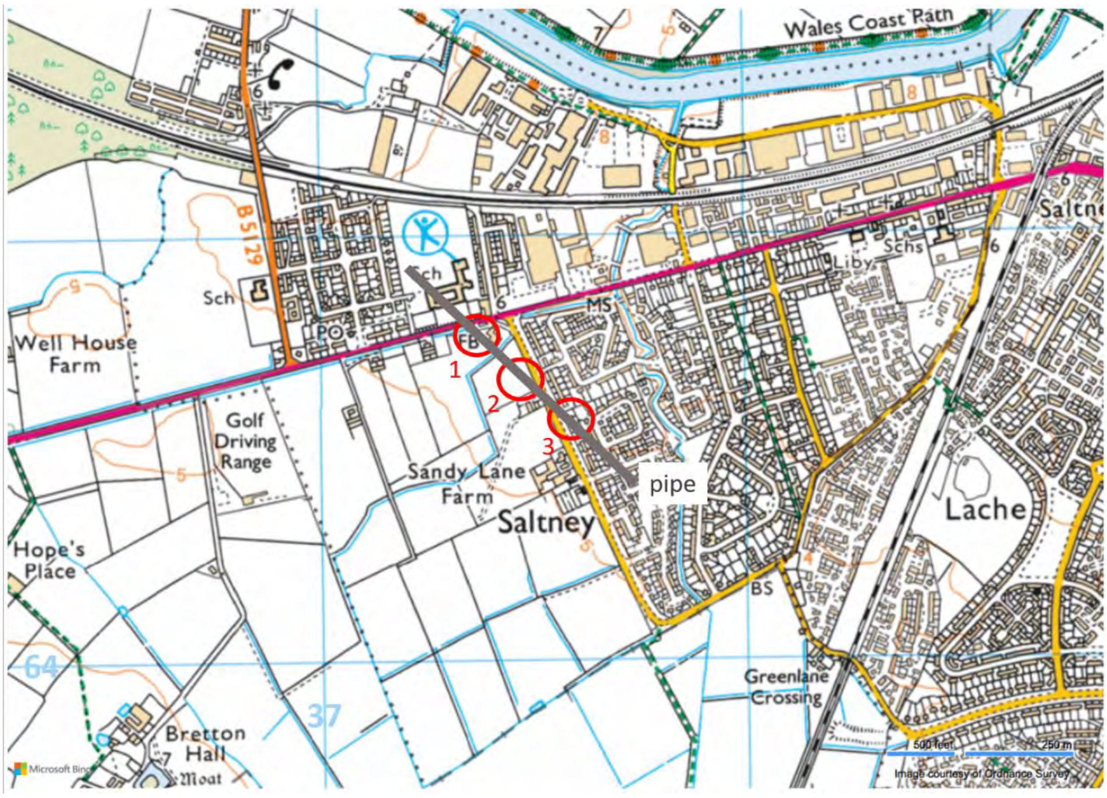


Figure 1 - Map of Bretton village site

In Figure 1, the grey bar is the buried pipe, and the measurements were taken at three locations marked by three red circles.   is the map of the Christchurch site. In total, four locations were used to measure the vibration in Christchurch.

Methodology

In Bretton, two Type PCB 393B04 accelerometers were attached externally to the 300 mm cast iron pipe. The accelerometers were connected to a National Instrument Data Acquisition System (NI-DAQ/ NI-USB-4432). The sampling rate was 2000 Hz. The vibration of the pipe wall was captured by the accelerometers and recorded by the computer connected to the Data Acquisition System. The test set up for this site is shown in Figure 3 schematically. The accelerometers were placed on the top and bottom (12 o'clock and 6 o'clock positions) of the pipe, respectively. Two magnets and nylon straps were used to hold the accelerometers in place (see photos in Appendix A). The measurement period was 45 mins to make sure multiple pumping events could be recorded and analysed.

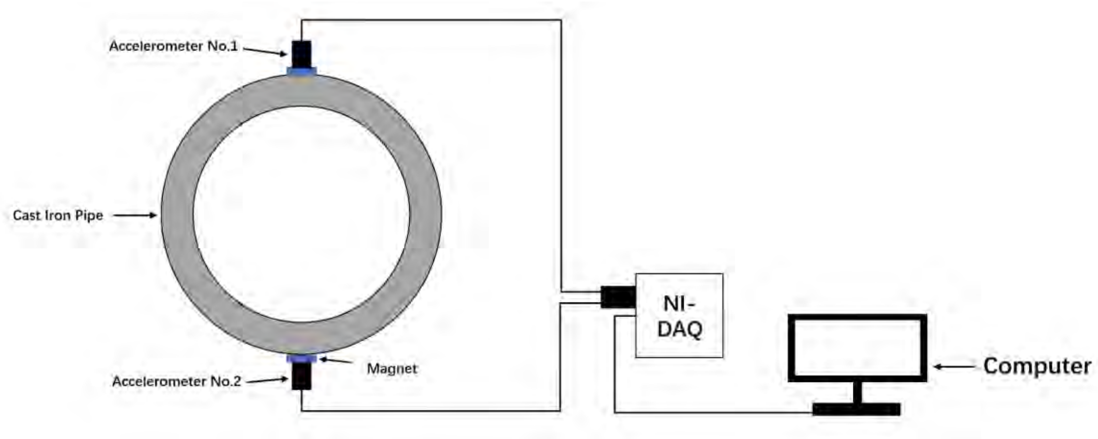


Figure 2 Test setup for Bretton Site

The setup for the Christchurch site was slightly different, as shown in Figure 3. Three accelerometers were used there. An extra accelerometer was added to the 400 mm ductile iron pipe (at 3 o'clock position) to provide additional data. Appendix A shows some photographs of the equipment taken at these two sites.

The acceleration was converted to displacement by using double integration implemented numerically:

$$s(t) = \int_{-\infty}^{\tau'} \int_{-\infty}^{t} a(\tau)\, d\tau d\tau' \tag{1}$$

where $s(t)$ is the displacement and $a(t)$ is the measured acceleration. This conversion enabled an estimation of the maximum displacement of the pipe wall and its spectrum, caused by the transient pumping events and background noise.

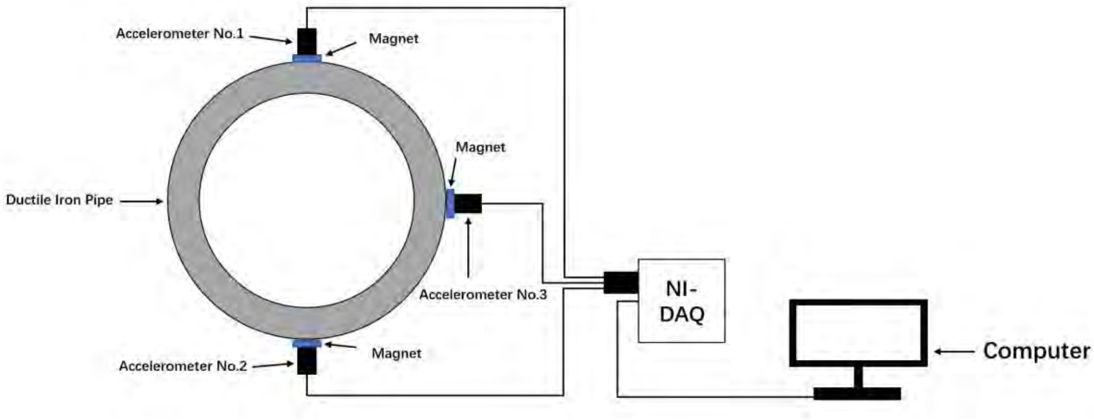


Figure 3 - Test setup for Christchurch Site

Results

Bretton, Chester

There were 3 measurement locations in Bretton village (see Figure 2). In total, 14 pumping events were observed in the recordings over two days of measurements. Each pumping event produced a clear transient pressure event. These events were similar in terms of their time evolution and the maximum displacement reached at the peak of each event. The maximum pipe wall deformation was in the range of 1-2 μm and each event lasted for approximately 500 msec. Figure 4 is an example of the time history of the pipe wall displacements recorded on the two accelerometers (A1 & A2) for a transient event measured in Bretton village at location 1.

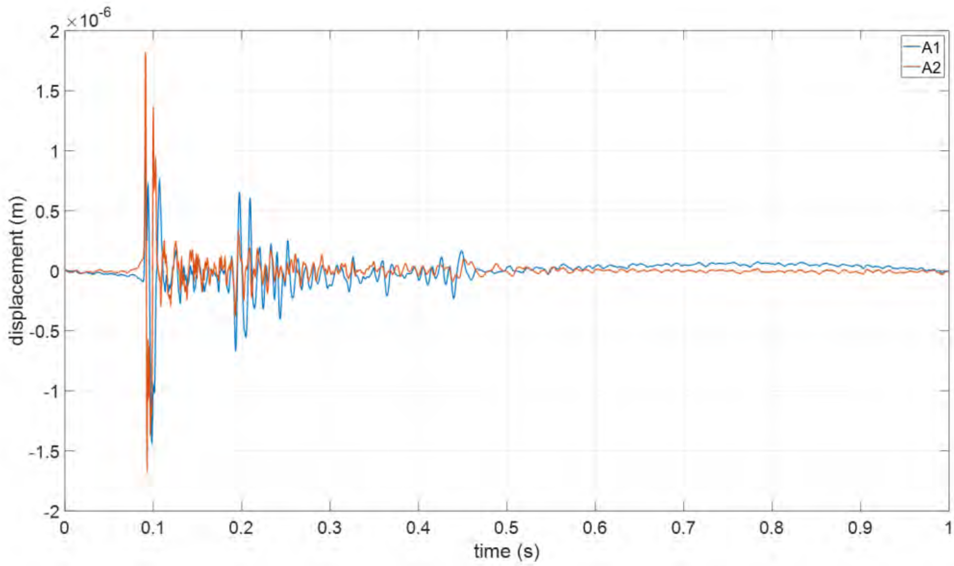


Figure 4 - An example to show the displacement signal captured by A1 and A2, as a function of time. A1 is the top accelerometer, A2 is the bottom.

Fourier analysis was applied to the collected data to determine the spectral composition of the pipe wall vibration caused by passing of transient events and presence of background noise. A time window of 1s was used to select the data related to each transient event (Figure 4) and to attain sufficiently high spectral resolution. A 3rd order Butterworth band-pass filter (50Hz - 500Hz) was applied to remove any bias in data. The spectra calculated for the 14 transient events recorded at locations 1-3 were averaged. The results of the Fourier analysis for accelerometers A1 and A2 are presented in Figure 5. and Figure 6. These show the mean spectra and standard deviation in the spectral variability of the displacement between the three locations and different transient events, with the background noise spectra for comparison. Appendix B contains graphs of the vibration velocity spectra measured at the three locations.

It is possible to make several conclusions from these results:

1. The maximum spectral amplitude of the pipe wall displacement caused by a transient event is below 100 Hz.
2. In this frequency range, the spectra recorded on the top (A1) and bottom (A2) accelerometers were close in amplitude (within 10-20%), i.e. there was a relatively small variation in the vibration pattern along the circumference of the pipe.
3. The amplitude of the background noise spectra was 1-2 orders of magnitude smaller (average SNR = 26 dB) than the spectrum of a typical transient event.

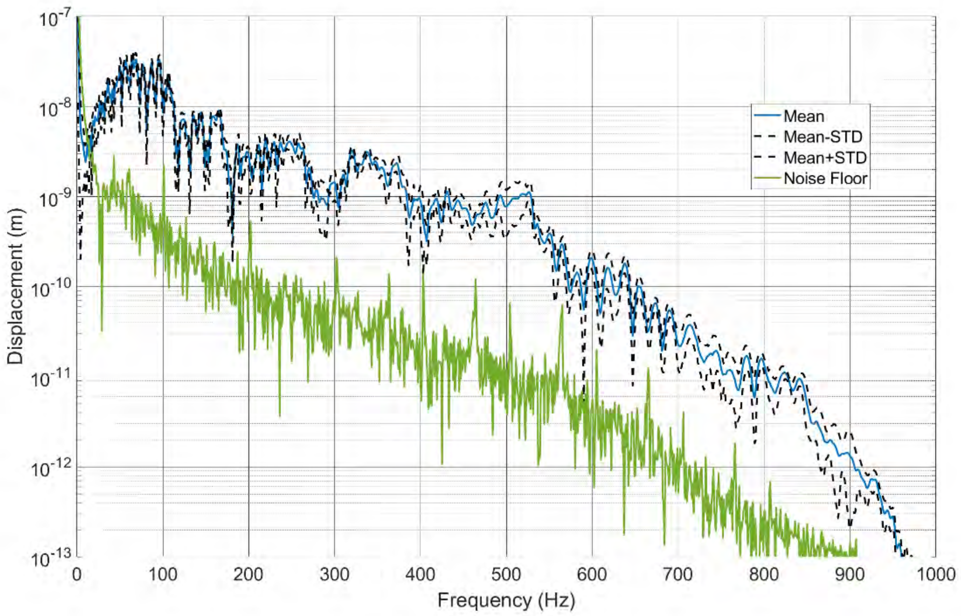


Figure 5 - The variation of the pipe wall displacement spectrum measured across the three locations in Bretton village with accelerometer A1 and background noise spectrum

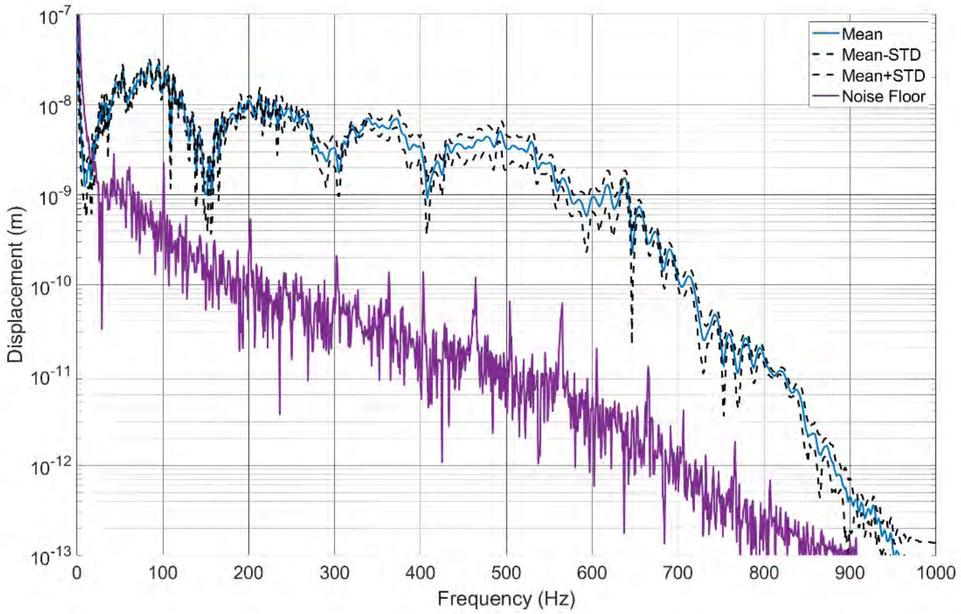


Figure 6 - The variation of the pipe wall displacement spectrum measured across the three locations in Bretton village with accelerometer A2 and background noise spectrum

Christchurch Site

The data acquisition was carried out at 4 different locations. The pumping was managed by several pumps; soft start cycles were programmed to avoid generation of transient events. Accordingly, no clear transient events were observed in the data.

Figure 7 and Figure 8 shows an example of the time history of pipe wall vibration recorded. The maximum amplitude of background noise is generally below 100 mm. The readings taken on the three accelerometers are very similar in the pattern and amplitude. Figure 9 and Figure 11 show the averaged background noise spectrum.

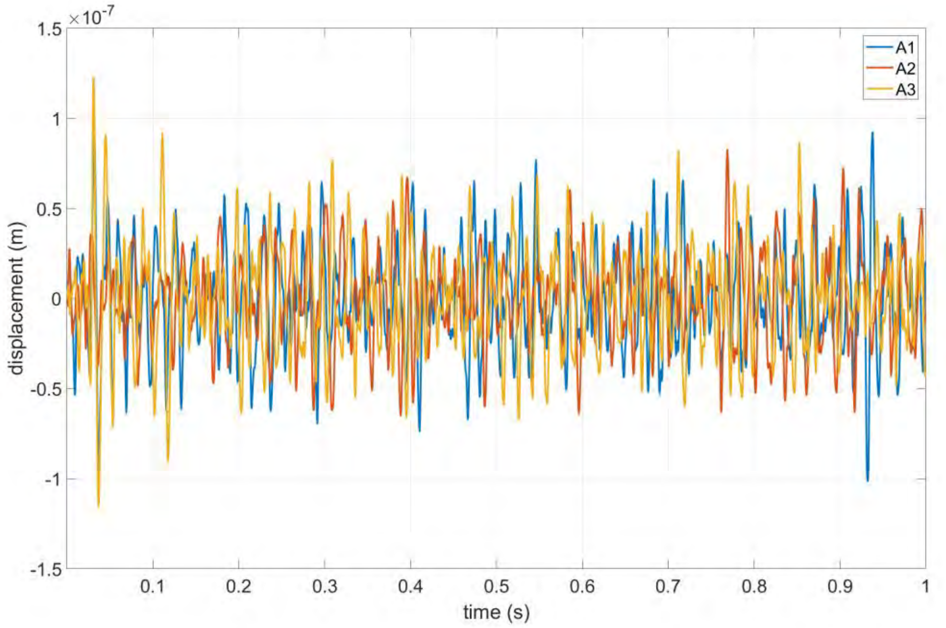


Figure 7 - An example of the vibration displacement recorded at location 1 in Christchurch.

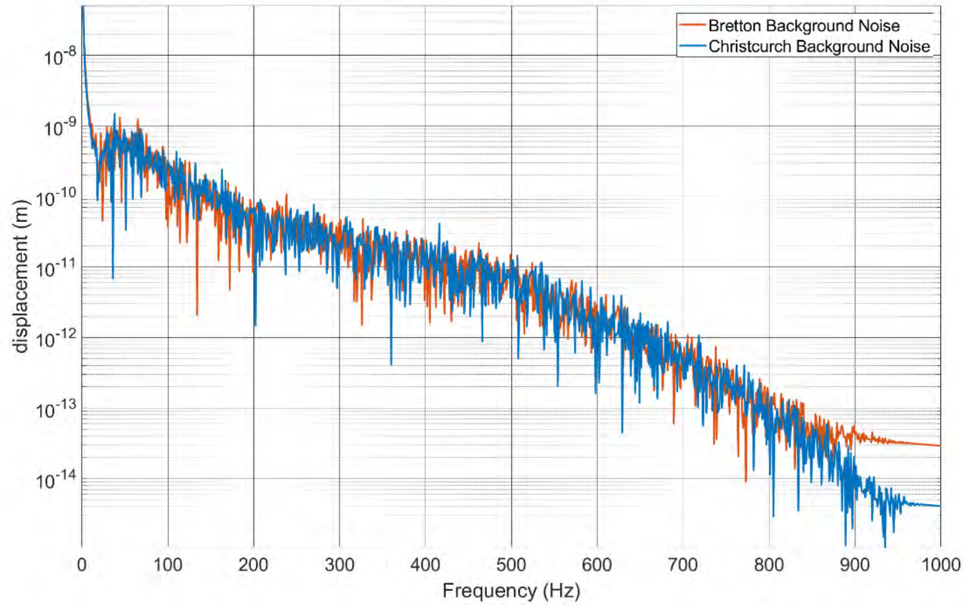


Figure 8 - The comparison between the background noise spectra recorded in Christchurch and Bretton.

Figure 8 illustrates the comparison between the spectra of background noise recorded from the measurements at Christchurch and Bretton sites. The background noise spectrum for Bretton was the average taken from the two accelerometers at all three locations. The background noise spectrum shown for Christchurch was the average taken at sites 1, 2 and 4. The background noise spectra shown in Figure 8 are very close in amplitude and shape, suggesting that the measurements taken at these two sites were not affected by any site-specific sources. This may be due to ambient noise of the accelerometers.

Some accelerometer data taken at location 3 contained irregular outlier events. Figure 9 is an example of this, measured by accelerometer A1 (top) at location 3. Figure 10 shows the displacement spectrum of this event. The presence of a peak in the spectrum around 500 Hz suggests that this type of noise event can have an impact on the actual level of background noise.

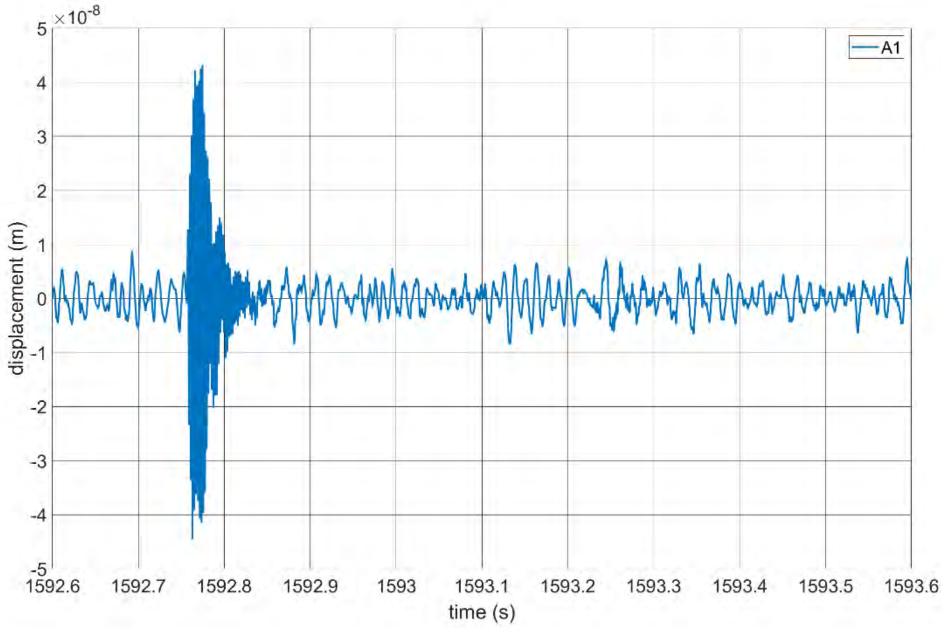


Figure 9 - An example of an outlier event observed in the accelerometer data measured at Christchurch site, location 3

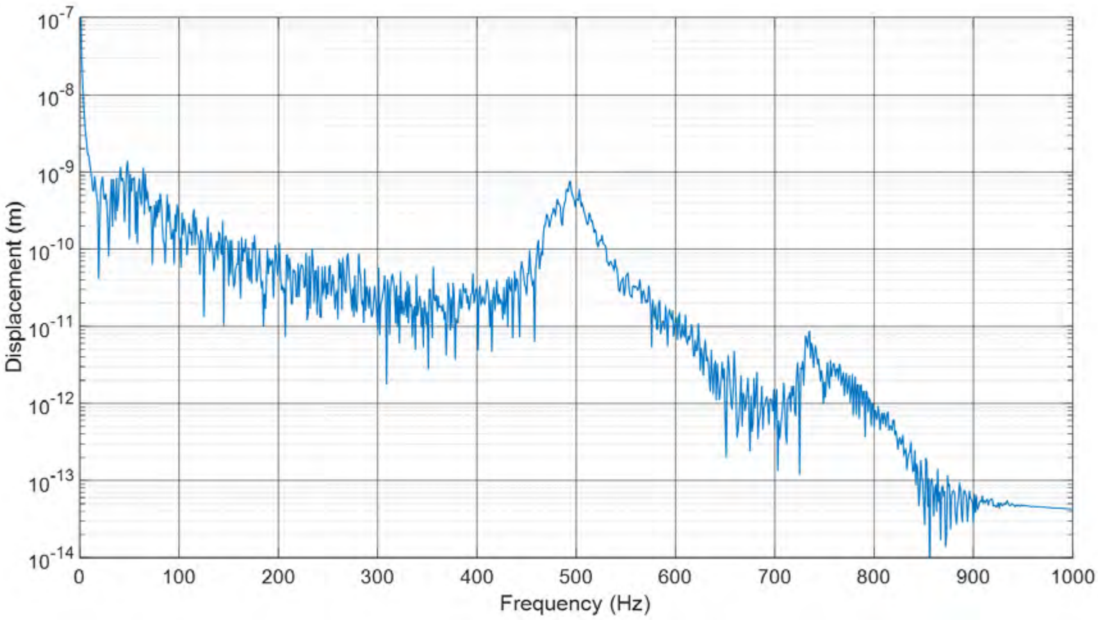


Figure 10 - The displacement spectrum of the noise event shown in Figure 9.

Weymouth Site

At the Weymouth sites, an 800mm and 1100mm pipes were tested. Soft start pumps are used on the 800mm site, but not the 1100mm site.

There appears to be enough sound energy in pump noise to use with the acoustic sensor being developed. The operation regime of some pumps may contain higher frequency harmonics at frequencies that may cause the pipe to respond in a more complex manner which needs additional investigation. See figures 12. & 13.

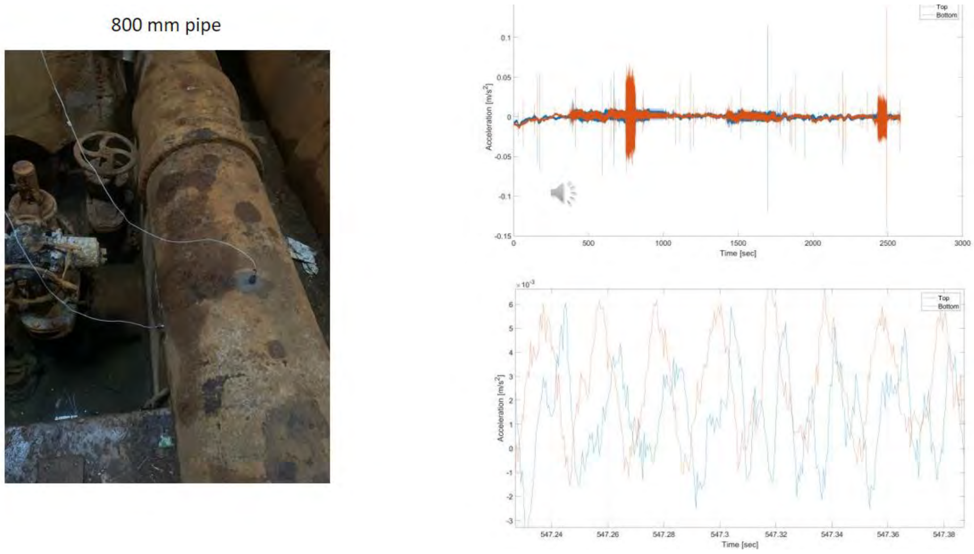


Figure 12. – 800mm pipe, Weymouth

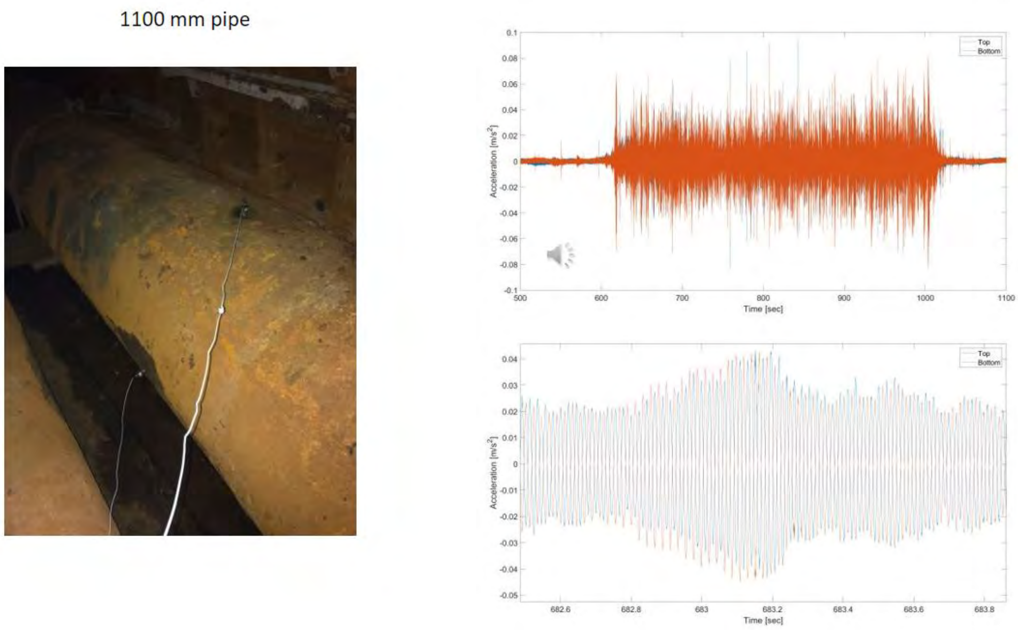


Figure 13. – 1000mm pipe, Weymouth

Conclusions

This report summarises the data recorded in Bretton and Christchurch on 300 mm cast iron and 400 mm ductile iron rising main. The results obtained in Bretton suggest that the pump can generate transient events that cause 1-2 μm dynamic deformation events in the pipe wall lasting up to 500 msec. The peak in the spectrum of these events is below 100 Hz. These events are clearly detectable above the level of background noise that spectral level is at least 26 dB below that of the transient event.

These events were not observed in the data recorded in Christchurch, and this is believed to be because the pumps were programmed to operate in a mode avoiding sudden pressure surges. The average background noise spectra recorded in Bretton and Christchurch were very similar, suggesting that there were no special site-specific sources of noise and vibration. The variation in the data between the individual accelerometers were relatively small suggesting that the wall of the pipe was vibrating relatively uniformly. There were some outlier fluctuations in the accelerometer data observed in Christchurch at location 3 on accelerometer A1. The spectrum of these events peaked around 500 Hz. The origin of these outlier events is unknown.

Appendix A

Site Photographs: Bretton village

Accelerometer installation on the pipe

Data acquisition equipment onsite

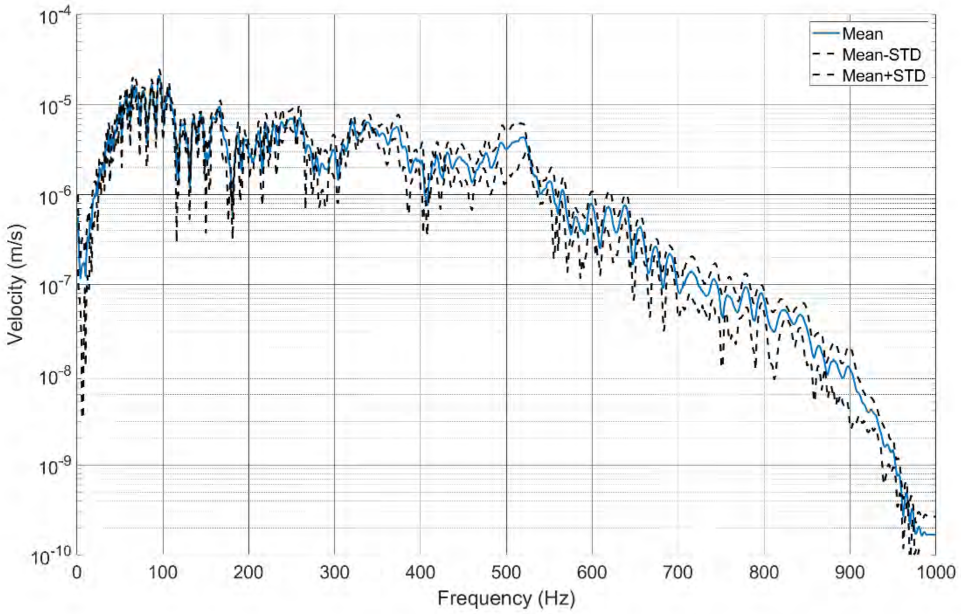
Site Photographs: Christchurch

Accelerometers attached to the pipe

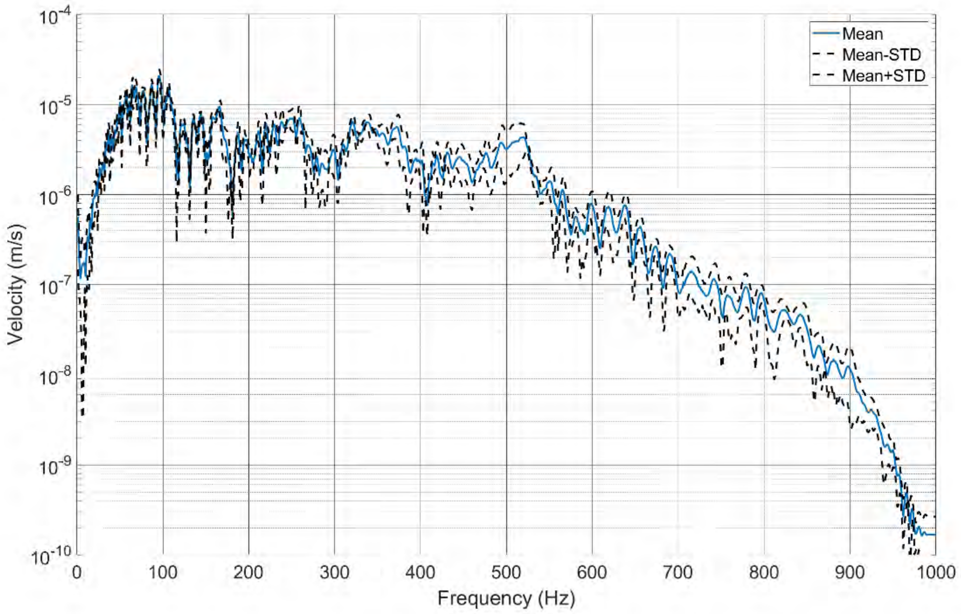
Data acquisition equipment on site

Appendix B

Vibration velocity data for pumping events detected in Bretton village



Location averaged vibration velocity spectrum and its standard deviation, recorded on Accelerometer A1.



Location averaged vibration velocity spectrum and its standard deviation, recorded on Accelerometer A2.

Appendix 3. U1 – Computational Modelling

Features of Interest for Detecting Wall Defects in Rising Mains Based on COMSOL Simulations

The University of Sheffield

Contents

Figures

1 Introduction

To facilitate the development of a new technique for detecting defects in rising mains, a numerical model has been built in COMSOL Multiphysics®, with the objective of discovering which parameters within the pipe soundscape change the most in the presence of defects.

The model was run with four different kinds of defects:

- Pitting – Internal
- Pitting – External
- Reduced pipe wall thickness – Internal
- Reduced pipe wall thickness – External

These are simple cases, but should provide a basis for determining which parameters are of the most interest.

1.1 The Base Model

The models combine a pressure acoustics model in the water column, with an elastic wave model in the pipe wall. A mesh is used to solve the numerical model.

Unless otherwise specified the models are set up as follows:

- The sound source was a plane of oscillating pressure across the pipe, 3.0m from a defect.
- The defect is located at 0.0m. Various defects were modelled and are described in each section.
- The mesh is finer close to the defects.
- To minimise the effect of the mesh on the results, with and without defect cases were modelled for each situation, with the same mesh used for each. In the with defect models the relevant sections are filled with water; in the without defect models, they are made of the pipe material instead.
- The source is more than 1 wavelength from the end of the pipe, and both pipe ends finish with PMLs (Perfect Matched Layer) to reduce internal reflection.
- The results shown are for 300Hz.
- The z-axis follows the length of the pipe, the x- and y- axes cross the plane of the pipe. As such the radial velocity is a combination of the x- and y- components.

The pipe is modelled as ductile iron, with properties:

Young's modulus:	172 GPa
Poisson ratio:	0.275
Density:	7,150 kg/m^3

The fluid is water.

Model dimensions:

Pipe internal radius:	0.055 m (0.11 m diameter)
Pipe wall thickness:	0.01 m
Total pipe length:	7 m
Region of interest:	0.11 m (has higher density mesh)

Mesh separation along main pipe length: 0.05 m

1.2 Defects

1.2.1 Pitting - Internal

To emulate internal pitting, the defect in this simulation has been created by subtracting a sphere from the inside of the pipe wall.

The pipe, including the modelling mesh are shown in Figure 1.

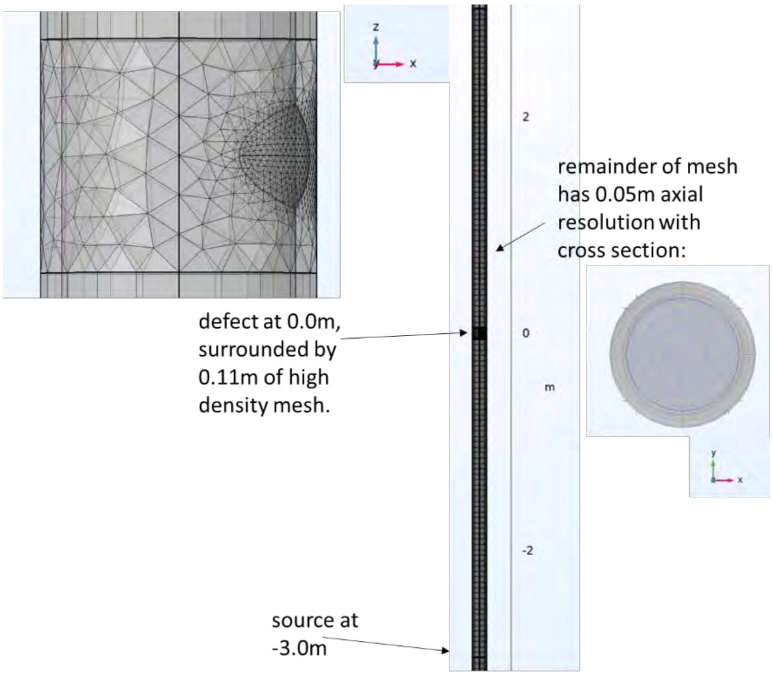


Figure 1: Internally pitted pipe wall: mesh

1.2.2 Pitting – External

The defect is in the same position as described in section 1.2.1, but instead a sphere has again been subtracted from the outside of the pipe wall.

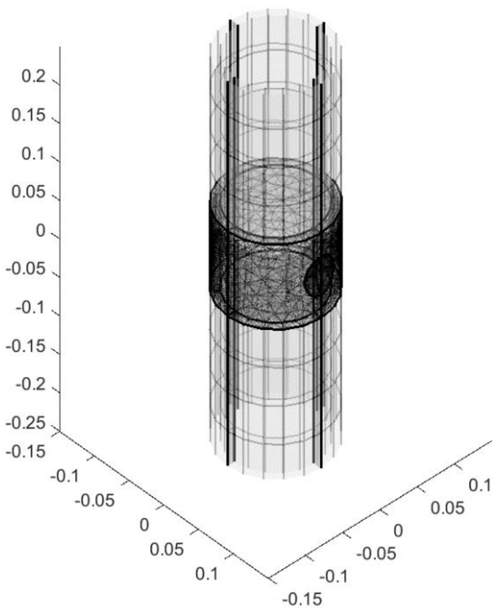


Figure 2: Externally pitted pipe wall: mesh

1.2.3 Reduced Pipe Wall Thickness - Internal

The defect is in the same position as described in section 1.2.1, in this case the pipe wall has been reduced to half its original thickness, with the thinning occurring on the inside of the pipe wall, such that the fluid fills the volume. The mesh for this situation is shown in Figure 3.

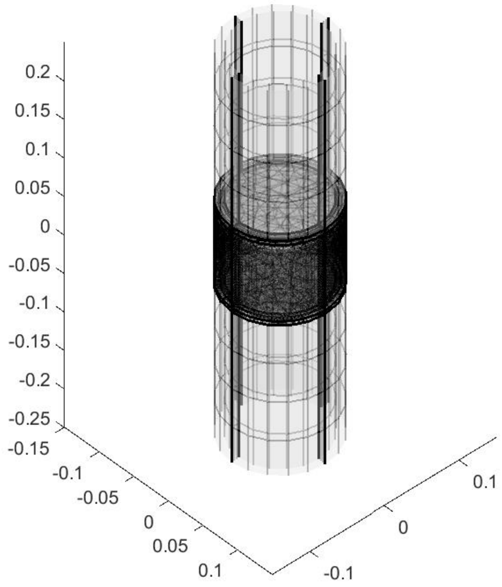


Figure 3: internally reduced pipe wall thickness: mesh

1.2.4 Reduced Pipe Wall Thickness – External

This case is very similar to that described in section 1.2.3, except that the pipe wall is removed on the outside, as shown in Figure 4.

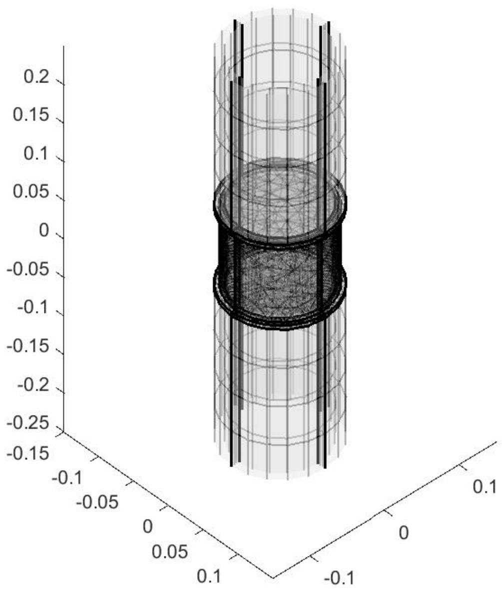


Figure 4: Externally reduced pipe wall thickness: mesh

2 Summary of Results

This system comprises a fluid (water) and an elastic material (ductile iron pipe), coupled together. The parameters which might be expected to best describe the system are the pressure inside the fluid, the fluid's velocity (axial and radial) and the pipe's acceleration.

The acceleration of the pipe wall is commonly used to detect leaks in water pipes, often at a significant distance from the leak itself, as the noise of the leak propagates along the pipe wall. This technique has the advantage of being non-invasive, however, in water pipes it has been observed to have limited range as the leak noise attenuates across joints and other features. The pressure has also been used to detect leaks in water pipes. It tends to have a longer range/detect smaller leaks, but requires contact with the water column.

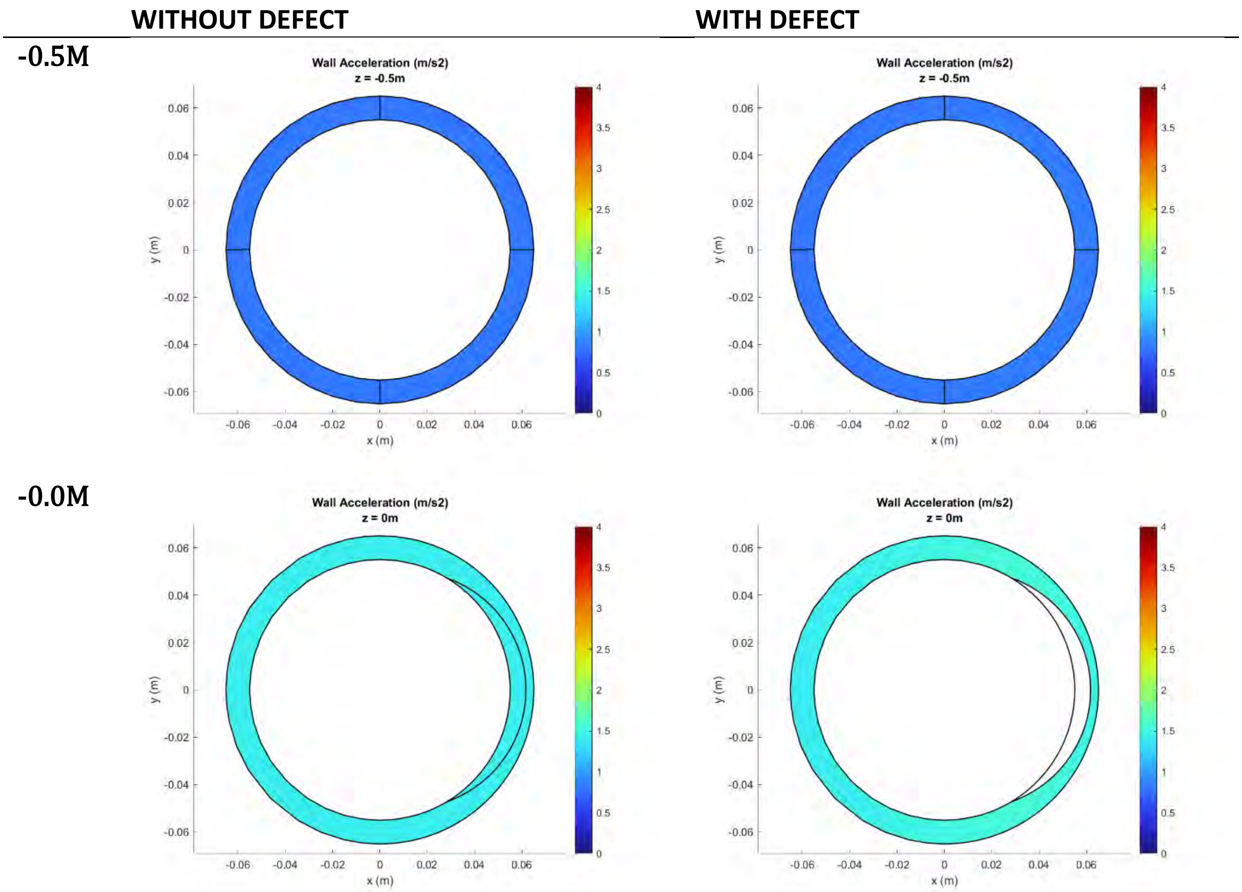
Here we are looking at whether either of these methods is likely to work to detect the types of defects found in rising mains, and whether other metrics might be more informative.

2.1 Acceleration in the Pipe Wall

For the 2 metres of pipe simulated, no difference was seen between the acceleration for a non-defective pipe and a defective pipe, for internal or external pitting or for an externally thinned pipe. An example of the acceleration at different planes along the pipe length, for an internally pitted pipe, are shown in Figure 5. It can be seen that there is a very small difference in wall acceleration at the defect itself, but this is no longer visible within ±0.5m of the defect.

The wall acceleration for the internally thinned pipe is similar in magnitude to the case with no defect, but different in behaviour: a bending mode can be seen in the 3D plots in Figure 6. This may be due to the lack of surrounding soil – further investigation is probably required here.

From the above, the acceleration of the pipe wall has limited scope for finding defects.



WITHOUT DEFECT **WITH DEFECT**

+0.5M

+1.0M

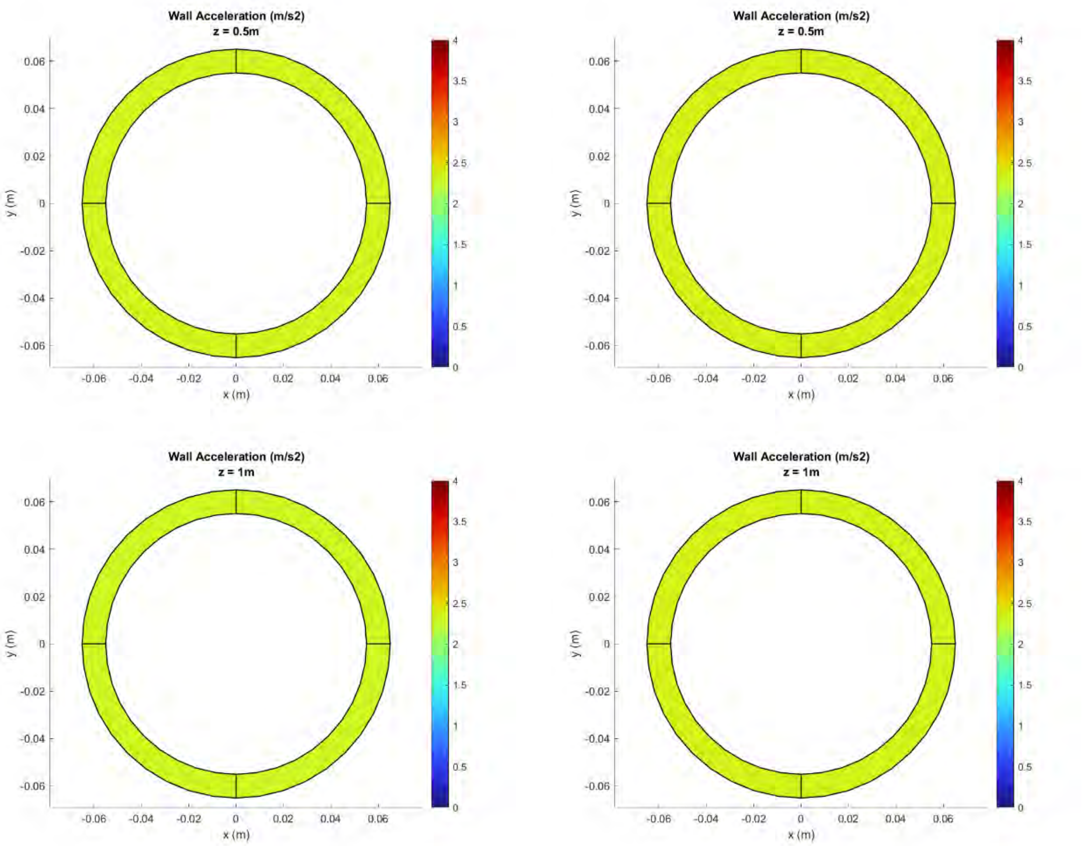


Figure 5: Acceleration in an internally pitted wall, at distances specified from the defect, where the acoustic source is at -3.0m.

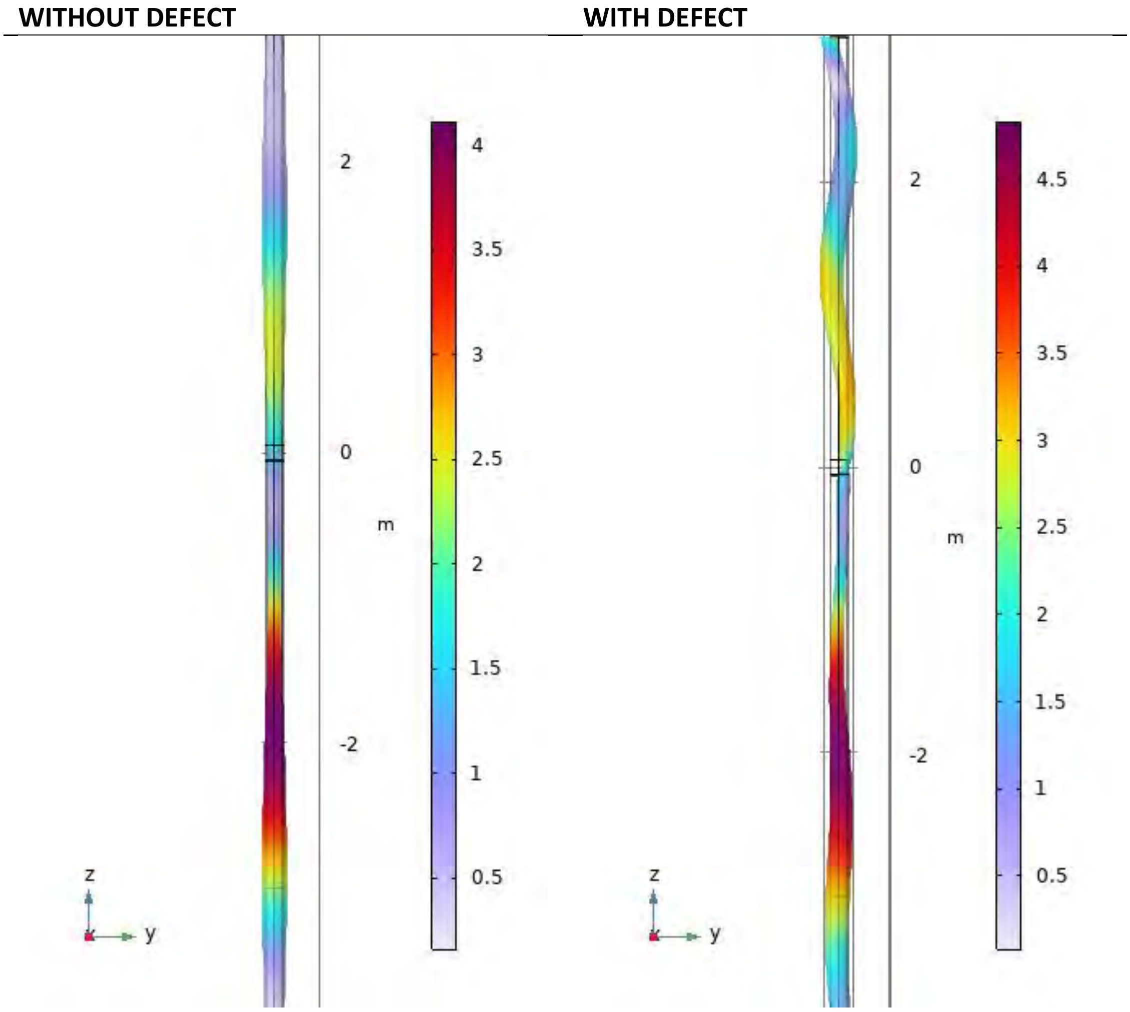


Figure 6: Internally thinned pipe; colour scale shows the acceleration of the pipe wall, ***the deformation of the pipe shows the pipe displacement multiplied by a factor of 120,000.***

2.2 Pressure/Axial Fluid Velocity

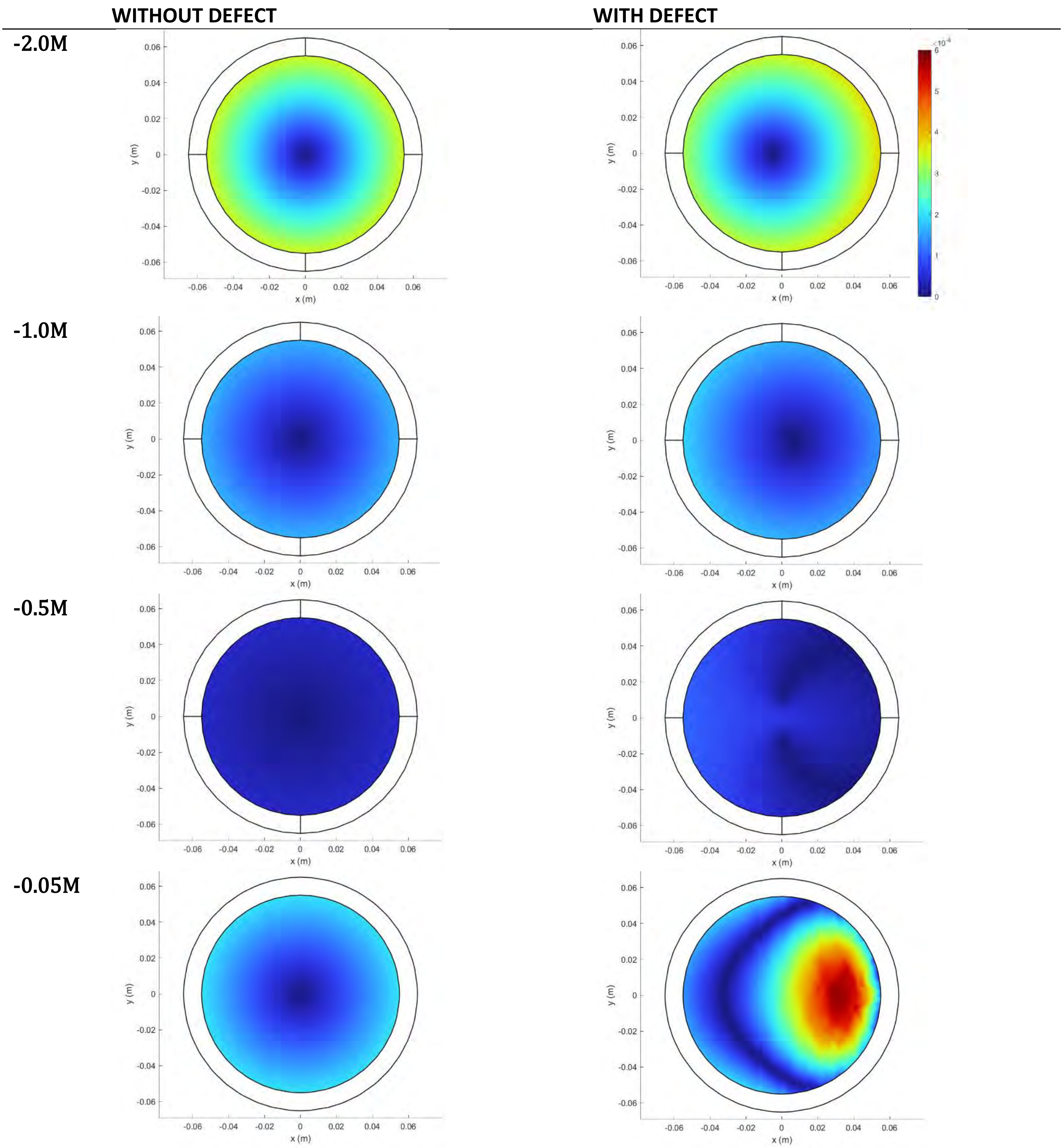
None of these defects influence the pressure, nor the z-component of velocity along the length of the pipe. Given that the pressure waves are travelling axially along the pipe, it is not surprising that they are strongly coupled with the axial component of the fluid velocity. It is of note that the pressure is not a parameter of interest given that pressure measurements are already a common means of defect detection in water pipes.

2.3 Radial Fluid Velocity

The radial fluid velocity has proven to be the most interesting parameter of the system. Figure 7 shows the change in the radial fluid velocity with distance from internal pitting. It can be seen that it is significant for the 0.1m immediately next to the defect, and leads to visible asymmetry at larger distances. Figure 8 and Figure 9 show the results at the defect and 1.0m downstream from the defect respectively for the four defect types. It can be seen that the radial velocity picks up the defect clearly.

The internal thinning of the pipe is picked up most clearly, over the longest distance. As discussed in section 2.1, from analysis of the acceleration and displacement of the pipe wall, it has been found that this is due to an additional mode of motion that is introduced with this defect, where the pipe bends along its length. This may be suppressed when the pipe is held in soil, further investigation is needed in this area. The pitting cases are only detectable over a short distance, with the asymmetry introduced the defects are barely visible at 1.0m. Similarly, an externally thinned pipe leads to no noticeable difference in radial velocity 1.0m from the defect. The externally thinned pipe may also be more difficult to detect due to the symmetry of the change in velocity detected – an asymmetric velocity profile could be discovered using a single plane. However, it may be possible to detect the sudden increase in velocity using a scan along the pipe length.

It should be noted that the radial velocity for all these cases is significantly smaller than the axial velocity: the maximum axial velocity is 0.05m/s, whereas the maximum radial velocity is $6x10^{-4}$m/s. This will require careful separation of the axial and radial velocities.



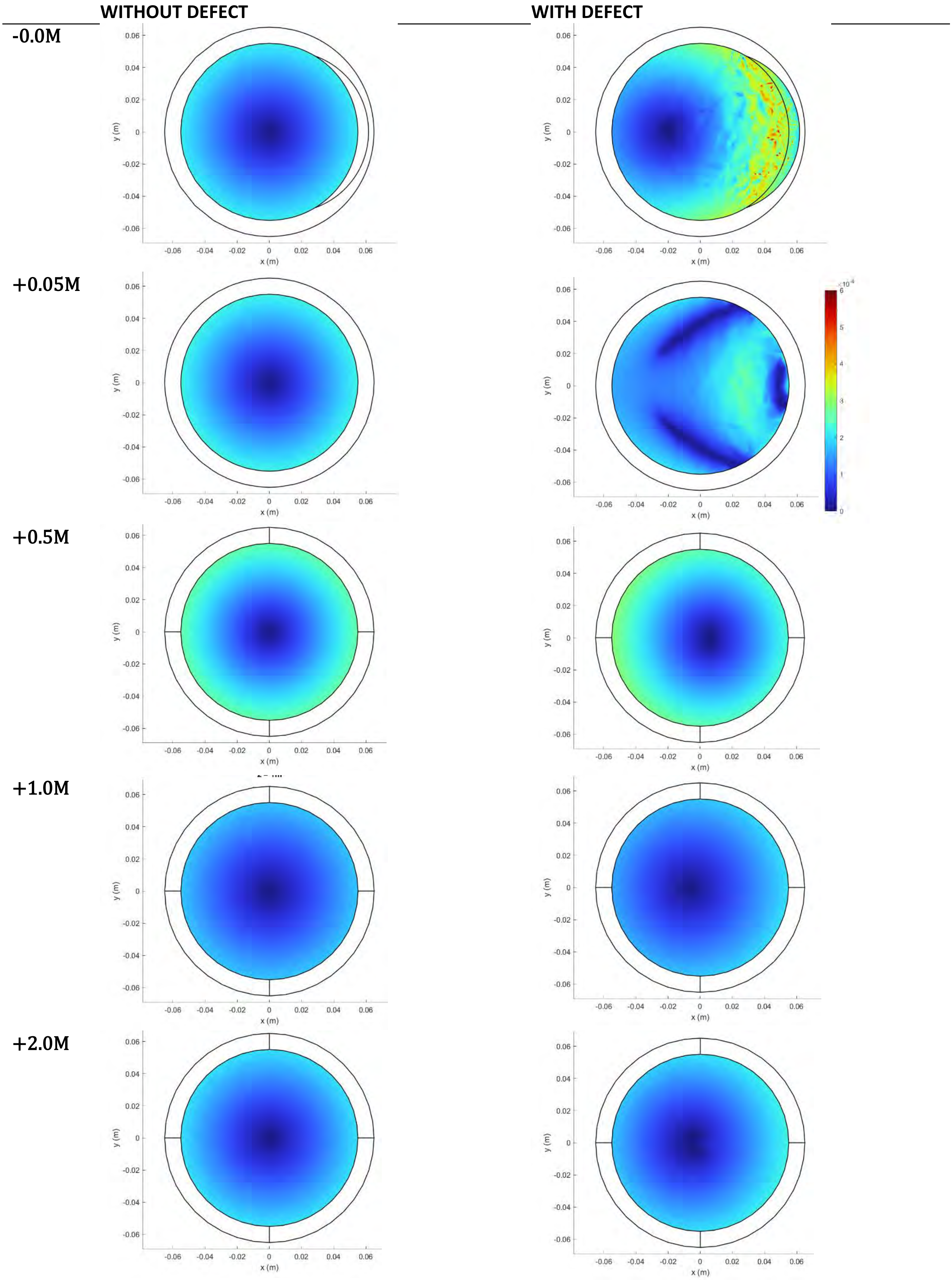


Figure 7: radial fluid velocity for an internally pitted wall, at distances specified from the defect, where the source is at -3.0m.

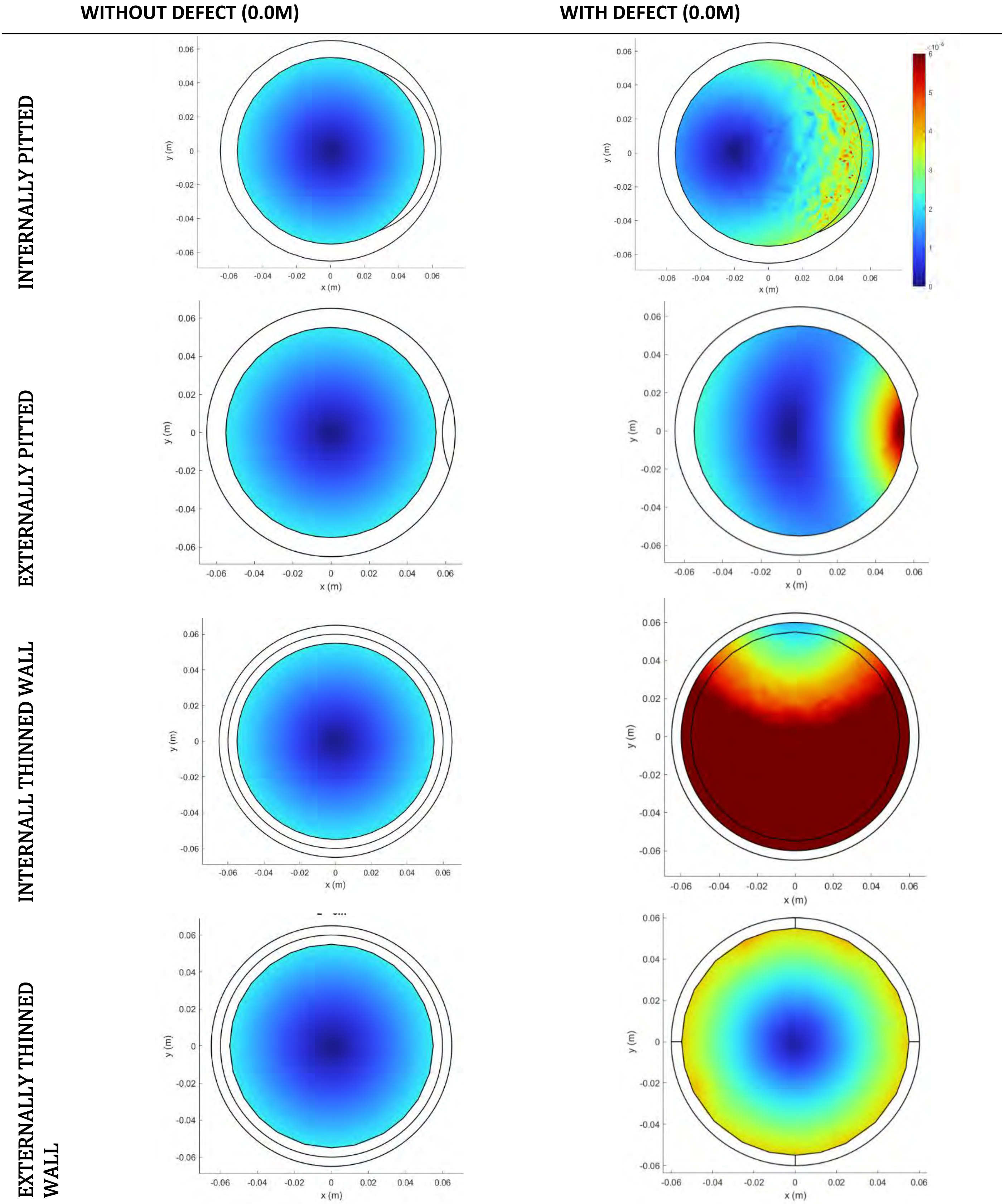


Figure 8: Radial fluid velocity for each type of defect at 0.0m from defect.

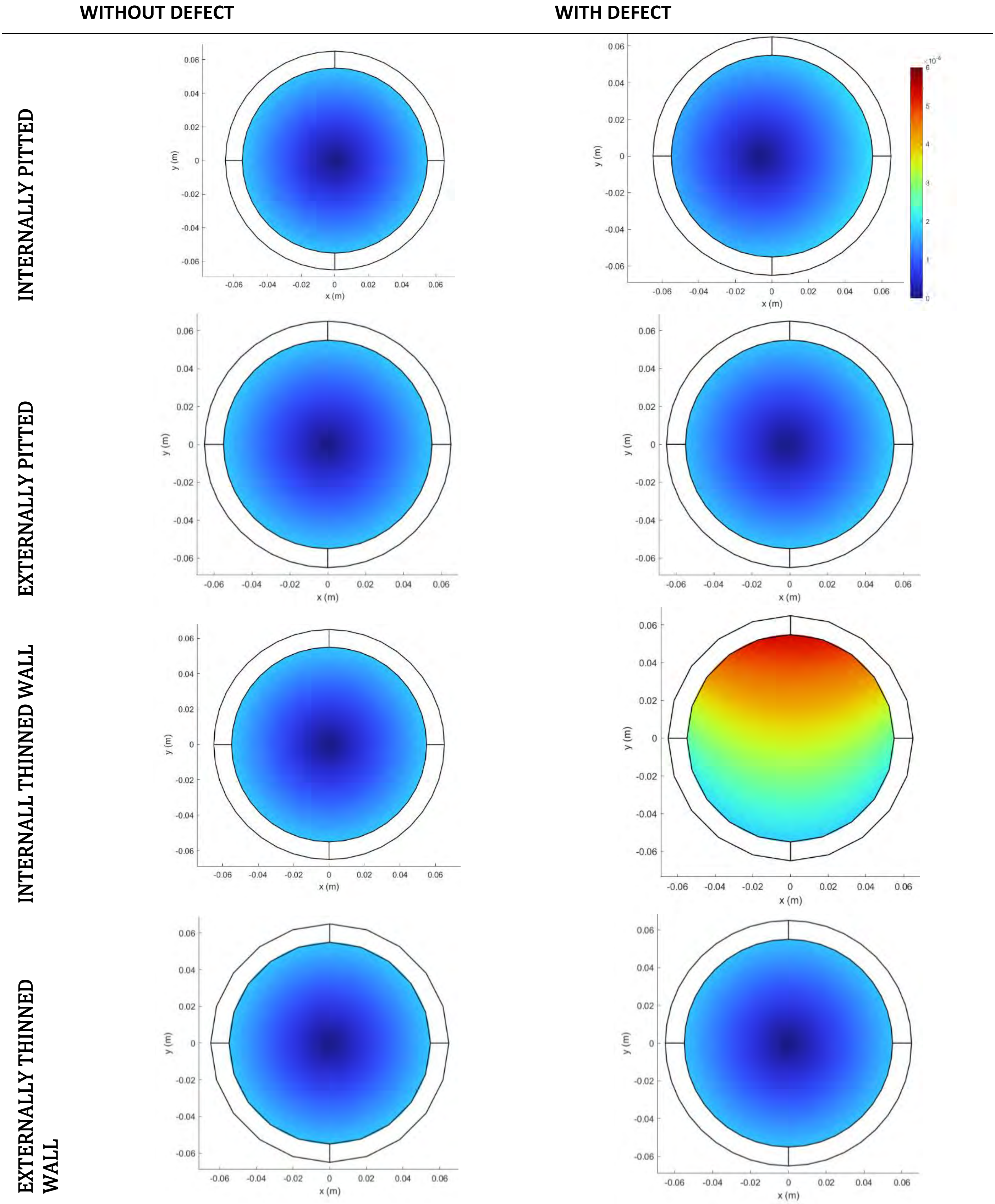


Figure 9: Radial fluid velocity for each type of defect at 1.0m downstream from defect.

3 Conclusions

Based on these simulations, the radial fluid velocity is expected to find defects most effectively. It could be used to find any of the defects simulated here. This could be measured directly, or more likely, using accelerometers and performing the necessary conversion.

Appendix 4. D1- Site Findings Report (Draft)

Document Name:	D1 Site Findings Report				
Document Number:	L09-D1		Revision:	1	
Drawn By:	M East	Checked By:		Issue Date:	16.09.2022

Site Findings Report
Deliverable D1
[L09-D1]
PipeBOTS in Rising Mains

Prepared for Rachel Cunningham/David Walters
Thames Water

16th September 2022

PAS 99 Integrated Management Systems IMR535435
ISO 9001 Quality Management FM38723
ISO 14001 Environmental Management EMS535432
OHSAS 18001 Occupational Health and Safety Management OHS535433

Document Name:	D1 Site Findings Report				
Document Number:	L09-D1		Revision:	1	
Drawn By:	M East	Checked By:		Issue Date:	16.09.2022

1 Version Control

Change record

Version	Status	Date	Author(s)	Summary of changes
0.1	Draft	12/09/2022	Meriel East	Site copy for note taking
0.2	Draft	15/09/2022	Meriel East	For review
0.3	Draft	16/09/2022	Meriel East	Final review
1.0	Release	16/11/2022	Meriel East	Release to Thames Water

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Management Approval

Name	Position
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2 Site Visit Details

Location	Water Recycling Centre, Stony Lane, Christchurch, BH23 7LQ
Description	Site visit to Wessex Water treatment works and pumping stations in Christchurch.
Lead	Helen Tivenan (Wessex Water)
Attendees	Ned (Chris) Willet Meriel East
Date	14. 09. 2022

3 Table of Contents

4 Introduction

This report details the activities and information gathering from site visits carried out at rising mains sites, to inform the design specification for access to pipelines. All wastewater networks have their own working requirements. At this stage, the Wessex Water Christchurch site will be used as the example for designing an access system and POC robotic NDT sensor package.

A final version of this report will be issued as a deliverable to Thames Water as part of the project deliverables pack. Photos taken onsite, measurements, diagrams, and information noted through conversation with the operations team are all included.

Two flow meter chambers and four stations were visited on the day (listed chronologically). These are briefly described below:

- Flow meter chambers are simple chambers accessed through a manhole, where Wessex Water have attached external flow meters.
- Dry well pumping stations - where the rising mains and pumps are contained within a building, with an underground storage tank. The buildings have control cabinets upstairs, and stairway access to the pumps.
- Wet well pumping stations - where the pumps and rising mains are contained in different pits, accessed from ground level.

The **objectives** of the site visits were to:

- Attend site visit(s) with operations teams
- Record observations
- Discuss / understand logistics
- Analyse access requirements:
    - Space & confinement
    - Practicalities / logistics
    - Health and safety
    - Operational restrictions
- Photograph & produce diagrams of site

5 Site Map – Waste Water Treatment Works

Layout

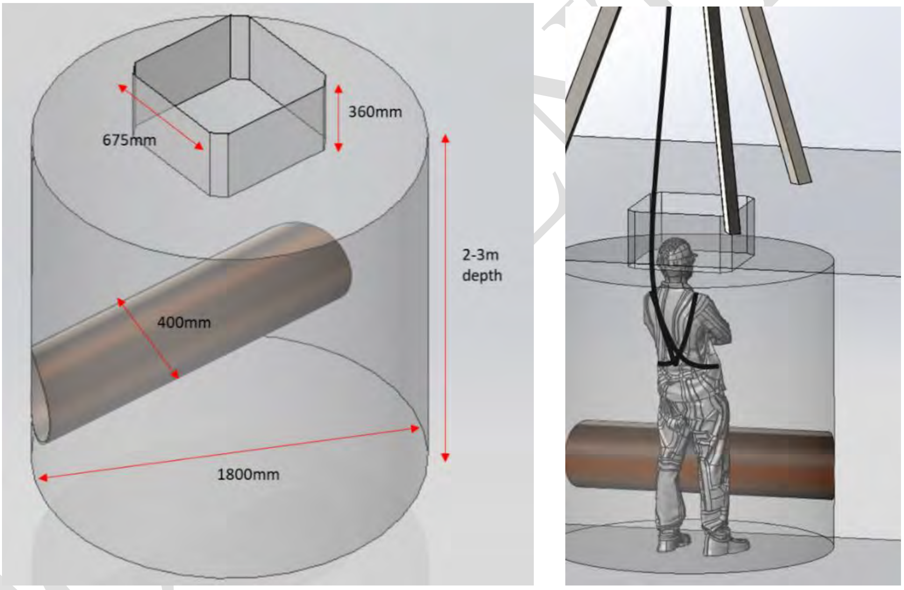
- Pumping stations are roughly 2 miles apart
- Small villages may have rising mains that are 50-150mm in diameter, large towns, and cities up to 800mm.

6 Flow Meter Chambers

Standard setup for flow meter chambers, where two external flow meters are strapped to the outside of the pipe, measured via a meter box. Flow meter readings are updated every 6 hours; data becomes available live if an alarm is triggered.

Access Requirements:

- Manhole cover (offset from rising main)
- Winch over manhole cover
- Trained operator inside confined space
- Personal gas meter to measure cumulative exposure to Hydrogen Sulphide (H_2S), methane, and oxygen levels inside chamber
- Vented for 5-10 minutes before entering to allow time for build-up of H_2S and methane to escape
- Operators typically need to pump out collected rainwater before access



Figures 1a & 1b – Manhole layout & dimensions for standard Flow Meter Chambers

Flow Meter Chamber 1

The standard setup for a flow meter chamber is a prefabricated concrete container, surrounded by gravel and backfilled with cement.

Rising Main diameter	400mm
Chamber diameter	1800mm
Chamber depth	2m
Power	Generator only
Washing facilities	Main office building
Location	Main office building at treatment works

Figures 2a & 2b – Photographs of flow meter chamber 1

Flow Meter Chamber 2

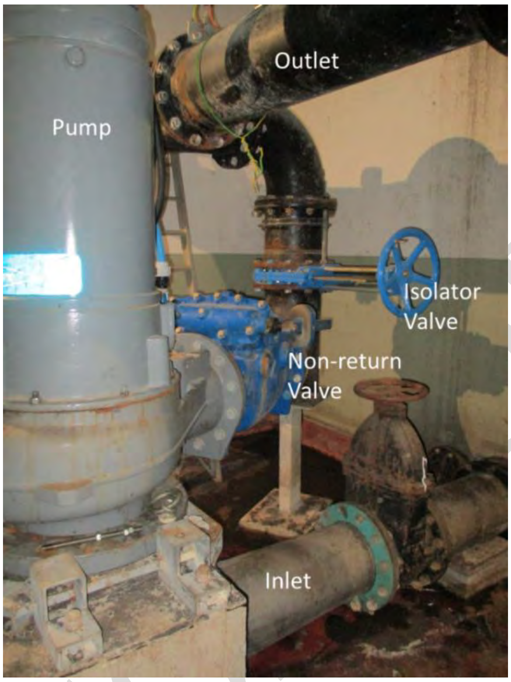
Riser Main diameter	400mm
Chamber diameter	1800mm
Chamber depth	3m
Power	Sockets inside pumping station
Washing facilities	Outside tap for kit washdown
Location	Adjacent to Pumping Station 1

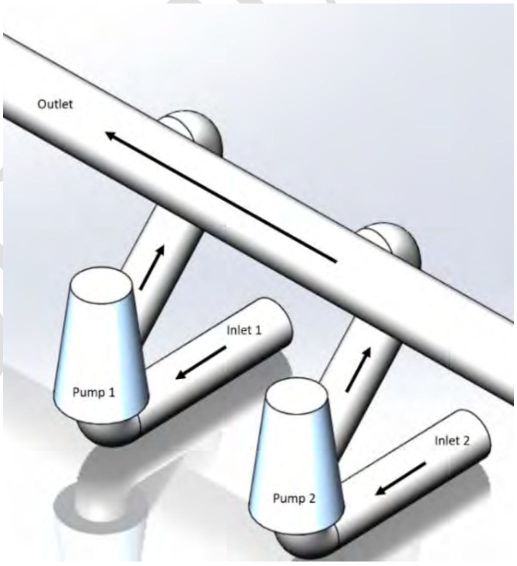
Figures 3a & 3b – Flow meter chamber 2 outside pumping station 1 (left)

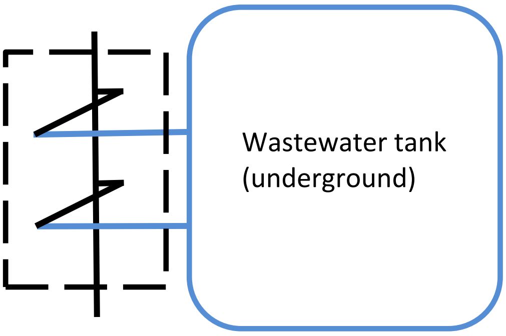
7 Pumping Stations

Pumping Station 1

Pumping station type	Dry well
Cleaning facilities	Outside tap
Area	Near major road, locked yard
Power sockets	2 x 110V
No. pumps	2
Other notes	Hoists for lifting equipment between levels (highlighted access grate). 2 pumps; alternating cycles, to reduce wear on machines and allow pumping cycles to continue if any maintenance work is required on either one. Pumps made of a rotor and stator, sometimes with a macerator.







Figures 4a, 4b & 4c – Image of pumping station 1 and diagrams of pipe layout

Document Name:	D1 Site Findings Report				
Document Number:	L09-D1		Revision:	1	
Drawn By:	M East	Checked By:		Issue Date:	16.09.2022

Pumping Station 2

Figure 5 - Pumping station 2 location

Pumping station type	Wet well
Cleaning facilities	None
Area	Residential, under a public walkway, some temporary barriers
Power sockets	Unknown – may be inside pumping station /controls building
No. pumps	2
Other notes	Shallow pipes, easily accessed

Figures 6a & 6b – Pumping Station 2

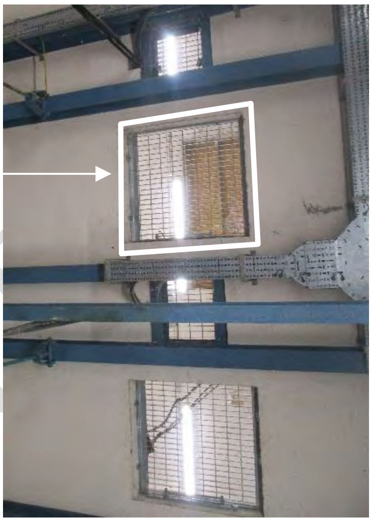
Pumping Station 3

Pumping station type	Wet well
Cleaning facilities	None
Area	Residential, locked yard
Power sockets	None
No. pumps	2
Other notes	Shallow pipes, easily accessed

Figures 7a, 7b & 7c – Submersible -type pumping station

Pumping Station 4

Pumping station type	Dry well
Cleaning facilities	Outside tap
Area	Residential, locked yard
Power sockets	4 x 230V
No. pumps	3
Other notes	Hoists for lifting equipment between levels (highlighted access grate)



Figures 8a & 8b Control room & equipment hoist access (highlighted)

Figure 9 – 3 pumps in underground dry well

8 General Notes

Operations Teams

- Vaccinations required for working with sewage (E.g. Hepatitis B & C, Tetanus).
- Different teams within a water company do different operations – we were shown around sites by the maintenance team, inspection is done by a different group.

Current Inspection Methods

- Currently, internal inspection is done reactively with pushrod cameras, not proactively (unless for example a new building site requires it). It is not done under pressure – only the water head pressure. A pushrod is usually inserted through a T-valve or through drilling directly into the pipe, leaving the valve attached for future use.
- There is the potential to drill at any angle of the clock face
- 'Hatch boxes' are sections which have been designed to be removable and can be used to access the inside of the pipe.
- 'Smart Ball' and 'Sahara' NDT technologies have been trialled previously in potable water, where a passive system is deployed in a main and collected using a net at the water treatment works where the riser mains lead to an open tank. Evidently, the data from these trials did not provide enough useful information to become a mainstream NDT process for Wessex Water at the time.

Pipe Materials & Sizes

- A rough timeline of when different material pipes were installed was discussed:
    - Cast Iron & Welded Steel -1940s
    - Asbestos – 1950s & 1960s
    - UPVC – 1970s
    - Concrete-lined ductile steel – 1980s
- Acidic soils corrode the concrete-lined ductile in particular; Wessex Water have problems with clay-rich soils in their areas.
- Asbestos pipes can 'slump' if the ground is saturated with water for a long period of time; the fibres start to expand and the pipe sags in the middle, leading to longitudinal cracking. This is a common failure mode for this material.
- Pipe size tends to be population dependent. Rising mains in small villages range from around 50-150mm in diameter, and up to 800mm in large towns and cities. Smaller pipes are often used to reach a higher pressure for pumping vertically / at a sharp incline.

9 Conclusions

There are several conclusions around system deployment which have been made based on the observations.

Accessing buried assets through a wet well pumping station is potentially a better fit with the Synthotech operational skillset, as the depth and size of pipes appeared suitably similar to a typical access trench size for working on gas pipelines. However, this will not be a deciding factor. Whilst dry well pumping stations have hoists for moving equipment between floors, the actual pipe that would be accessed is at a height. Maintenance teams usually use scaffolding to do any work at a height on these outflow pipes. This would introduce an extra level of technical requirement to the procedures and may cause additional, unnecessary complications.

There is the additional obstacle of sharp direction changes at pumping stations; the direction change is frequently at 90 degrees or greater, and the vertical pipes would provide a significant challenge for a crawler robot, meaning this design option is ruled out if the focus is inspecting a pumping station. Flow meter chambers through manhole access would be a more suitable access point for the rest of the pipeline.

There is currently no live operating procedure for inspection under pressure. If live working is a key requirement, then the project will need to consider the option of designing a new procedure. There is also the potential that operations could involve deep excavation.

Appendix 5. D2 - Sensing Requirements Capture

Sensing Requirements Capture

Deliverable D2

PipeBOTS in Rising Mains

Prepared for Rachel Cunningham/David Walters

Thames Water

31st August 2022

PAS 99 Integrated Management Systems IMR535435
ISO 9001 Quality Management FM38723
ISO 14001 Environmental Management EMS535432
OHSAS 18001 Occupational Health and Safety Management OHS535433

1. Version Control

Change record

Version	Status	Date	Author(s)	Summary of changes
0.1	Spreadsheet	16/08/2022	Pravin Smart	Research Spreadsheet
0.2	Draft	30/08/2022	Meriel East	Research Summary (New Document)
0.3	Updated Draft	29/09/22	Meriel East	Updated with new data available
1.0	Release	16/11/2022	Meriel East	Release

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Management Approval

Name	Position
Simon Langdale	Director

2. Table of Contents

3. Introduction

This document outlines the findings from Synthotech's background research on non-destructive testing (NDT) methodologies and application of sensor technology in a rising main (RM). Information has been collected predominantly from academic papers, with industrial applications read more widely to understand the real-world limitations of the technologies described.

The aim of this document as a project deliverable is to support The University of Sheffield (UoS) in the design of a suitable sensor array, by conducting thorough background reading on the sensor options identified by the cohort in the early stages of the project. It also serves as a technical overview of the engineering constraints on conducting NDT in a rising main. UoS work focusses on the use of accelerometers to determine pipe thickness, so to support this, a background study has been conducted to ensure that all other possibilities have been considered and recorded.

4. Pipe Populations

This section introduces the overall picture of the project aims in the context of sensing requirements. Data on the UK rising mains is shown below. It was taken from various academic sources and summarised in two charts.

Table 1 - Utility provided network data; pipe installation data, length, and number of failures by pipe material collected between 2005 and 2018. (reference..)

Material	Installation range	Total (km)	Failure (No.)
Iron (cast)	1881 to 1921	11735	26600
Asbestos cement	1920 to 1941	7259	14053
PVC (unplasticised, post-chlorina	1960 to 2001	6126	11942
PE (medium and high density)	1981 to present	10538	4356
SDI (Steel and ductile iron)	1960 to present	1902	1067
Total		**37560**	**58018**

The distribution of pipe types in the UK is of varying diameter, material, and age. This is quantified in Table 1 and illustrated in Fig. 1. Approximately 36% of pipes are metallic, consisting of mainly cast iron, along with ductile iron and steel assets. Polyethylene (PE), Polyvinyl Chloride (PVC) and Asbestos Cement (AC) materials make up the remaining population.

Older pipes are of greater priority for inspection, due to their higher failure rates and associated risk (Fig. 2); only a small proportion of pipe failures are in newer PE pipeline, meaning it has a lower inherent risk of failure. Early 'legacy' plastics tend to be PVC and have a higher failure rate. Modern plastics have more advanced properties and have relatively low failure rates.

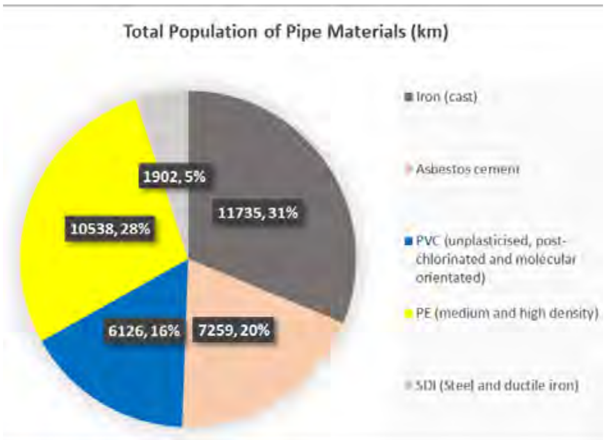

Figure 2

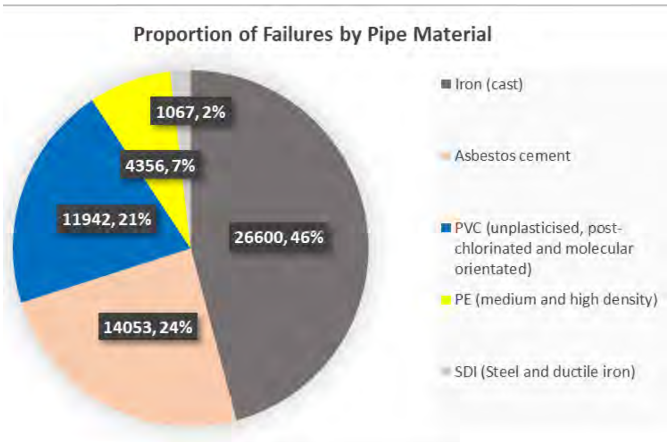

Figure 1

Data provided by Thames Water on pipe sample inspections (between 2000 and 2021) (a sub sample of all failures) shows that over three quarters of the failures are caused by material deterioration. A more detailed analysis of the pipe portfolio may be reviewed during the detailed design phase, to ensure that the solution(s) designed will cover the problem sufficiently to progress towards a viable product (see section 10).

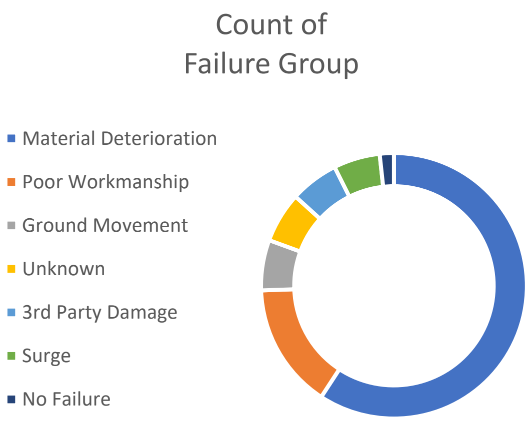

Figure 3

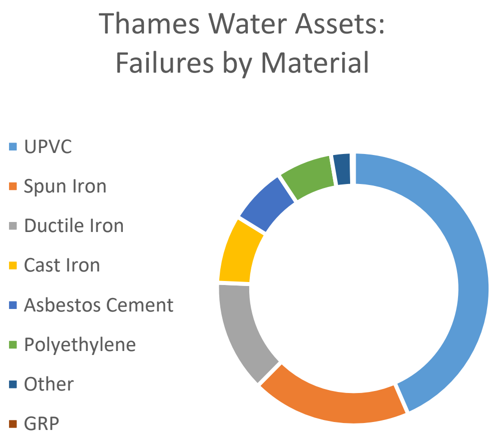

Figure 4

5. Target Specification Sensors

The Sensor Specification will encompass the technical requirements and aims for the electronic communications between the sensor package, the pipe wall, and the operator. The main areas of interest include but are not limited to:

- Refinement of data capture
- Area of pipe surface scanned per minute
- Accuracy of defect location
- Resolution of defect size detectable

6. Pipe Failure Modes

The typical failure modes for each material are listed by mechanism type.

Mechanism 1 – 'Pipe Intrinsic' refers to failures related to the dimensions and mechanics of a pipe, as well as installation-related damage.
Mechanism 2 – 'Environmental' includes any failure related to the natural surroundings of the pipe.
Mechanism 3 – 'Operational' failures occur due to intervention and/ or use. This may include maintenance activities or day-to-day running over time. It does not include installation.

Table 2

Material	Mechanism 1 - Pipe Intrinsic	Mechanism 2 - Environmental	Mechanism 3 - Operational	Typical failure modes
Iron	Pipe diameter	Cold temperatures	Cyclical pressure fatigue	Circumferential break
	Manufacturing defects	Frost	Transient pressure	Joint failure
	Graphitization	Cold internal water temperature	Management operations	Longitudinal failure
	Pipe protection	Highly corrosive soils	Construction and repair	Chemical attack
	Rigid joints			
	Accidental damage			
Steel and ductile iron	Thin pipe wall	Highly corrosive soils	High pressure	Chemical attack
	Manufacturing defects		Cyclical pressure fatigue	Joint failure
	Rigid joints		Pipe protection	
Asbestos Cement (AC)	Pipe diameter	Warm temperatures	High pressure	Circumferential break
	Manufacturing defects	Low rainfall	Cyclical pressure fatigue	Joint failure
	Rigid joints	Fluctuating soil moisture	Pipe protection	Chemical attack
		Clay and peat soils (shrink swell potential)		Longitudinal failure
		Highly corrosive soils		
PVC	Poor joint assemblage (solvent)	Warm temperatures	High pressure	Joint failure
	Storage (UV light exposure)	Low rainfall	Cyclical pressure fatigue	Longitudinal failure
	Manufacturing defects	Fluctuating soil moisture		Chemical attack
	Loading sensitivity to point loads	Clay and peat soils (shrink swell potential)		
		Sandy soils (wash out)		
PE	Poor joint assemblage	-	-	Joint failure
				Longitudinal failure

7. Ultrasound Methods

Ultrasound was identified as one possible method for scanning RM pipe sections for signs of failure.

This group of methods is generally not a preferred one for detecting surface cracks or metal fatigue. General disadvantages of the method include:

- High material porosity impacting quality of signal
- Vulnerable to signal interruption from debris
- Fine balance required between wave frequency and measurement resolution to deal with attenuating materials such as cast iron or other plastics
- Requires surface pre-treatment of scale/oxide removal

Table 3 and Table 4 summarise this category. All methods are compatible with the pipe materials, with two exceptions; no information was found for Asbestos Cement (AC), and EMAT is not compatible with PE or PVC. AC pipes are part of a legacy network, forming a small proportion of the overall asset base; roughly 6% of failures were AC pipes between 2000 and 2021, according to data from TW (Figure 3). Depending on the key problem areas, AC pipes may or may not be prioritised for inspection. Further information will be required if they need to be part of the solution(s) developed in the project.

Sensor type	Sensor method	Decription	Detection/ assessment	Measurement limitations	Advantages	Disadvantages
Ultrasonic (PZT)	Pulse echo (PE)	A pulse type wave is transmitted at a defined frequency.	Crack/ corrosion detection		Accurate defect localisation	Small inspection area, limited on thick wall pipes
	Phased Array (PAUT)	Small element UT in an array. Each element is pulsed individually, timings are computationally calculated to create phased aspect.	Crack/ corrosion detection		Good pipe coverage, ability to dynamically control UT beam - dynamic depth focusing	Large sensor array, expensive, experienced operator required.
	Guided wave/ long range (GWUT/LRUT)	Uses a transducer ring around external pipe surface to transmit guided UT waves in both directions. Long measurement range, able to detect defects and features.	Crack/ corrosion detection	Large pipe area, requires cleaning for transducer ring to be fitted	Long inpection range (material dependent, but potentially between 100-200 m)	Complicated, inaccurate sizing due to complex propagation through pipes. Large, heavy transducer array required for external inspections, attenuation through plastics limits signal, but operational frequency can be changed to improve on defect measurements.
	ToFD	Two probe arrangement (transducer and receiver). Using the time of flight, length, location and height of defect can be identified.	Crack/ corrosion detection		More accurate sizing than pulse echo	Slower than pulse echo. Minimum depth required to be operational, difficult to interpret.
	IRIS - Internal Rotational Inspection System	Rotary mirror directs ultraound pulse from a single transducer based on the PE method. A wider area can be covered.	Crack/ corrosion detection, wall thickness	Potential to miss areas of interest, unable to detect cracking	No contact between sensor and surface needed, full circumference inspection with a single sensor	Transmitter/receiver need to be mounted on central axis of pipe for accurate measurements.
	Acoustic Resonance Technology (ART) or Resonant Acoustic Methods (RAM)	Ultra-wide band ultrasound generates oscillations in the target material, which begins to resonate and further amplify the oscillations. Frequnecies are characteristic of thickness and material of the target	Axial/ circumferential crack and corrosion detection, wall thickness (metal loss), ovality	Min. depth 0.8mm	Minimal surface preparation needed, can penetrate beyond surface coatings. Able to identify coating disbondment in lined pipes.	More complex processing than conventional ultrasonic methods, limited to point scans, resolution of mapping dependent on sensor spacing and measurement speed.
Ultrasonic/ Electromagnetic (EMAT)	EMAT	High frequency current pulses create an eddy current on surface layer of metal. Lorentz force arises from eddy current and polarising force, exciting an ultrasonic oscillation.	Crack/ corrosion detection, wall thickness	Metallic only, low sensitivity (additional processing methods needed to improve this)	Could potentially be used to generate transverse waves, increasing measurment range, similar to guided wave ultrasonics.	Close contact with surface is still required and coatings can still impact measurements. Cannot be applied to non-ferromagnetic pipes alone. Limited to material surface. Surrounding ferromagnetic components could influence measurements, more expensive than conventional piezoelectric UT
Acoustic elastic (PZT)	UT - non linear acoustic	Acousto-viscoelastic theory used UT to link up with stresses within viscoelastic materials such as plastics, but may also be used in metals.	Crack/ corrosion detection, stress	New, reliant on complex calculations and only examined with PE thus far. Relies on viscoelasticity.	Can measure residual stress in viscoelastic materials.	Needs pristine baseline of tested material for comparision (further development)

Table 3

Sensor type	Number of sensors	Prefered mounting system	Speed of scan	Area of scan	Cost (£k)
Ultrasound			Dependent on method, number of sensors and mounting system	Dependent on method, number of sensors and mounting system	
Ultrasonic (PZT)	Single or multiple	Close to pipe circumference, either on arm or ring. Potentially could be positions in ring arrangement away from circumference.	Slow with single transducer	Small	0.4
	An array of multiple in single transducer	Close to circumference of pipe	Slightly faster than PE, larger area scanned, but still slow with single transducer. Ring configuration faster but costly.	Section scan area good, but small surface area	25-165
		Modified ring arrangement required to be applied to internal pipe diameter (inverse of current approach)	Fast scan speed over large distance	Large area	50-175
		Two arms or ring structures: one for transmitter, the other for receiving.	Slow with single transducer / receiver pair, faster as an array.	Small	
	Single	Axial - central point critical for inspection	Moderate, but limited with single sensor and speed of movement	Medium	0.4
	Multiple	Circumferential	Slow with single transducer, faster as an array.	Small	
Ultrasonic/ Electromagnetic (EMAT)		Close to surface with arm or ring mounting	Slow with single transducer, faster as an array.	Small	6
Acoustic elastic (PZT)		Same as pulse echo	Slow with single transducer, faster as an array.	Small	

Table 4

8. Electromagnetic Methods

Electromagnetic (EM) methods have several advantages over ultrasonic NDT, but come at a greater expense. This would be of importance when scaling up the POC to prototype and production TRLs in future projects. Below are the acronyms used in the tables for this section:

ECT/ECA	Eddy Current Testing / Eddy Current Array
PEC	Pulsed Eddy Current
BEM	Boundary Element Method
RFEC	Remote Field Eddy Current Testing
MFL	Magnetic Flux Leakage
PPR	Pipe Penetrating Radar

Table 5

Sensor method	Description	Detection/ assessment	Measurement limitations
ECT/ECA	AC in a coil creates a magnetic field, which induces eddy current in conductive material. Defects disturb eddy current path which is measured by the coil.	Material thickness, crack defects and corrosion, material conductivity, measures non-conductive coating thickness	Min. 1mm crack
PEC	Similar to ECT and ECA approach, but current is pulsed and the decay rate is measured. This translates into a thickness measurement over the probe.	Material thickness, crack defects and corrosion, material conductivity	
BEM	Similar to EC methods, with a broadband frequency spectrum vs a single frequency. Ranges between 50 Hz and 50 kHz.	Material thickness, crack defects and corrosion, material conductivity, measures non-conductive coating thickness	
RFEC	Exciter coil drives a low frequency AC signal. A direct EM field attenuates rapidly by circumferential eddy currents, while an indirect field diffuses radially outward through pipe wall. This field spreads along the pipe with little attenuation. Both paths re-diffuse back though the pipe wall and are dominant in the remote field zone. Any abnormalities are reflected in the data as changes to signal magnitudes and phase.		
MFL	Powerful magnet used to saturate material with flux lines, which distort at defects. A sensor detects the mag flux distortions that leak from the surface. This only measures in one plane; 3 required to cover axial, circumferential and radial leakage.	Corrosion pits, metal loss, wall thickness measurements, small defects, depth location of defects	defect detection from 2 mm diameter
Magnetic particle	Magnetic yoke magnetises ferromagnetic material, if defects exist subsurface, magnetic force deforms around defect. Magnetic particles in liquid carrier base are inspected to identify defect location.	Surface, subsurface defects	Only top 2.5 ish mm inspected
PPR	Same principle as ground penetrating radar, but within a pipe. Antenna transmits EM waves, which is reflected at boundaries. Able to penetrate further than acoustic/ultrasonic methods.	Material thickness, pipe-soil interface mapping	
Inductive proximity	Inductor coils interact with metal objects only, giving a measurement of distance	Magnetic flux measures distances from a probe; resolution can	May not be precise enough, needs to be 1-5mm from surface

Table 6

Sensor method	Description	Detection/ assessment	Measurement limitations	Pre-enabling required?
ECT/ECA	AC in a coil creates a magnetic field, which induces eddy current in conductive material. Defects disturb eddy current path which is measured by the coil.	Material thickness, crack defects and corrosion, material conductivity, measures non-conductive coating thickness	Min. 1mm crack	
PEC	Similar to ECT and ECA approach, but current is pulsed and the decay rate is measured. This translates into a thickness measurement over the probe.			No surface preparation required
BEM	Similar to EC methods, with a broadband frequency spectrum vs a single frequency. Ranges between 50 Hz and 50 kHz.	Material thickness, crack defects and corrosion, material conductivity, measures non-conductive coating thickness		
RFEC	Exciter coil drives a low frequency AC signal. A direct EM field attenuates rapidly by circumferential eddy currents, while an indirect field diffuses radially outward through pipe wall. This field spreads along the pipe with little attenuation. Both paths re-diffuse back though the pipe wall and are dominant in the remote field zone. Any abnormalities are reflected in the data as changes to signal magnitudes and phase.			Surfaces potentially require cleaning prior to inspection. May also need to be empty.
MFL	Powerful magnet used to saturate material with flux lines, which distort at defects. A sensor detects the mag flux distortions that leak from the surface. This only measures in one plane; 3 required to cover axial, circumferential and radial leakage.	Corrosion pits, metal loss, wall thickness measurements, small defects, depth location of defects	defect detection from 2 mm diameter	Cleaned, unlined surface required
Magnetic particle	Magnetic yoke magnetises ferromagnetic material, if defects exist subsurface, magnetic force deforms around defect. Magnetic particles in liquid carrier base are inspected to identify defect location.	Surface, subsurface defects	Only top 2.5 ish mm inspected	Outer coating may need to be removed prior to inspection
PPR	Same principle as ground penetrating radar, but within a pipe. Antenna transmits EM waves, which is reflected at boundaries. Able to penetrate further than acoustic/ultrasonic methods.	Material thickness, pipe soil interface mapping		Unknown - might be similar to UT methods where a clean surface is required. Unclear in the literature

Table 7

Sensor method	Advantages	Disadvantages
ECT/ECA	Sensitive to small and subsurface cracks and defects.	Limited to conductive materials only, data interpretation is complex.
PEC	Unaffected by insulating coatings, can operate submerged.	Provides a relative measurement, impossible to detect small scale pitting.
BEM	Non-contact approach, not sensitive to corrosion products, can scan through coatings, linings, depth dependent on the diameter of probe.	Unable to detect pinholes, provides average thickness measurement, difficult to identify pits, time consuming data capture process, pipe needs to be clean and empty for inspections by pigging, poor resolution, only used on ferrous metals.
RFEC	Does not require close contact with circumferential surface of pipe.	Requires a lot of skill and experience to interpret the data, detector coil may need to placed at least 2 x the pipe diameter away from exciter coils.
MFL	Good sensitivity to pitting.	Close contact with surface required, surface cleaning needed, small diameter pipe inspection not currently possible, requires calibration to properly interpret signals.
Magnetic particle	Good for surface and subsurface identification of cracks, fast inspection.	Limited to ferromagnetic materials only, post demagnetisation may be required, max depth sesnsitivity approx. 2.5 mm.
PPR	Able to locate through all pipe materials, can be performed within pipe without antenna touching pipe, may also identify surrounding pipe environment and detail voids.	Signal strength attenuates faster in clay or saturated soils (soil limitations), experience with data interpretation required, unable to detect leakage, limited evidence of void detection within pipe material, water and debris may scatter pulse.
Inductive proximity	Can detect distance to metal surface through non-metal, i.e. through any built-up residue, no cleaning required. Resolution of distance in the order of µm.	Possibly not enough resolution on the pipe surface to detect cracks, only larger patches of metal loss. Change in diameter may not be large enough to be detected above general signal noise. May need an impractically accurate start location. Distance calculated by voltage, so noise may be too large to pick up defects.

9. Inspection Capabilities

The features and types of degradation which can be detected in pipelines are dependent on the pipe material and inspection methodology. Magnetic-based approaches are particularly useful for detecting pitting, cracking and corrosion induced defects within metallic assets, however the same inspection technique may fail for non-metallic assets. The type of defect may also be material specific. Prior knowledge of the pipe material would enable a targeted inspection, effectively assessing the pipe condition and/or the presence of defects. Table 8. outlines the types of features and defects which could be detected under the right conditions for the inspection methods previously discussed. Green boxes refer to a good level of detection, amber refers to low level of detection or if detection of feature is arrangement dependent, while red refers to a lack of detection. White boxes are unknowns at this time.

10. Ongoing Research

Further information on the most suitable method is ongoing and will run for the duration of the detailed design phase (Ph2). As the understanding of the problem evolves, there may be reasons for changing to a different sensing method, so this may serve as a reference for design alterations as the project progresses.

Table 8.

Inspection features	UT - PE	UT - TOFD	UT - PAUT	UT - GWUT/LRUT	UT - IRIS	UT - EMAT	UT - ART		ECT/ECA	PEC	BEM	RFEC	MFL	Magnetic particle	PPR
Axial (longitudinal) cracks															
Circumferential cracks															
Near surface cracks															
Internal surface pitting															
External pitting															
Internal material loss (thickness)															
External material loss															
Wall thickness															
Voids or defects within pipe material															
Voids in surrounding soil															
Pipe wall stress or strain OR material property															
micro-cracking															
Surface pH															
Material degradation related surface chemistry															
Dents / ovalities (internal geometry)															
External cracking															

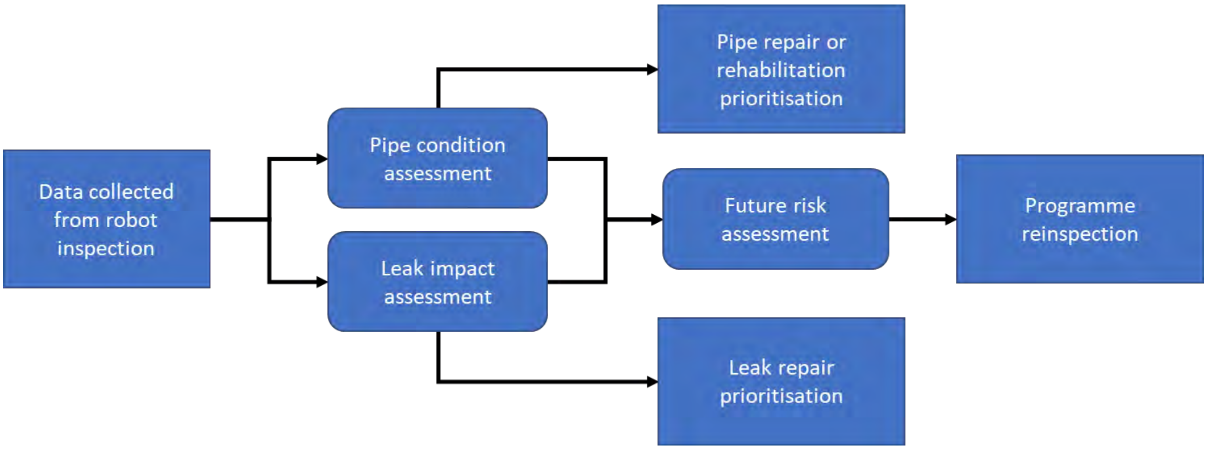

Figure 5

Further work will also aim to scope out the possibility of using the data collected during a robotic inspection for pipe condition and future risk assessments. This aims to build on a prototype assessment framework (Figure 5) that will enable effective management of assets through a data driven risk scoring system. The purpose of this will help to inform remediation costs and strategies, whilst also providing a tool to predict remaining asset life and an appropriate asset monitoring program. This will require further research and data collection to determine critical input parameters and weighting for each assessment.

Appendix 6. D3 - Specification

Target Design Specification
L09-D3

Deliverable D3
PipeBOTS in Rising Mains

Prepared for Rachel Cunningham and David Walters
Thames Water

3rd January 2023

PAS 99 Integrated Management Systems IMR535435
ISO 9001 Quality Management FM38723
ISO 14001 Environmental Management EMS535432
OHSAS 18001 Occupational Health and Safety Management OHS535433

Change Record

Version	Status	Date	Author(s)	Summary of changes
0.1	Draft	01/09/2022	Meriel East	First Draft
0.2	Draft	13/12/2022	Meriel East	Draft
0.3	Draft	19/12/2022	Meriel East	Draft
0.4	Draft	03/01/2023	Ben Loades	Draft review
1.0	Release	03/01/2023	Meriel East	Released for feedback
1.1	Release	31/01/2023	Meriel East	Following group feedback
1.2	Release	13/02/2023	David Walters	New format

Reviewers

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David Walters	Eng Innovation	Thames Water	David.walters@thameswater.co.uk

Management Approval

Name	Position

This document outlines the target specification for a proof-of-concept robotic platform to test the sensing methods developed in Phase 1 of the project PipeBOTS in Riser Mains. It will provide structure and design constraints for the detailed design in Phase 2.

Knowledge has been gathered in technical meetings and site visits (see D1 Site Visit Report) to highlight the main considerations for detailed design in the second phase.

Scope for Phase 2

- An outline of the intended end-to-end process will be provided in the Phase 2 report, including access feasibility.
- Testing will take place in a combination of indoor lab environment and outdoor simulated buried asset environment.
- Vibroacoustic testing is the main priority; ensuring that there is capability for detecting deterioration as the main outcome of this project.
- Gas pockets and ragging will be acknowledged in the report.

POC Specification

Table 1

Item	Testing Objectives	Proposed Design / Materials / Tests / Constraints	Success Criteria
1	Determine if chosen POC system can operate in 300mm pipe	Test rig pipe diameter is 300mm	POC device can operate, and measurements can be taken in test rig of 300mm diameter
2	Determine if chosen POC system can operate underwater in 300mm pipe	Test rig filled with water to head of 10m.	POC device can operate, and measurements can be taken in water filled test rig of 300mm diameter
3	Determine optimal distance, placement & mounting of accelerometers from pipe wall	Halo mounted accelerometers - sensors need to be close to the pipe wall and coupled with water. Various diameter halos may need to be tested.	Demonstrate that meaningful pipe material / condition observations can be made in the data with mounting and location of accelerometers optimised
4	Determine optimal number of sensors from 1 to 6	PCB designed for maximum of 6 sensors	Understanding of capability of sensor system and minimum number needed for detailed circumferential measurement
5	Determine what level of accuracy can be achieved using the accelerometer / vibroacoustic technology for measurement of pipe wall thickness in new, clean ductile iron pipe	Accelerometer / vibroacoustic technology	Observations in data have a high enough accuracy to be statistically significant
6	Determine what level of accuracy can be achieved using the accelerometer / vibroacoustic technology to identify machined defects in new clean ductile iron pipe	Accelerometer / vibroacoustic technology	Observations in data have a high enough accuracy to be statistically significant
7	Determine what level of accuracy can be achieved using the accelerometer / vibroacoustic technology to identify actual defects in corroded ductile iron pipe (sample)	Accelerometer / vibroacoustic technology	Observations in data have a high enough accuracy to be statistically significant
8	Determine suitability of data captured - for post processing purposes	Noise rejection technology	Demonstrate that noise can be filtered out and meaningful pipe material / condition observations can be made in the data

9	Determine system power supply requirements	Proposed power supply - 2KVA 110V with a 16A adaptor (standard generator)	Robot crawler, sensors and sound generator operate satisfactorily during tests
10	Determine the time required for each measurement step	Initial survey method to be stop / start	Gain sufficient data to determine future survey speed (with continued development)
11	Determine number of measurements needed per metre for suitably detailed survey	Initial survey method to be stop / start	Robot crawler, sensors and sound generator operate satisfactorily during tests
12	Determine the optimum sound pressure generator system, either pneumatic or electrical	Sound / pressure generation system - needed for acoustic measurements	The chosen sound / pressure generator system works satisfactorily
13	Determine accuracy of meterage / linear measurement system	Existing tractor / crawler cable measurement system	Meterage / measurement requirements met for pinpointing defects (TBC)

POC Exclusions

- No new sensor invention
- No live pipe field trials
- No simulated gas pockets
- No simulated ragging (i.e. not testing undissolved wipes in the simulated environment)
- No continuous / moving measurements will be taken – robot will stop to take acoustic measurements.

Higher TRL – Commercial Specification for Future Development

This table outlines the specification for a higher TRL product, to give context to the POC project.

Table 2

Item	Testing Objectives	Proposed Design / Materials / Tests / Constraints	Success Criteria
1	Determine ability of POC design to operate in range of flow velocities expected in rising mains	Motor speed, maximum vehicle speed, traction of wheels on pipe surface, weight, water resistance	Robot can move against the flow velocities experienced in a rising main environment
2	Determine maximum speed of crawler upstream & downstream	Motor speed, maximum vehicle speed, traction of wheels on pipe surface, weight, water resistance	Robot can operate in the flow velocities experienced in a rising main environment and speed optimised
3	Determine that robot can be inserted through drill, bond & bolt insertion in a rising main	Collapsibility of sensor halo / mounting, smallest possible form factor & smallest possible hole size for insertion	Robot can be inserted through drill, bond & bolt insertion in a rising main
4	Determine that POC device meets the required pressure rating	Design, seals & gaskets	Robot able to operate underwater at rising main pressures (with a factor of safety applied)
5	Determine clean down, operating and Health & Safety considerations	Operating environment is pressurised pumped raw sewage	Safe operation of system
6	Test POC design to minimise ragging during operation	Streamlined design, reduced scope for buildup of rags	Ragging of robot & sensors not encountered during operation
7	Determine accuracy of defect depth measurement	Sensor & system design, current & future technological capabilities	Accuracy significantly better than current methods
8	Determine crack detection / identification thresholds	Sensor & system design for crack detection	Successful crack identification & location, false positive rejection
9	Determine max possible range upstream & downstream	Tethered robot, considering ragging & silt	Target range of rising main inspection per insertion
10	Determine smallest bend radius possible to traverse	Tethered robot, considering ragging, multiple bends	Target range of rising main inspection per insertion
12	Determine maximum speed upstream & downstream	Tethered robot, considering ragging, silt & flow velocities	Target range & duration of rising main inspection per insertion
13	Determine data resolution & scope for continuous operation	Minimum time taken per measurement for acoustic velocity to be accurate	Reduce likely survey durations to minimum
14	Determine how silt in invert of pipe affects robot operation	Track / crawler design	Robot survey is not impacted severely by silt
15	Determine signal processing techniques needed for gas pockets	Gas sensors incorporated in robot / crawler body	System can identify gas pockets & maintain measurement capability

Appendix 7. D4 - Lab Tests Report

Document Name:	L09 PipeBots in Rising Mains				
Document Number:	L09-T-002			Revision:	1
Drawn By:	PS	Checked By:		Issue Date:	

L09 – PipeBots in Rising Mains

Test Report Number
L09-T-002
Deliverable - D4

Test Number	L09-T-002
Location	Synthotech, ICAIR
Test Description	Robotic Crawler and Pushrod Speaker Lab Testing
Present	JW, AKW, PS, MT, WL(UoS), JBW (UoS), KH (UoS)
Date	July – October 2023
Report completed by	Pravin Smart
Reviewed by	Alexander Williams
Signed off by	

1 Contents

2 Figures

3 Introduction

Based on the specification outlined in Deliverable 3, a submersible crawler, sensor array and sound generator were built to facilitate testing of the Proof of Concept (PoC) Rising Mains inspection system. To test the system in the simulated environment, individual subsystem testing, and safety assurances were required. Development within these areas was important to ensure the system worked together, as failure within the crawler, sensor or sound generator would mean that asset inspection could not take place operationally.

3.1 Aims

The purpose of this deliverable is to document the testing and refinements of the system to ensure that the whole system can be used for operational measurements when deployed into a simulated test environment for asset inspection.

3.2 Objectives

The objectives of the lab tests were to test and demonstrate the safety aspects of operating a robotic crawler underwater, ensure the sensors were functional underwater and that they collected measurement data properly, and ensure that the sound generator could produce an appropriate sound pressure level to be able to take measurements in a simulated environment. These objectives for each core element of testing are broken down below:

The suitability of the crawler to function underwater:

- Internal pressurisation and hold duration.
- Operational control of the crawler and movement.
- Visualisation of the front/rear from the crawler platform.
- Condition testing of the above in wet and dry conditions.

The quality of the data captured by the crawler for pipe integrity analysis:

- Functionality of accelerometers under water.
- Resolution refinement of accelerometers.
- Assessment of required output frequency of accelerometers.
- Feasibility of user interface and software.
- Collection of data for future hardware/firmware/software debug.

The sound pressure level generated by the speaker build:

- Functionality of sound generator in dry and submerged conditions.
- Submersion and leak testing of sound generator.
- Measurement of Sound Pressure Levels (SPL) underwater.

4 System testing reports

4.1 Crawler Operations and Pressurisation Tests

Apparatus

The equipment used for the test is listed below:

- PoC Crawler Assembly
- Crawler Specific 40 m Umbilical Tether
- Visual display and control unit
- Additional visual display unit
- Power cables
- Bike pump
- 6 mm tubing and push fitting
- Digital Manometer (<2Barg)
- Plastic tub filled with water

Test arrangement

Figure 1 and Figure 2 show the robotic crawler assembly, the control unit and displays, and the arrangement of how these are all connected to the crawler via a connection box on the umbilical connector. These are standard Synthotech control and display units used for crawler-based CCTV inspection of gas mains between 12” and 48”.

a)

b)

Figure 1 (a) Crawler assembly and tether connection, and (b) visual control and display units displaying front and rear camera output from the crawler.

Figure 3 shows the arrangement of the crawler’s internal pressurisation system. The bike pump was connected to the main connection box to feed air into the crawler through the umbilical tether. An offtake connection was connected to a pressure gauge (manometer) to monitor and measure the internal pressure. Finally, a control valve isolated the pressure within the system. This check would ensure that system users could determine if there was a leak within the body of the crawler prior to submersion and during operations underwater. Having an equal or higher internal pressure would effectively minimise the risk of water ingress to the electronics and reduce the likelihood and severity of potential shocks.

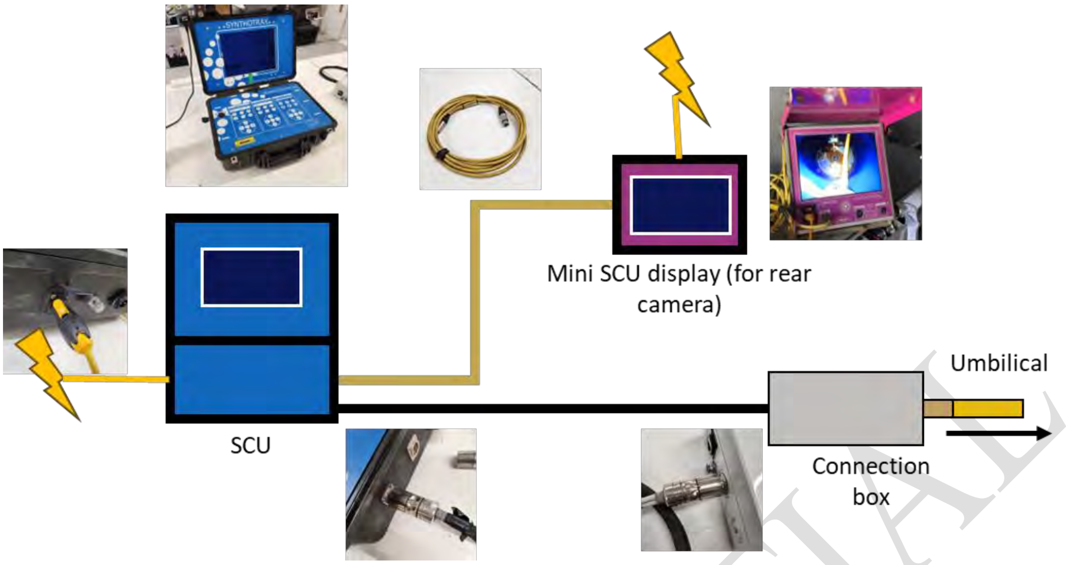

Figure 2 Synthotech Control Unit (SCU) arrangement for crawler power, control, and visuals.

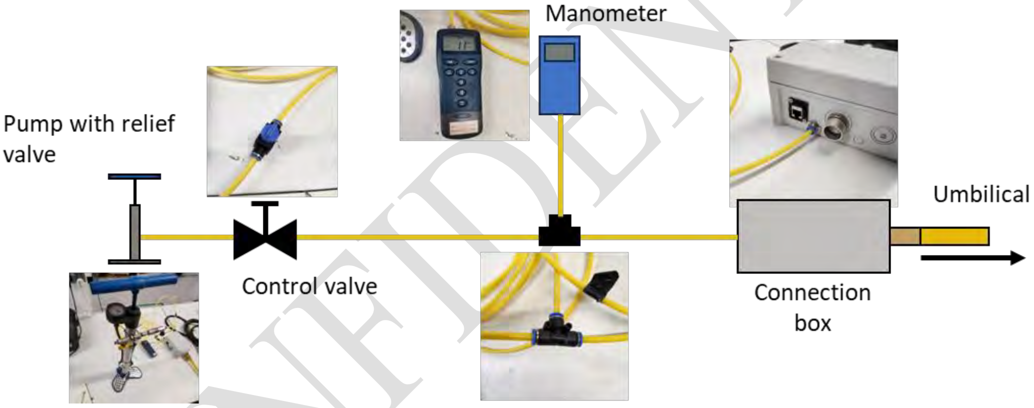

Figure 3 Internal pressurisation system and pressure monitoring arrangement.

Methodology

Tests of the crawler were relatively simple, focusing on ensuring all aspects of the converted CCTV crawler were operational after build and within water. Tests initially started under dry conditions and moved to wet once confident in results. Tests are described as follows:

Dry testing

- The crawler was placed on the floor and movement control was checked with the control unit.
- Camera image and quality were visually checked on the control unit and visual displays
- Internal system pressurised to 500 mbarg and monitored over time

Wet testing

- The crawler was submersed in a water-filled container whilst powered
- Dry tests were repeated whilst submerged

Results

- Crawler controls and movement worked well under dry conditions.
- Front and rear camera outputs to visual displays were good.
- Internal pressure pumped to 530 mBarg and dropped to 527 mBarg after 10 minutes of submersion in water.
- Crawler controls, movements and visual outputs were all functional when the crawler was submerged in water.

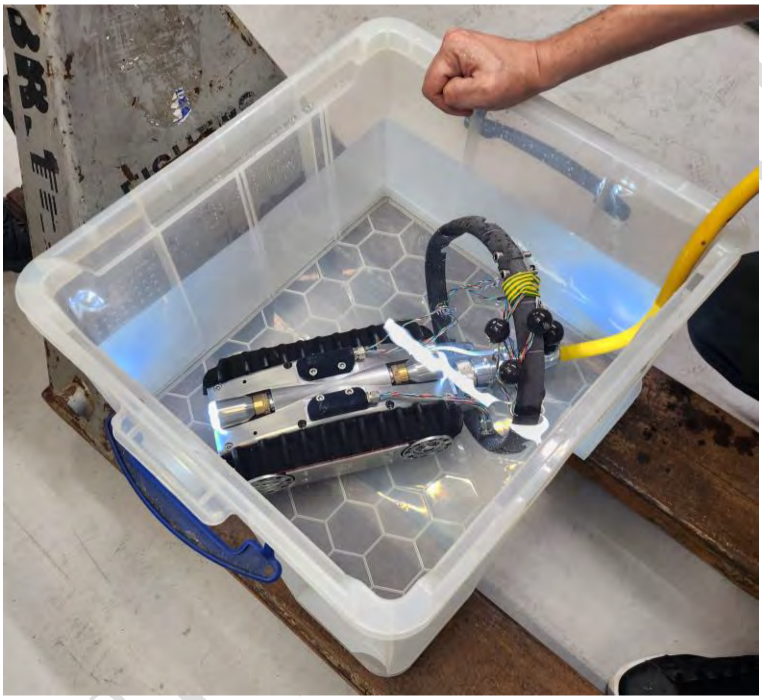

Figure 4 Submerged crawler operations.

Conclusion

The crawler's operation and functionality were confirmed to be suitable for underwater use. The internal pressurisation system held to a suitable level of pressure, however, if the system will be used in high-pressure environments within the next stage, this will need to be revisited to ensure the seal holds under these conditions. However, for operational testing up to 1 barg, the current arrangement is expected to hold its seal. Going into simulated trials, an approximate pressure of 500 mbarg should be used and maintained frequently during testing. Overall, the crawler component is suitable for simulated testing within a water-filled pipe.

4.2 Sensor Data Acquisition

Apparatus

The equipment used for the test is listed below:

- Laptop with PipeBots UI program installed
- PoC Crawler Assembly
- Crawler Specific 40 m Umbilical Tether
- Visual display and control unit
- Additional visual display unit
- Bike pump
- 6 mm tubing and push fitting
- Digital Manometer (<2 barg)
- Speaker and signal generator

Test arrangement

Figure 5 shows the arrangement used for collecting sensor data from the crawler, with an RS485 to USB cable connecting the laptop with the user interface to the connection box of the umbilical tether. This is connected to the internal electronics and sensor controller within the robotic crawler.

Figure 5 Data Acquisition Arrangement.

Methods

Testing focused on the refinement of the signal received by the accelerometers and how this was received, packaged, and sent to the user interface for displaying and saving collected data. Technical development here was crucial as asset inspection with a flawed data acquisition system would not be ideal throughout simulated testing and future asset inspections i.e. garbage in = garbage out.

Therefore, tests examined the response from sensors under stimulus, using the signal generator and a coupling under dry and wet conditions. Sound frequencies between 50-100 Hz were used during this stage. The shape of the output data was iteratively reviewed, and the hardware/ firmware/ software was debugged until the data quality was what was expected. Additional tests were performed on submerged pipe at ICAIR and the simulated test rig at STARS.

Results and Commentary

- Upon initial testing the sensors failed due to a chip failure when the entire system was submerged underwater. Further investigation into this revealed this chip failure was on the acquisition boards, which when removed improved the signal and the sensors were then able to operate underwater. This enabled water tests to commence.

- Full water testing occurred, and the sensors did not fail when submerged, however, the data collected by the sensors was of inadequate quality. Investigation into this indicated that the sampling rate of the sensors was too low, which led to an aliasing error in the data. An example of this is shown in Figure 6a) when the sound generator is turned on. As the system was trying to sample data from 6 accelerometers at once, with 3 data packages per accelerometer, data was being lost on the way to the user interface. Updates to the user interface and crawler firmware corrected this bug, improving the data quality for analysis, at the cost of increasing the scan time at a single location i.e. data was collected from each individual sensor separately and concurrently vs simultaneously.

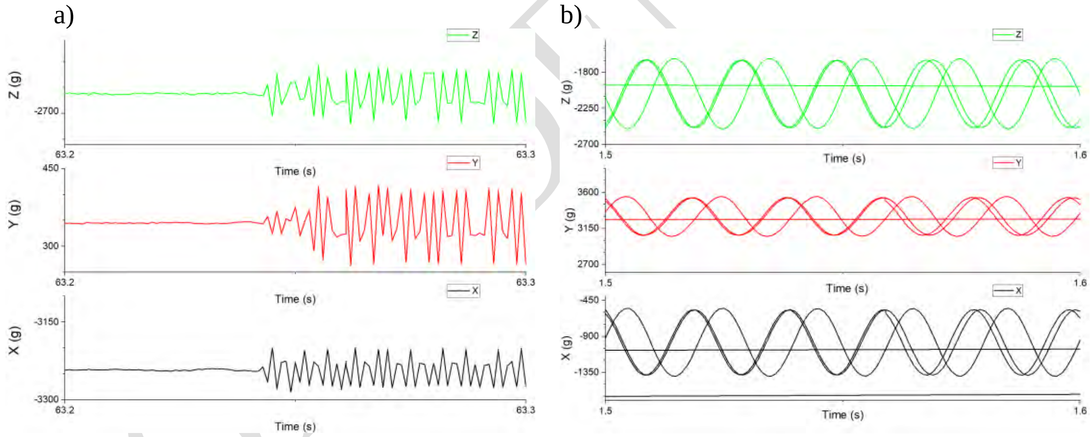

Figure 6 Example of data acquisition with a) under-sampling and b) optimised sampling.

- Further classification of the signal was performed in the submerged pipe at ICAIR test. Figure 7 presents an example of the refined data when there is no sound and when there is sound at 100 Hz. The signal was confirmed to be much clearer for in-pipe simulated testing.

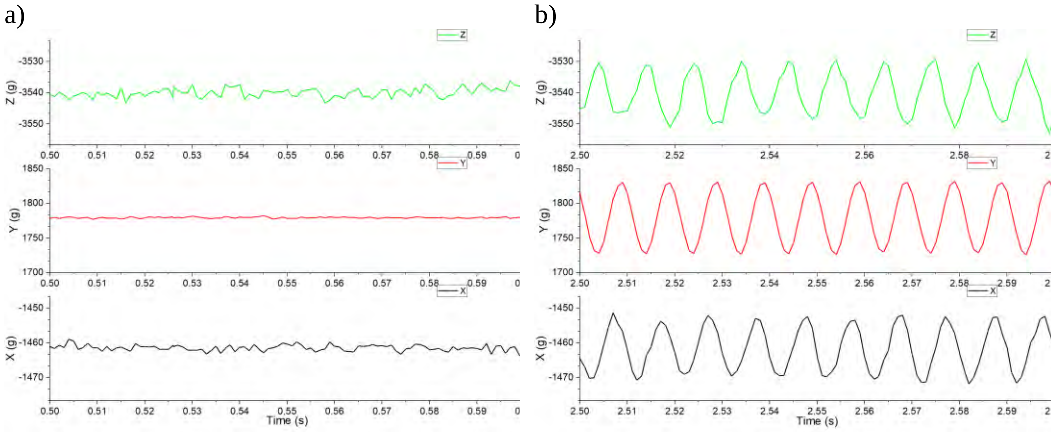

Figure 7 Example of corrected data when a) sound generator is off, and b) sound generator is on.

- Additional data was collected to understand the impact of the crawler when taking measurements. This produced additional noise in the data, and performing a Fast Fourier Transform (FFT) analysis of that data highlighted that these noise frequencies were usually below 30 Hz. This could therefore be removed with a high pass filter or bandpass filter depending on the environmental conditions. Going into future testing it would be good to understand the background noise as part of the measurement process to assist data post-processing. An example of this data is displayed in Figure 8 which outlines how static and dynamic signals compare, and how post-processing could remove the noise from the crawler when driving. This also suggests that measurements could be taken on the move, however, this will need to be confirmed in simulated testing.

- The caveat at taking measurements of the system whilst driving in its current configuration is that sections of the pipe would be missed during an inspection. This is due to the way the sensors collect the data, separately and concurrently with each sensor gathering data for 6 seconds before moving to the next sensor for a full circumferential scan. When static, this is not a problem, but when moving, areas could be missed. Improved hardware that facilitates faster data capture and transmission rates can ensure this becomes less of a problem in the next phase to increase the potential for simultaneous sensor monitoring.

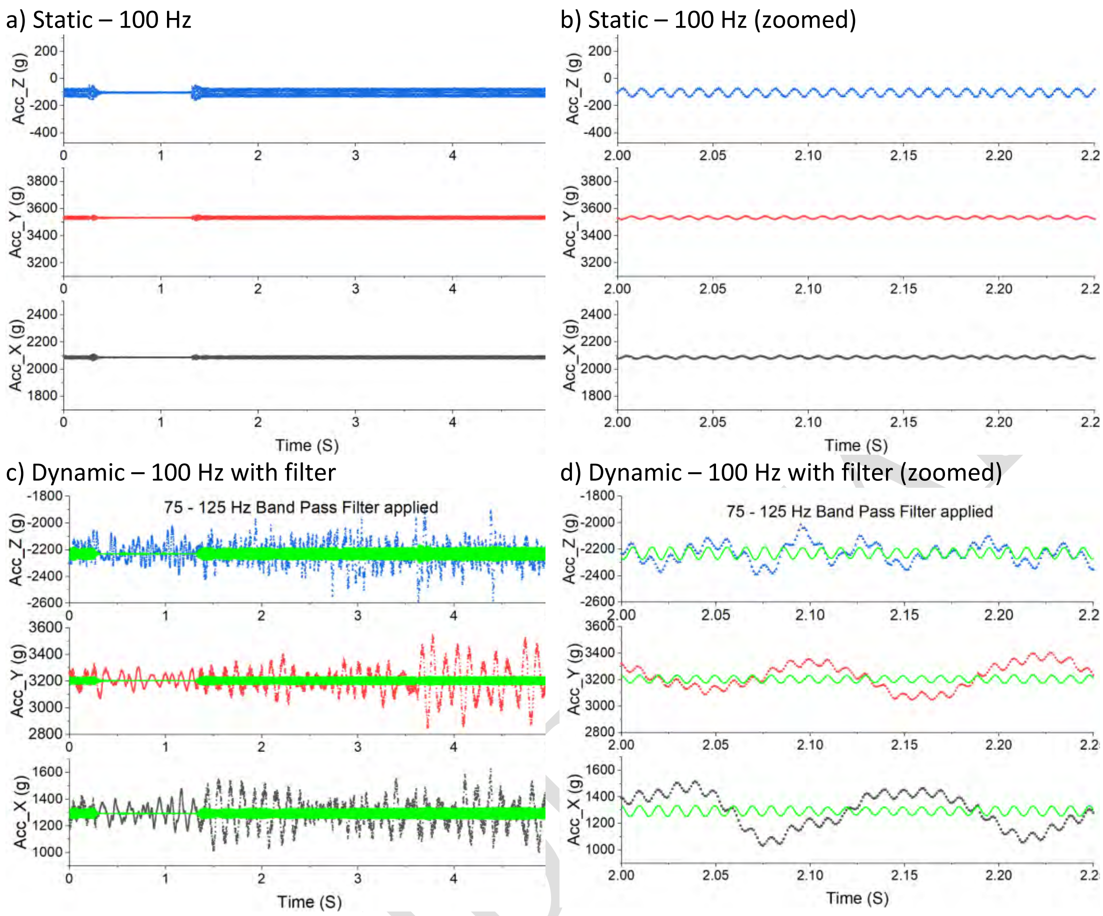

Figure 8 Static measurement vs dynamic measurement at 100 Hz. Bandpass filter applied to dynamic measurement to remove additional noise from crawler movements. Y axes are scaled to match the Y range for comparison.

- Additional tests performed on the ICAIR pipe assessed the data collected at different locations of the test rig where defects were present. The test rig used, and scan locations are displayed in Figure 9. Figure 10 shows the position of the accelerometers on the sensor halo for reference. Figure 11 presents some of the results taken from the nearest accelerometer to the defects with the amplitude of the data centralised around zero. Investigation of the data suggested that the accelerometers X, Y and Z amplitude increased at the defect locations compared to the “no defect” zone. This was initially thought to be linked to the position of the sensors in relation to the sound generator, however, fully examining the data on the other sensors showed that the amplitude of the accelerometers close to the defects increased more compared to the accelerometers lower down on the pipe’s clock face. An example of this data is presented as amplitude plots in Figure 12. Whilst not definitive, the additional amplitude and the shape changes to the plots are something which could indicate the presence of a defect. Tests on the simulated test rig at STARS, with the movable sound generator will be able to confirm whether this is a result of sensor proximity to sound generator or a result of a sound wave changing close to a defect.

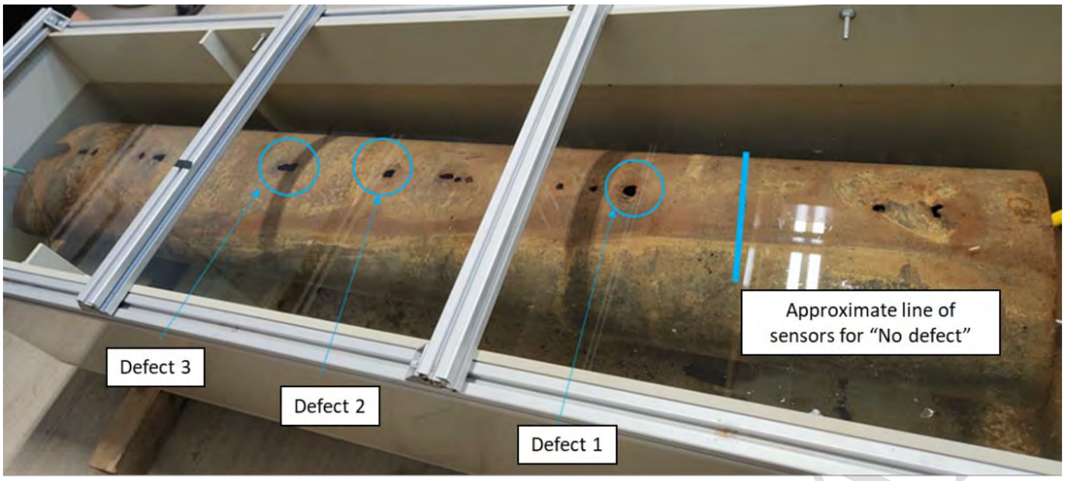

Figure 9 ICAIR Test rig with references to the location of scans.

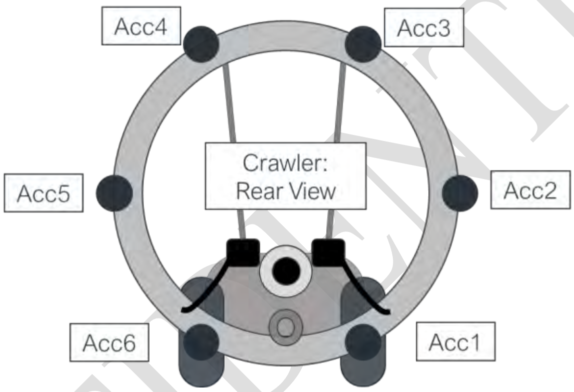

Figure 10 Reference diagram for accelerometer number and position on the sensor halo.

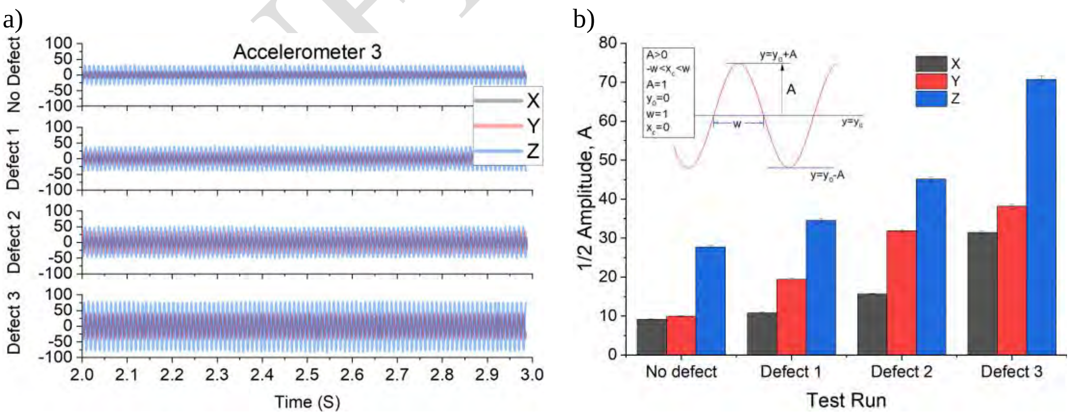

Figure 11 Example data from accelerometer 3 to assess scan quality and compare vibrational amplitude.

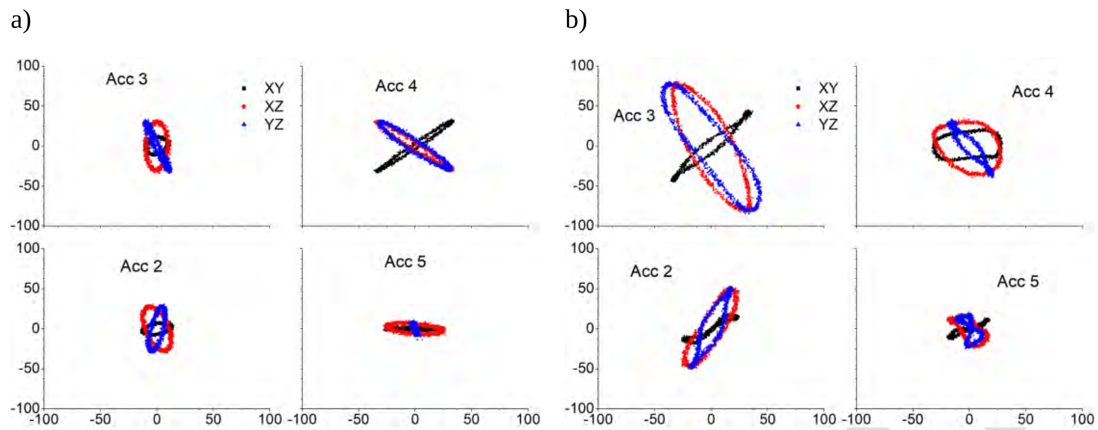

Figure 12 Amplitude plots of accelerometers 2,3,4 and 5, showing XY, XZ, And YZ changes when sounded at 100 Hz, showing a) no defect area and b) defect 3.

Conclusion

The data acquisition process has been iteratively modified and updated to get the correct output signal data from the accelerometers. This process took longer than anticipated due to the difficulties of refining the sampling rate, the sampling process and reducing the loss of data fidelity during scans, all within the restraints of hardware. The current system is now sufficient to prove the sensing concept in a simulated test environment, however, looking ahead a review of the data collection process and hardware will be required to improve data collection efficiency going forward.

4.3 Submersion and Transient Speaker Test

Apparatus

The equipment used for the test is listed below:

- Acoustic signal generator
- Transient Speaker push-rod assembly
- 15W cabinet speaker
- 60W cabinet speaker
- 30W underwater cabinet speaker
- Plastic tub filled with water
- Accelerometers from PipeBots Crawler
- Hydrophone (UoS)
- ICAIR test rig (UoS)

Testing arrangement

Figure 13 shows the finalised arrangement of the sound generator. This comprised an adapted camera assembly, replacing the camera with a modified marine speaker for submersion underwater. Throughout tests, it was identified that an amplifier was required to increase the speaker's sound pressure level. The amplifier could then be connected to a signal generator unit (or the PipeBots UI through the DaQ laptop) or via Bluetooth to a mobile device.

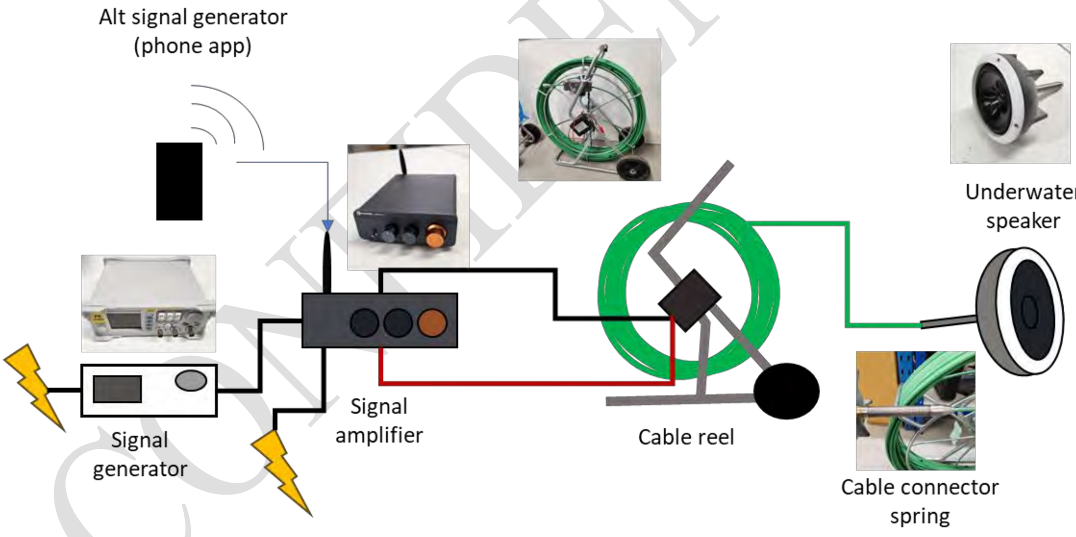

Figure 13 Finalised sound generator arrangement.

Methods

Initial checks of the speaker assembly sound and housing seals were performed:

- 15W speaker tested in dry conditions when connected directly to a signal generator
- 15W speaker build was submersed into a water-filled container for 10 minutes, whilst connected to a signal generator – see Figure 14.

a) b)

Figure 14 (a) Transient 15W cabinet speaker and pushrod assembly, and (b) plastic tub for initial submersion testing.

Once the amplifier was incorporated and the sound level improved, alternative speaker configurations were tested to ensure adequate sound pressure levels when submerged underwater. Speaker configuration tests were performed at ICAIR, with the speakers presented in Figure 15. Speakers were submersed at one end of the test rig, while a hydrophone was positioned on the far end, as shown in Figure 16. Sound was played at 100 Hz using a signal generator connected to an amplifier, while the hydrophone measured the sound pressure response.

a) b) c)

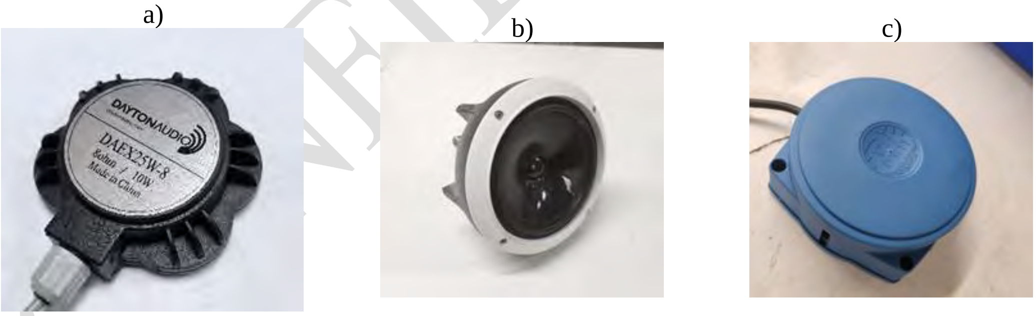

Figure 15 Speaker configurations that were tested for SPL levels underwater – a) 10W Dae audio exciter, b) 60W Visaton marine cabinet speaker and c) 30W Thomann underwater cabinet speaker.

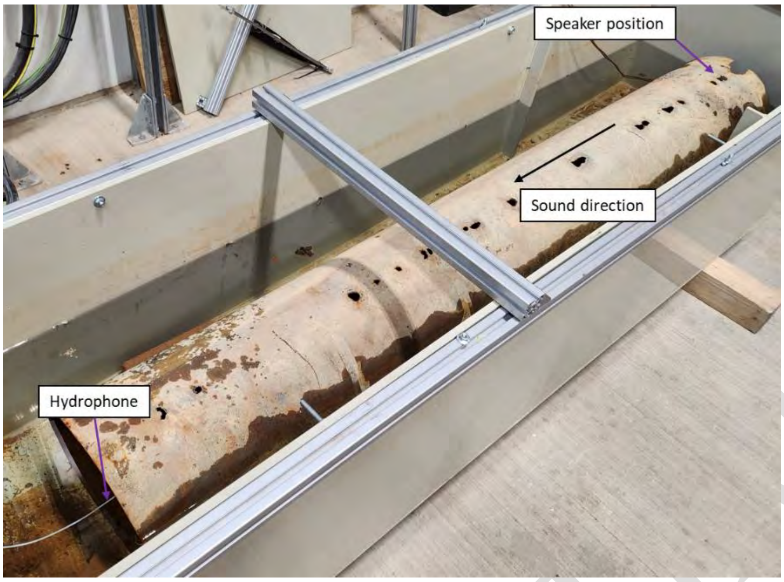

Figure 16 Ex-situ rising main test rig at ICAIR, Sheffield - labels indicate the locations of the hydrophone and speaker during speaker configuration tests.

Results & Commentary

- The 15W cabinet speaker output was very quiet. No leaks were detected over the 10-minute submersion cycle, and ripples were observed throughout the test to confirm speaker operation. The sound was audible from the speaker after submersion. The speaker does work in this application but there were concerns that the sound generator would not be loud enough for adequate sensing – prompting the need for an amplifier. The amplifier improved sound output however there is a risk of damage to the amplifier and speaker when increasing the amplitude of the sound wave on the signal generator, this will need to be monitored during operations.

- Hydrophone tests demonstrated that the purpose-built underwater speaker (Thomann) produced the greatest SPL out of the 3 speaker configurations (Figure 17 & Figure 18). The 60W Visaton system performed an order of magnitude below the underwater speaker (0.545 vs 0.047 pressure amplitude), while the water-resistant audio exciter produced the smallest sound pressure. As the 60W Visaton speaker is compatible with the push-rod reel assembly and produces a decent SPL, it would be tested in the simulated test rig. The Thoman underwater speaker would also be tested alongside some of the simulated tests to understand the impact of the SPL on defect detection.

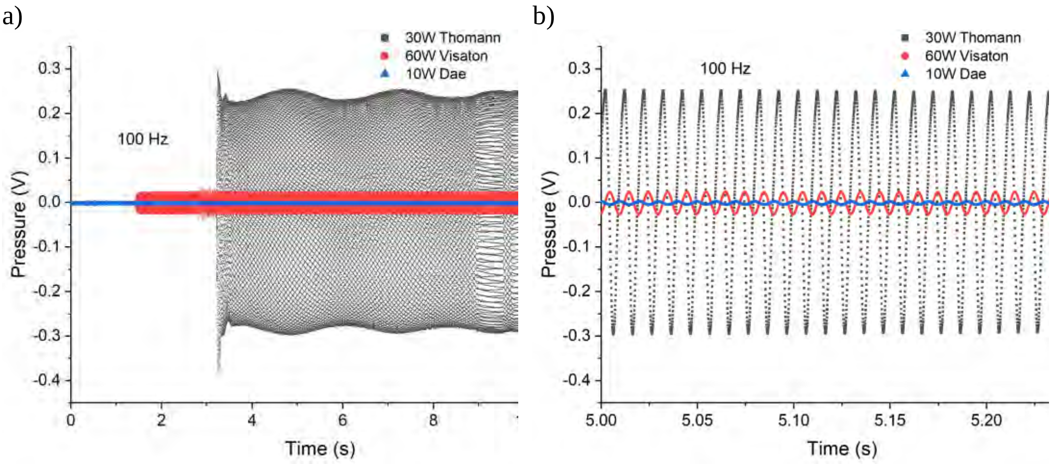

Figure 17 Hydrophone response from speaker configurations at 100 Hz, showing a) the full sampling range and b) a 0.25-second sample.

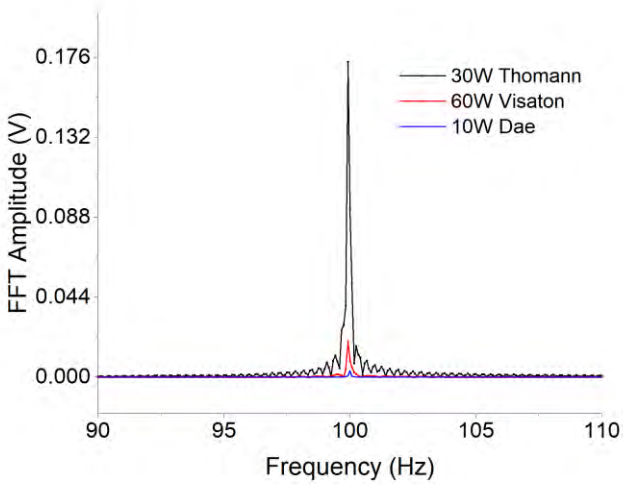

Figure 18 FFT response of speaker output

Conclusion

Testing was able to demonstrate that off-the-shelf cabinet speakers could be modified for underwater sound generation and could be combined with existing push-rod camera technology to effectively position the speaker within an underwater pipe environment. Ideally, an underwater-specific speaker would be preferred to produce adequate sound pressure levels. In the next stage, it will be important to understand how these speakers could be adapted for operational use. For simulated testing, the modified 60W Visaton speaker will be used as this provides more versatility around positioning the speaker within the STARS test rig. Repeat measurements with the 30W Thomann speaker will also take place alongside simulated defect testing at STARS to determine if the sound pressure level impacts detection sensitivity.

5 Outcomes and Recommendations

Overall, tests were able to demonstrate the functionality of the overall system to operate and position the sensors to generate adequate sound to stimulate the sensors to collect sound data correctly underwater. The outcomes can be concluded as follows:

The suitability of the crawler to function underwater

- Internal pressure successfully holds during submerged operations
- Successful control of crawler and visual display underwater

The quality of the data captured by the crawler for pipe integrity analysis:

- Accelerometer's function and collect data when submersed
- Data acquisition iteratively and successfully refined to measure data over or under-sampling
- Data collection process and data quality up to standard for simulated inspections
- Increased confidence in measurements going forward

The sound pressure level generated by the speaker build:

- Successful generation of sound through pushrod speaker when submerged
- Increased understanding of underwater SPL with different speaker configurations to test in the simulated test rig

While this work was able to demonstrate that the individual subsystems worked and would work as expected in pipe inspections, additional areas of refinement to the system were identified to improve the overall efficiency and quality of data collection. Recommendations for how this could be achieved are discussed below.

Sensor array design – During accelerometer testing, the halo configuration which held the potted sensors was shown to affect the sensors, effectively coupling the vibration of all the sensors together. This resulted in the removal of the potted sensors from the halo to "freely float" around the structure in the same configuration. Should this design be considered going forward, the design should be reviewed to minimise the impact of coupling of vibrations across all physical connections.

Speaker configuration – It was clear that the purpose-built underwater speaker produced the best SPL underwater, however, it is not clear how dependent the accelerometers are on the SPL for defect detection in situ. Further testing on sound generation devices should be undertaken to ensure the dependence of SPL on the sensitivity of detection. This will ultimately determine what designs/ speaker systems would be most effective from a cost/build/performance point of view.

Data acquisition rates and overcoming limitations – Currently the data is being collected by focusing on one sensor at a time, which allows us to reach the 1000 Hz data rate required but does not simultaneously update all sensors live. This then requires us to hold the crawler in one position for 30 seconds per scan, which, over time, will increase the test times unacceptably. A change in microprocessor, to one that can clock data in and out much faster, would alleviate the issues we see and would allow us to send the data via RS485 up to 10 times faster. This would then allow us to send more data, such as sensor measurement timestamps, temperature and pressure data, without loss of sensor fidelity.

Sensor orientation – The sensors are currently randomly oriented, making it more difficult to resolve the axes into a vector that will show whether there is an increase in amplitude or not, whilst under a defect. Changing the rubber mould and processes around moulding will allow us to orient the sensors accurately and having a method of “locking” those sensors in position, whilst keeping them somewhat free-floating, will ensure there is no loss of accuracy due to orientation shift.

Appendix 8. D8 - Closure Report

Project L09 - PipeBots in Rising Mains
Phase II Closure Report
Deliverable D8

Prepared for Project Partners

31/10/2023

PAS 99 Integrated Management Systems IMR535435
ISO 9001 Quality Management FM38723
ISO 14001 Environmental Management EMS535432
OHSAS 18001 Occupational Health and Safety Management OHS535433

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1. Version Control

Change record

Version	Status	Date	Author(s)	Summary of changes
0.1	Draft	07/08/2023	Pravin Smart	New Document
0.2	Draft	20/10/2023	Pravin Smart	Updated with figures and internal review comments
1.0	Released	30/10/2023	Pravin Smart	Final Issue

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Management Approval

Name	Position

Distribution

Name	Organisation	Format

Contents

2. Introduction

This is the closure report for Phase II of the PipeBots in Rising Mains Project. The document outlines the work undertaken by Synthotech in line with the PipeBots in Rising Mains (PBIRM) project proposals.

The Pipebots for Rising Mains project objective is to investigate, test and develop internal pipeline condition assessment technology. The aim of the work is to complete proof of concept trials to test the feasibility of using robotic platforms to house and transport fluid-borne triaxial accelerometers as novel inspection tools. Such a tool would enable operators to assess the condition of mains, identify defects and plan rehabilitation works. This capability would reduce the risk of failure leading to pollution, reduce the risk of flooding to customers and reduce the inconvenience and expense of emergency repair works. The challenge that needs to be addressed can be split into 3 areas:

A. Is the pipe deteriorating and where?
B. How severe is the identified deterioration?
C. How long until deterioration reaches a critical threshold?

This project phase (Phase II) focused on criteria A and B, which involved the design, build and test of a low TRL prototype (Proof of Concept – PoC) to demonstrate the proposed approach to defect detection in foul rising mains.

Synthotech worked closely with the University of Sheffield (UoS) to develop the proof-of-concept sensing system within this phase. The agreed-upon sensor system harnessed and measured the internal vibroacoustic pressure within a pipe fluid in order to identify the presence of defects within a pipe. This phase aimed to demonstrate the viability of using vibroacoustic for defect sensing in a simulated rising main environment, with a focus on identifying regular and defective pipe features in ductile iron pipework, as well as the limits of defect detection.

The scope of work within this project phase were as follows:

- Agree with UoS on a specification for sensors, access, and operational requirements
- Design & manufacture a functional prototype robotic sensor platform
- Design an end-to-end process that adheres to standard operational regulations
- Carry out system testing in laboratory/ simulated environments

The project summary section of this report outlines how we have achieved these objectives over the course of the project.

3. Phase II Summary – Technical Build, Development and Testing

3.1. Design & manufacture of system prototype

The early stages of Phase 2 focused on the design and build of the proof-of-concept system. Three areas of development were defined: PCB and electronics development for sensing and system control, the crawlers design and overall build, the transient generators design and build, and operational user interface.

PCBs and Sensing

Printed circuit boards (PCBs) for the sensor control board and accelerometer boards were manufactured in accordance with the schematics defined during Phase 1(Figure 1a). It was determined between Synthotech and the University of Sheffield that six accelerometers were necessary to effectively identify and locate defects on the pipe's clock face, providing operators with defect positioning information. The existing camera and crawler control boards, standard components in Synthotech's other crawler-based CCTV systems, were repurposed to allocate resources for sensor development.

Initial testing and firmware development for the sensors were carried out before encapsulating them in a two-part flexible polyurethane resin using a spherical configuration (Figure 1b). This method aimed to safeguard the accelerometers and PCBs from the water environment while allowing them to detect external vibrations within a fluid and be independent of the direction of sound. Once encapsulated, the accelerometers were arranged in a halo configuration, centred within a 300 mm diameter pipe (used for concept validation). Sensors were positioned at the 1, 3, 5, 7, 9, and 11 o'clock positions on the halo, facilitating appropriate spacing for the tether connection, located at the 6 o'clock position (Figure 1c). The initial plan involved placing the potted accelerometers within the halo structure, but initial tests revealed that this arrangement caused all accelerometer readings to be coupled together. Therefore, a mechanical retrofit was developed to allow the potted accelerometers to float independently outside the halo while maintaining the same configuration, ensuring individual sound-sensing capabilities.

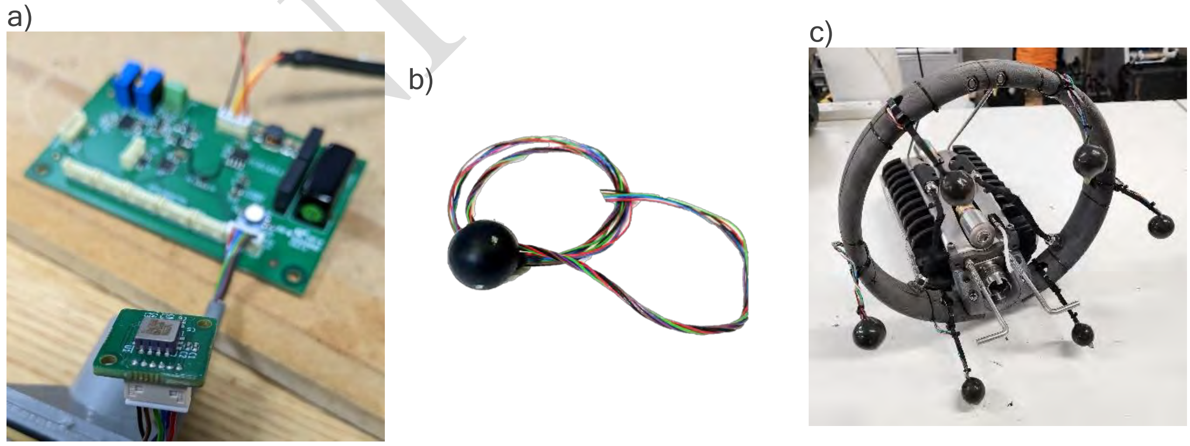

Figure 1 Sensor development

Crawler design and build

The proof-of-concept crawler design was adapted from a crawler-based CCTV system used within the gas industry for live asset inspection up to 2 barg conditions. This compact robotic vehicle would house the PCBs and electronics internally and provide a means to transport the sensor array along the length of a pipe. A final concept design was developed which included front and rear cameras, a streamlined crawler body, tracks for manoeuvrability and positioning, LEDs to assist in pipe visualisation, and a method to internally pressurise the system in order to prevent water ingress (Figure 2a). With the design confirmed for the purpose of proving the technology, materials were ordered for system assembly. Delays in the supply chain impacted crawler progression at this stage, however, once parts had arrived, the crawler was dry fitted and assembled, with tests performed on wiring connections, motors and tracks (Figure 2b & c).

a) b) c)

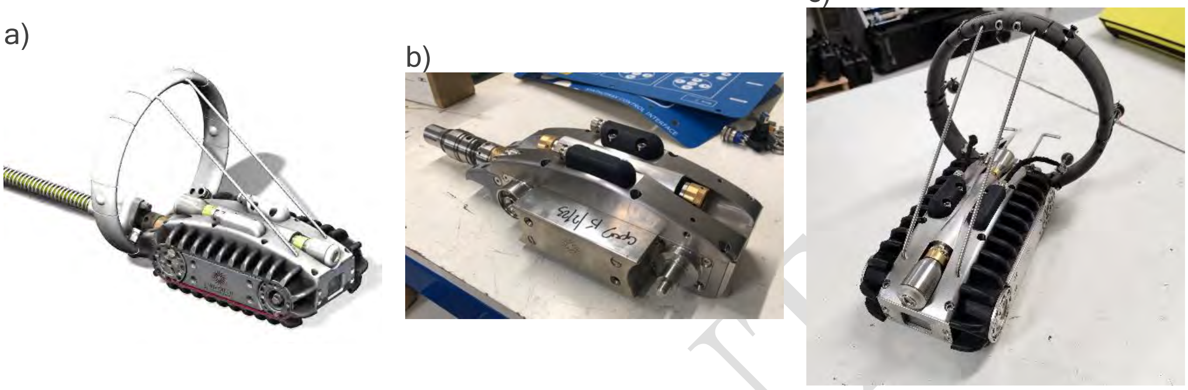

Figure 2 Sensor delivery development

Transient generator development

The design of the transient generator was initially based on the speaker specifications provided by the University of Sheffield from their experimental setup, which included a 15W Visaton cabinet speaker enclosed in a waterproof housing (Figure 3a). Synthotech made some modifications to this design by integrating the speaker with an existing fibreglass push-rod assembly, typically used for pushrod cameras in gas applications (Figure 3b). This adaptation allowed for the convenient placement of the transient generator within the test rig. During the testing processes, it was determined that an amplifier was necessary to enhance the sound output, and an alternative speaker with greater sound projection capability was also needed (Figure 3c). As a result of these adjustments, the final transient generator was capable of generating sound underwater.

a) b) c)

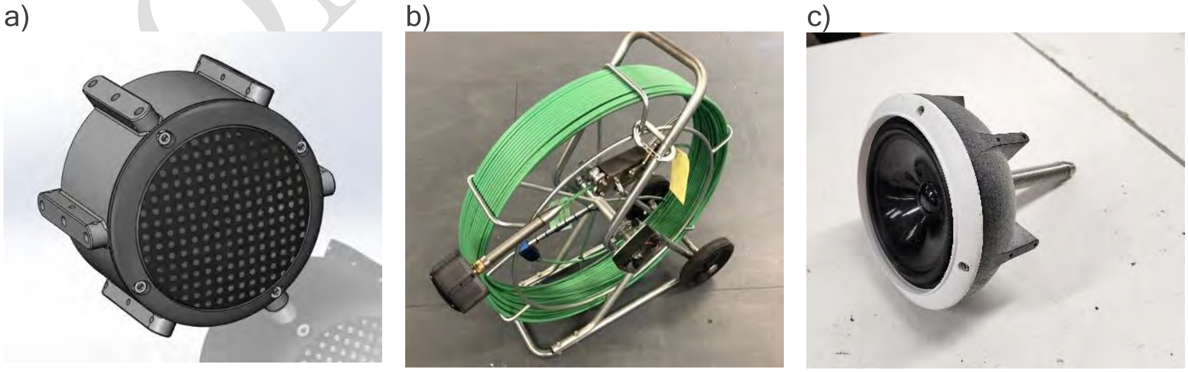

Figure 3 Transient generator development

Operational Graphical User Interface (GUI)

A prototype graphical user interface was created to enable communication with the robotic crawler, simplifying the transfer and retrieval of sensor data (Figure 4). This interface aims to provide operators with a visual means to verify sensor functionality, indirectly confirm transient generator performance through sensor data, and facilitate the capture of data for subsequent post-processing and analysis. Going forward, the aim would be to have this system automate the post-processing and analysis of incoming data to display the outputs and probabilities of areas of interest.

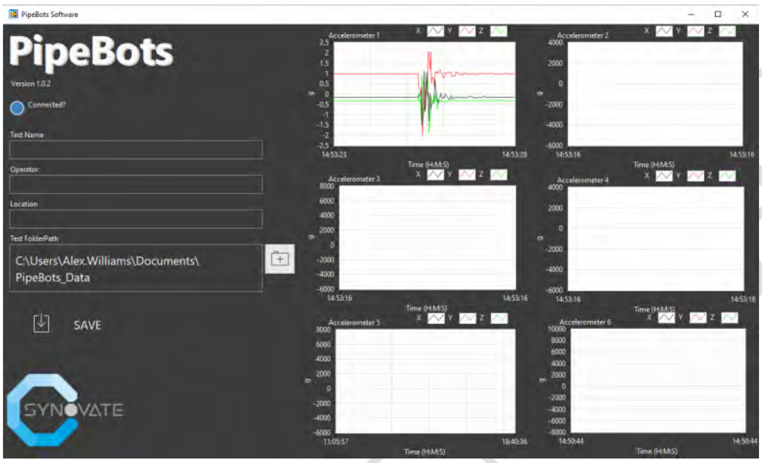

Figure 4 Example of PipeBots GUI for data capture and sensor functionality confirmation.

3.2. System Testing and Debugging

Following the assembly of each subsystem, individual testing was conducted to validate the construction quality, design, and functional performance within a controlled laboratory setting. Emphasis was placed on evaluating the fundamental capabilities of the crawler, assessing the sound pressure levels generated by the transient generator, and, most critically, ensuring the quality and precision of the data collected by the system. These tests were conducted at both Synthotech's laboratories and the ICAIR test rig, with support from the University of Sheffield.

System Testing at Synthotech`s Milner Court Campus, Harrogate

Testing at Synthotech initially occurred under dry benchtop conditions to verify the overall functionality of the system's construction and assembly. After this, the system was immersed in a water-filled plastic container. During testing, the crawler's performance was validated through the display of visible camera feeds on the monitoring units. Control operations for the robot were found to be effective, with the control unit responding instantly, both on the bench and when submerged. Additionally, the internal pressurization system demonstrated reliable performance by maintaining a pressure of approximately 500 mBarg throughout a 10-minute submersion. Testing of the transient generator validated the water-tight design and assembly of the speaker housing, ensuring its proper functionality underwater (Figure 5). It was observed that initial sound output levels were considerably low, necessitating modifications to the setup. Subsequently, the implementation of a higher-powered speaker and an amplifier significantly enhanced the sound output.

Figure 5 Crawler functionality and internal pressure testing when submerged in water.

The data gathered during the initial phases of testing proved insufficient in terms of the required data resolution for meaningful interpretation. A restricted data transfer rate hindered the acquisition process from the sensors, resulting in the loss of valuable data before reaching the Graphical User Interface (GUI) for visualisation and data capture. To address this challenge, a solution was devised involving the sequential and concurrent data capture from each accelerometer during a scan, as opposed to the simultaneous data capture from all accelerometers. While this approach increased the time needed to collect data, it ensured the capture of the essential data for subsequent processing (Figure 6). The recommendations for improvements are detailed in Deliverable 4, which highlights future enhancements, particularly concerning changes to the microcontroller.

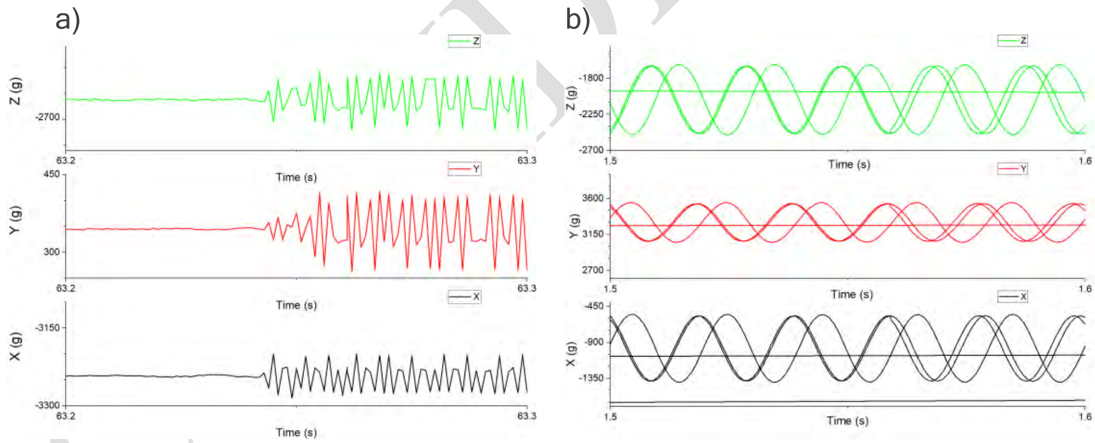

Figure 6 Refinement of data quality from a) improperly measured vibration data to b) clearer vibration data.

System Testing at ICAIR, Sheffield

The PoC system was transported to ICAIR for further laboratory-based testing on the University of Sheffield's test rig. This rig featured a submerged section of 300mm diameter rising main pipe with various defects. The purpose of this testing was twofold: to validate the quality of the accelerometer data from the crawler by comparing it with data from an independent accelerometer (York), and to assess the sound pressure levels generated by different speaker configurations. An independent hydrophone was employed to measure the sound pressure levels. Additional tests were conducted in both clear pipe sections and sections with defects to gain initial insights into the accelerometer responses in the presence of defects (Figure 7).

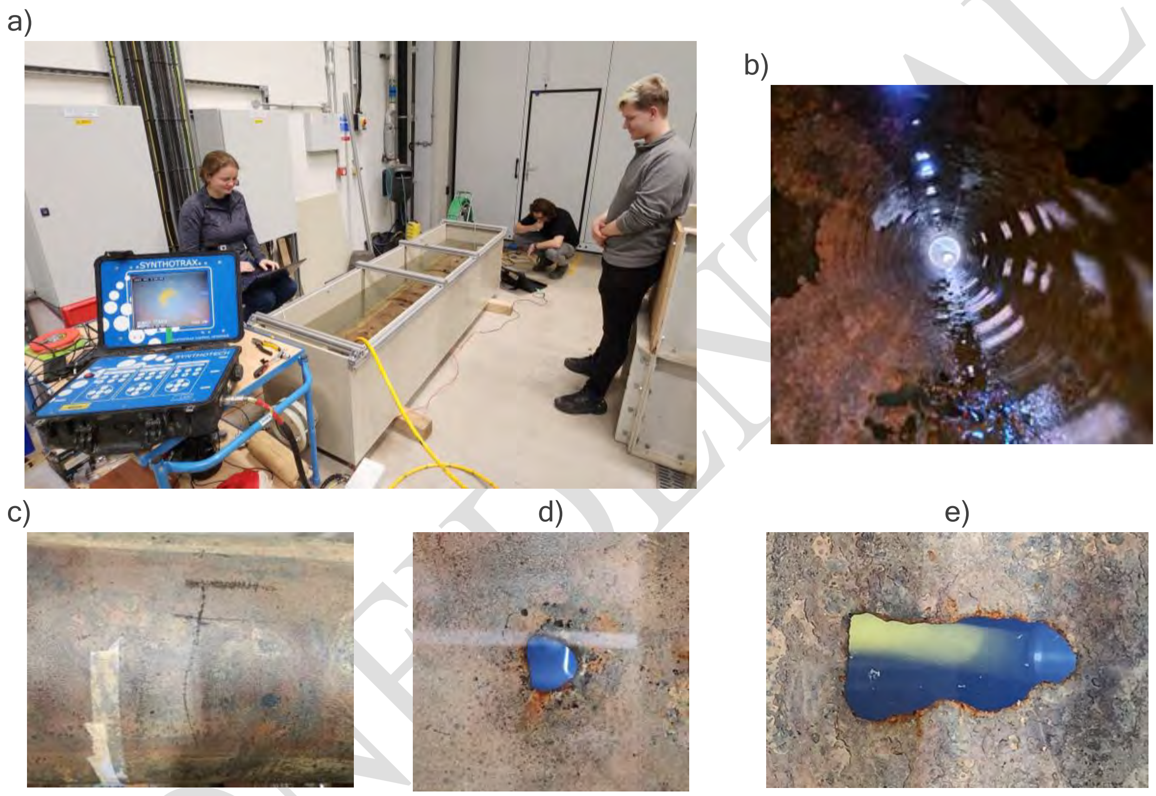

Figure 7 a) Lab Testing of the PipeBots system at iCAIR, Sheffield on (b) defective ex-situ rising main pipe. Tests performed on c) control section, d) approx. 1" Ø defect (defect 1 in Figure 8), and e) a larger extended defect (defect 3 in Figure 8). The defects were Top Dead Centre (TDC), between sensors 3 and 4 on the PipeBots halo.

The response of the PipeBots accelerometers closely matched that of the York sensor, affirming the data quality of the developed sensor system. During testing in both clear pipe sections and locations with defects, noticeable changes in the signal were absent at first. However, upon closer examination of the data in post processing, an increase in signal amplitude and a change in shape of the response was observed (Figure 8). Hydrophone experiments validated the adapted Visaton cabinet speaker's ability to produce an adequate sound pressure level in water. Nevertheless, there remained uncertainty regarding the correlation between the sound pressure level magnitude and the system's detection sensitivity for defects. Additional tests within the simulated rig would be required to confirm this relationship.

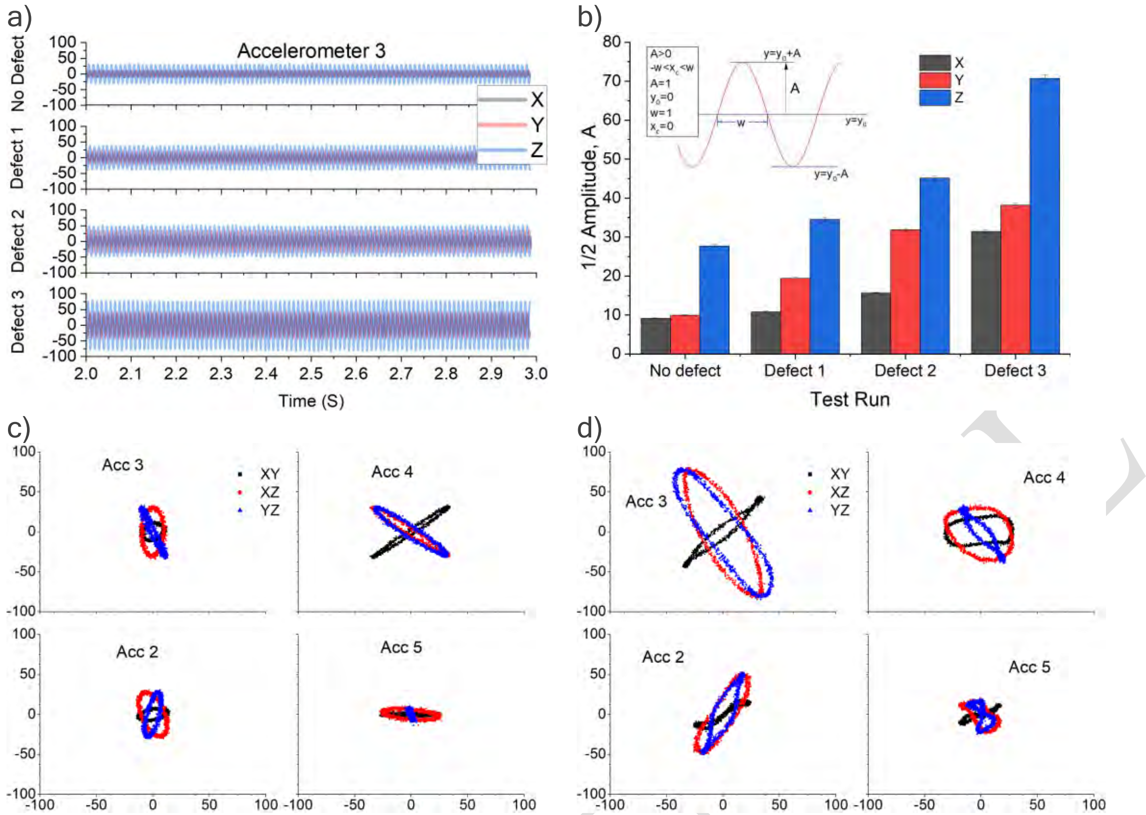

Figure 8 Outcomes of defect tests at ICAIR showing a) changes to accelerometer 3 vibrations over "no defect" and defect locations, with b) showing a comparative bar chart of this amplitude. c)shows the response of all functional accelerometers at the "no defect" location, while d) shows the same at the larger defect 3.

3.3. Simulated testing in buried pipe

Test rig development

To facilitate the simulated testing process, the creation of a suitable test rig became essential at the Synthotech Test and Research site (STaRs) in Ripon. This test rig was constructed using DN300 Ductile Iron pipe featuring PN16 flange connections. It comprised two potable water (blue) equal tees and four 2-meter segments of non-potable (red/cement-lined) pipe (Figure 9). These components were assembled in an existing trench and bolted together according to the manufacturer's prescribed torque settings before burial in sand and gravel. This setup effectively emulated the conditions of a buried pipe environment, serving as the principal testing platform for the system. It allowed for the simulation of access and egress into a pipe, the acquisition of baseline and defect measurements on-site, and the demonstration of the end-to-end data collection process. Before the start of testing, the rig underwent a pressure test, reaching up to 1 Barg and holding this pressure.

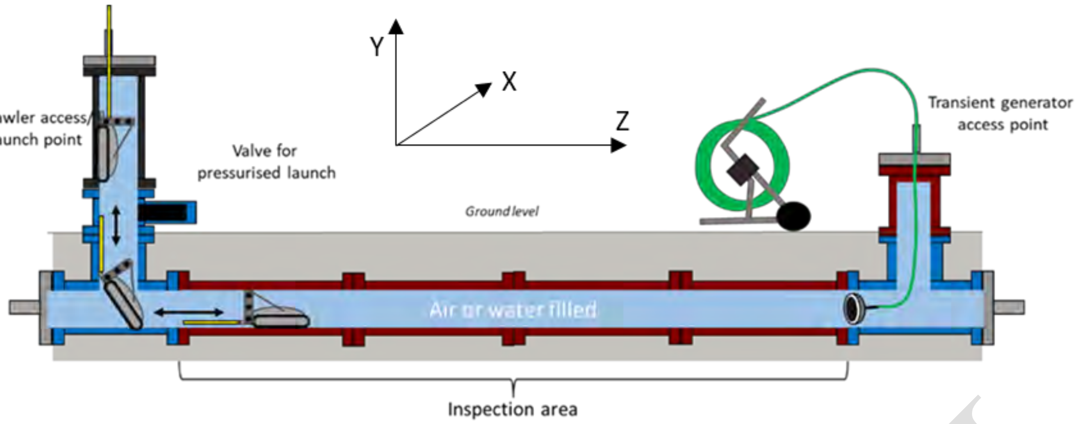

Figure 9 Schematic of the test rig, test configurations and sensor orientation.

Simulated Testing at STaRs, Ripon

The objective of the simulated testing was to validate the suitability of the crawler and halo's design for vertical insertion into the test pipe. This assessment included a dry run to evaluate the insertion process from a vertical, open rising main, followed by a wet deployment into the test rig using the same approach (Figure 10). On each occasion, the deployment and retrieval of the robot were executed successfully, and the overall functionality remained intact throughout the entire process.

a) b)

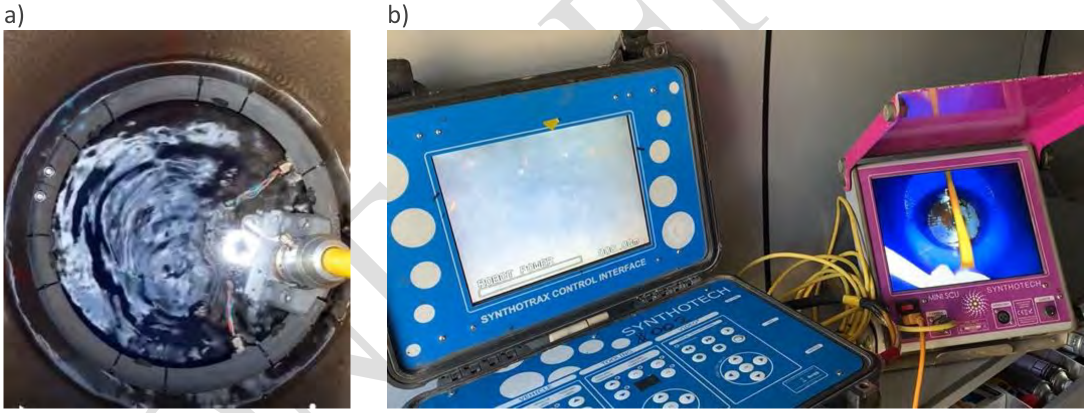

Figure 10 Wet deployment of crawler into test rig – a) crawler in wet rising main, b) control and display unit showing crawler visuals from within pipe.

Scans were captured within the test rig under static conditions, with the robot at rest, to evaluate both data quality and the consistency of repeated measurements. The variance among these repeated measurements was minimal, signifying that a single scan would be adequate for data collection during subsequent testing and operational procedures (Figure 11). Consequently, a complete circumferential scan would take approximately 36 seconds using the current data acquisition method within the PoC. It's worth noting that this duration could be reduced to 6-10 seconds if data were simultaneously collected from all accelerometers which can be completed within the next stage.

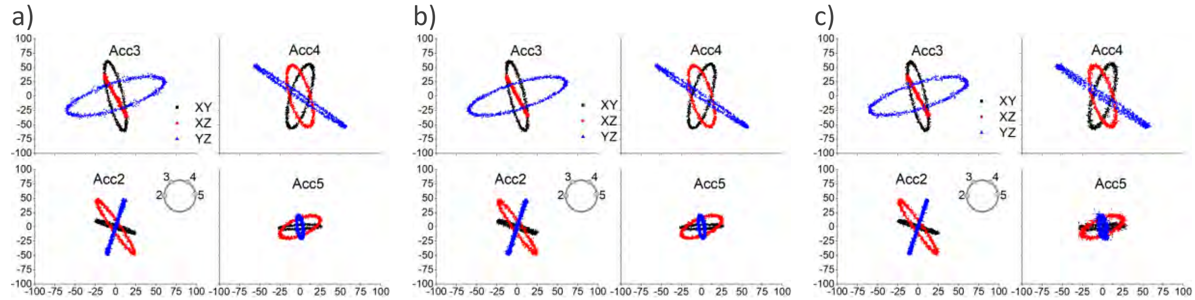

Figure 11 Example of repeat scans within test rig.

Testing showed that the orientation of accelerometers significantly influenced vibration output. Some sensors split vibration magnitude across multiple axes when misaligned, while well-aligned sensors represented it on a single axis. Future development should focus on accelerometer positioning, housing, and their integration into the field-ready design. Additionally, efforts should be directed toward improving data capture and post-processing. Joints were scanned to understand changes in the amplitude and position data compared to that of the pipe barrel. The crawler was aligned before a joint and moved forward, taking scans at different positions to track accelerometer data changes across the joint. These results are shown in Figure 12.

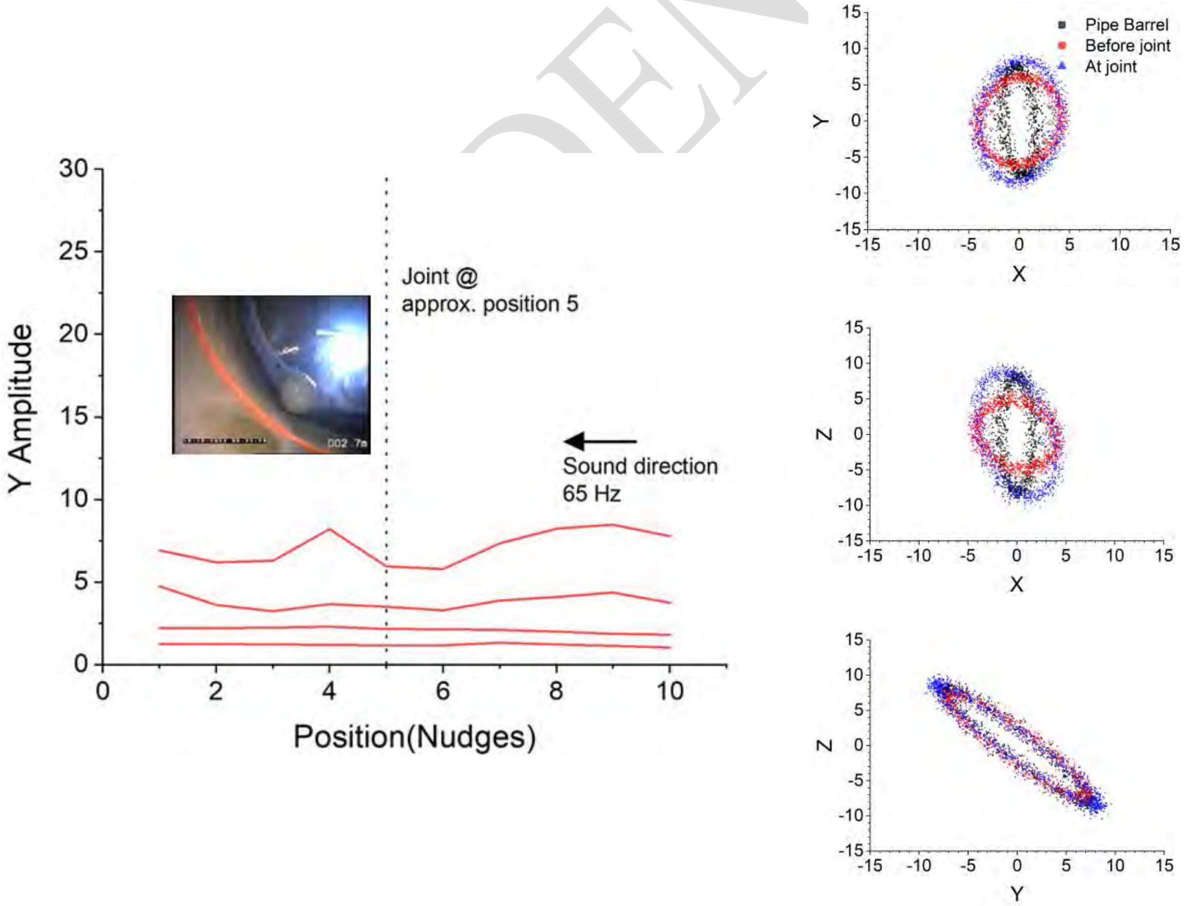

Figure 12 Joint detection with accelerometer 4 data, showing amplitude changes over position and comparing XYZ position data of the pipe barrel (black), pipe section before the joint (red), and the joint itself (blue).

To test the system's ability to detect significant pipe structure changes, defects were created in the test rig. A 1-inch hole was machined, threaded, and partially sealed to simulate internal material loss. The data was captured in the same way as a joint. Figure 13 demonstrates that this approach is capable of sensing the defect, as shown by the increased amplitude in Y around the defect, and also the angle change in the position data when compared to the pipe barrel. Further work to pinpoint the future orientation of sensors will ensure these changes in the position data are more obvious.

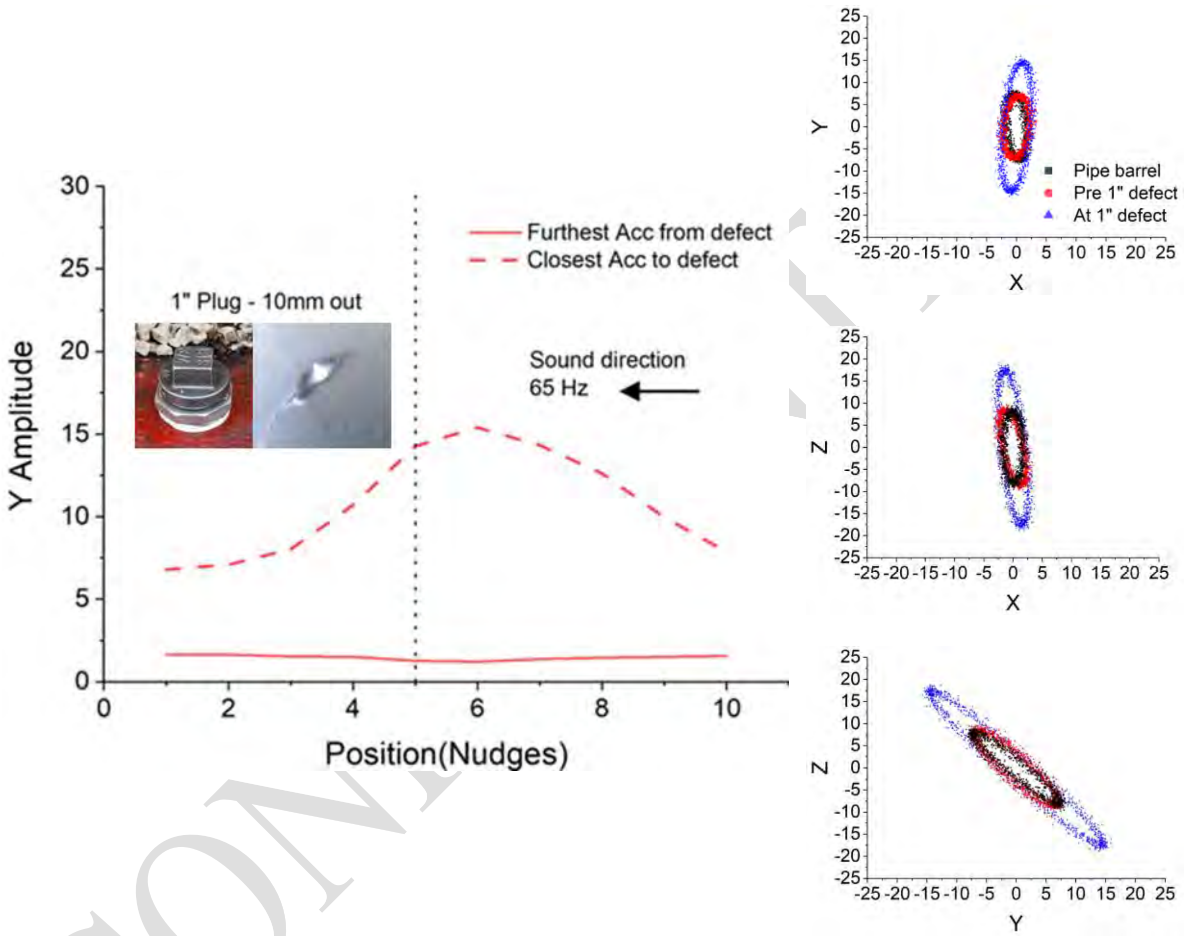

Figure 13 Defect detection with accelerometer 4 data, showing amplitude changes over position and comparing XYZ position data of the pipe barrel (black), pipe section before the defect (red), and the defect itself (blue).

The comparison between a joint sweep and a defect sweep has revealed significant distinctions in feature characteristics, particularly in the XY and XZ dimensions. Notably, joints exhibit a tendency to become more circular with minor amplitude changes, whereas the 1" defect displays subtle angle adjustments and increased Y-axis amplitude. While further testing and in-depth data analysis are required to validate these observations across a broader range of internal pipe features, this provides a foundation to develop a portfolio of feature characteristics that can be used by operators on site.

End-to-end Process Demonstration at STaRs, Ripon

Figure 14 Insertion trialling at STaRs.

To facilitate the deployment of the system into a live rising main, an end-to-end process was devised on how the current system could be deployed on a network rising main. Based on existing live access deployment of CCTV robotic inspection systems, the process involves isolating the crawler within a launch vessel that directly connects to a valve.

The operator would control the crawler from a position near the access point, whilst managing the crawler's tether which would pass through a glanding system - a methodology that allows a tether to pass in and out of a pressurised pipe without out leakage of the fluid from within the pipe. The tether is directly connected to the crawler, situated in the launch vessel. To purge the launch vessel before launch, chlorinated water is pumped in to remove the air. Any submerged system checks can then take place, in addition to leak tests of the vessel and connections prior to opening the gate valve for access to the live rising main.

To open the valve, the launch vessel must reach operational pressures. Higher pressures might require a bypass or bleed valve. Once the valve is open, the system enters the pipe and begins taking measurements. In the proof-of-concept phase, the development of the data acquisition has been the focus rather than the speed of inspection, with measurements taken incrementally. In the future with improved data capture and post-processing, data will be collected faster while the robot continually drives forward.

To retrieve the robot from the pipe, the robot is driven back to the launch point and pulled up into the launch vessel. Upon re-entry into the launch vessel, the valve is closed to isolate the rising main. Pressure in the launch vessel is relieved, and foul water is purged with chlorinated water. The system is left to sit for disinfection, and then air is pumped in to remove the water. Any launch tube pressure is again released. The launch tube can then be unbolted from the valve, equipment removed from the network and broken down for further cleaning and disinfection on-site. To manage foul water, it's advisable to employ a hazardous waste tank for collecting wastewater from purging and cleaning. A suitable portable bowser would enhance site manoeuvrability. Disposal should align with water company practices and regulations, possibly reintroducing the wastewater into the rising main system through disposal in a wet well or other accessible foul water drains.

Conclusion

From the detail above, the project has delivered a Proof-of-Concept robotic system that can be used on dead, live and pressurised pipe systems detecting variations in vibroacoustic signatures from pipe features remotely underground on a simulated test rig.

This is a significant step from desktop/laboratory concept testing to simulated remote underground testing delivering in-pipe mapping for environments where CCTV vision is not feasible or reliable. This proof of concept has proven the baseline technology works and this provided significant foundations for future rising main inspections where water companies have previously had limited options available.

There is still significant work to be undertaken to ensure that the system is capable of working on a wide range of materials and defects, but this Proof-of-Concept has provided confidence that this is a time development issue rather than a technology capability issue.

4. Project deliverables

The project was broken down into 9 different work packages and a summary of the status of those work packages is shown in **Error! Reference source not found.**. The project deliverables are made up of items from the project proposal, shown in Table 2. A detailed breakdown of the work packages is available within the annex (Table 4).

Table 1 Project work package breakdown summary

Work Package	Description	Status
1A	Field Work	Complete
1B	Lab Work	Complete
1C	Desktop Study	Complete
2A	Sensor Insertion	Complete
2B	Robot Platform	Complete
2C	Sensor Package	Complete
2D	Field Tests	Complete
2E	Additional - Transient generator	Complete
3	Reporting	Complete

Table 2 Project deliverables summary

ID	Deliverable	Status
D1	Site finding report	Complete
D2	Sensing requirements data capture	Complete
D3	PoC sensor and sensor delivery system specification	Complete
D4	Benchtop and lab testing report	Complete
D5	Simulated testing report	Complete
D6	PoC FMEA	Complete
D7	End-to-end process document	Complete
D8	Phase II closure report	Complete

4.1. Stage 1 – University of Sheffield

The first stage of the project was led by the University of Sheffield to investigate the sensing and NDT requirements, with a focus on vibration measurements. This involved a desktop study, lab work and site visits to capture field data.

COMSOL defect modelling

COMSOL models were used to simulate common defects, such as internal and external pitting, and to understand which variables were key to testing. The results indicated that measurement of the radial fluid velocity was the best approach to locating defects, either directly or using accelerometers with the appropriate conversion.

Site data capture - acoustics

Field data was acquired at Bretton Village and Christchurch to assess the frequency domain properties of rising main assets which would inform the design of the sensor array within the

Proof of Concept (PoC). Field capture was performed on 300 mm and 400 mm cast iron and ductile iron pipe respectively. Background noise was observed to be similar at both sites, there were no site-specific sources of noise and vibration. Pump operations on one site were also observed to cause dynamic deformation events between 1-2 mm that lasted up to 500ms, peaking below 100 Hz. Pipe walls were also observed to vibrate uniformly.

4.2. Stage 1 – Synthotech Feasibility

Synthotech carried out their own site visits to understand operational constraints for sensor deployment and conducted a technology review of alternative NDT technologies and their suitability with respect to common pipe failure modes and materials.

D1 - Site finding report

Site visits identified potential access points, leveraging existing flow meter chambers or submersible pumping stations due to similarities to gas operations and Synthotech's expertise. It was noted that an end-to-end operational procedure must be developed given the absence of live operational procedures for under-pressure rising mains. Further remarks were made about sensor delivery design and operational prerequisites, highlighting challenges associated with navigating 90° bends using current crawler technologies, along with the need for training & health monitoring for workers handling materials found inside rising mains, some of which could be deep excavations.

D2 - Sensing requirements data capture

Background research on sensing requirements and pipe population identified that the majority of failures were the result of material degradation. Failure mechanisms were identified for specific pipe materials which provided insight into the modes of failure and the locations where defects were likely to occur as well as conditions which would speed up asset degradation. A review of current NDT technologies was also examined with respect to pipe material, defect type detection, and their limitations. No single solution can be used across all pipe materials, and also be used for all defect types. Many limitations exist, whereby some degree of surface preparation and coupling is required for certain approaches which are not practical within a rising main environment. It was recommended that a wide portfolio of NDTs would be required to assess all types of defects within all asset materials, with only key degradation metrics carried forward into maintenance and future monitoring practices.

4.3. Stage 2 - Synthotech PoC Development and Demonstration

The insights gained from the initial phase were applied to Stage 2, which focused on designing and building a conceptual platform for evaluating the viability of robotic inspections. Stage 2 was led by Synthotech, with support from UoS. During this phase, the consortium determined the key elements to be tested as a Proof of Concept (PoC) to establish its feasibility for future development. In summary, Stage 2 aimed to lay the groundwork for a successful PoC, addressing system specifications, functional testing, system design risk management, and the future integration of robotic inspections into both trial and regular operational procedures.

D3 - PoC sensor and sensor delivery system specification

The PoC Specification for sensing and sensor delivery outlined two sets of criteria to measure the success of the system during PoC testing, and what needed to be demonstrated in a potential commercialised product. 14 objectives were identified within the specification that the

PoC would need to meet, which included: sensor delivery design, robotic operation within water pipes, sensor positioning for defect inspections, the sensor's level of accuracy for defect and feature sensing, survey methodologies and inspection times. Exclusions within PoC testing included live field testing, gas pocket simulation, ragging simulation, and continuous measurements. If the PoC were to be further developed into a higher TRL system, the developed system would need to demonstrate capabilities within realistic rising mains environments. Testing would need to include flow conditions, operational efficiency in inspections, ragging/gas pocket simulations, emergency procedures, and success in live field trials.

D4 - Benchtop and lab testing report

Laboratory testing was performed on the robotic platform, sensor packages, and transient generator to verify the proper functioning of each individual subsystem, a crucial step before advancing to simulated testing. The failure of any of these systems would result in incomplete data, rendering testing and inspection operations unable to provide insights into the condition of the pipe. Robot functionality was demonstrated under wet and dry conditions and was able to be internally pressurised to prevent water ingress, protecting the internal electronics. A substantial part of this effort was dedicated to enhancing the data collected from the accelerometer and optimising the data collection process. It became evident that future design modifications would be necessary, involving a shift to a faster microprocessor to expedite data transfer by up to tenfold. This enhancement would enable simultaneous data acquisition from all accelerometers. Currently, the system collects data from sensors individually and concurrently to gather the necessary data for analysis during simulated testing. The transient generator underwent testing in both wet and dry conditions, involving system adjustments to achieve a higher sound pressure level during testing. Additionally, alternative speaker options were assessed, ultimately identifying two types as suitable for achieving the desired sound pressure level in real-world conditions. This deliverable provides a summary of these findings and offers recommendations for future improvements.

D5 - Simulated testing report

The system underwent simulated testing in a 10-meter-long DN300 ductile iron test rig, replicating conditions found in buried water assets. The objective of this testing was to evaluate the system's capabilities, with a focus on understanding the practical aspects of sensor deployment within the pipe. This included assessing the design of the crawler and sensor array during the system's insertion through a vertical launch while considering dry, wet, and pressurised conditions. Additionally, access and robot functionality were demonstrated under static head conditions in both wet and dry environments. Data quality was examined by transmitting a 100 Hz signal through the transient generator. The accelerometers demonstrated a clear response, confirming the reception of the 100 Hz signal by the sensors. To assess sensor repeatability, multiple scans were conducted, revealing minimal measurement variations. This finding indicates that a single scan provides sufficient data, reducing scan time in operational processes. In pipe features such as joints were shown to be slightly different from pipe barrel measurements, but different to defects. Large 1" defects could be clearly marked out in the pipe with accelerometer data.

D6 - PoC FMEA
A Critical Failure Mode and Effect Analysis of the PoC system uncovered various failure points and their impact on different subsystems within the operational system. These failures were assessed based on their likelihood, severity, and detectability, resulting in a Risk Prioritisation Number (RPN). The most significant failures centred around water ingress and the potential for electric shocks to operators. Thorough pre-operation inspection and testing mitigate the likelihood of these risks of failure. Operational and safety procedures are detailed in D7 to guide the appropriate approach. This is essentially a living document that will be periodically updated to accommodate newly identified failure modes or design changes during the next development phase. The work within the FMEA appropriately outlines areas which could become a risk in later operations and where these could be minimised through design and process modifications. The next stage for risk management will be to develop a field trial/site risk assessment for a prototype field trial system, along with a technical and operational reference manual.

D7 - End-to-end process document
An overview of the potential end-to-end process for utilising this system was created by adapting an existing Technical Operation and Reference Manual (TORM) designed for the Synthotrax robot crawler. This adaptation was tailored to facilitate access and inspection of rising mains. The content encompasses a comprehensive list of necessary components and parts for operational purposes, along with pre-launch steps, such as system setup and preparation. Subsequently, it delves into a proposed launch procedure unique to this Proof of Concept (PoC), followed by the surveying process and system removal from the asset. It's important to emphasise that this approach represents just one possible avenue for access, which may evolve based on the size, type of asset, and future inspection system designs. For the time being, provided that a suitable access point is identified, this section outlines the essential procedures for ensuring secure entry and exit from a rising main, with a focus on minimising spillage during operations. The manual concludes with instructions for cleaning, disinfection, and maintenance procedures, accompanied by practical outcomes and recommendations.

D8 - Phase II closure report (This document)
Project delivery review, accomplishments, difficulties, and summary acquired knowledge.

4.4. Stage 3 – Project Management and Reporting

[Project Spend, Outcomes, Value for money etc]
To be delivered on Monday the 23rd October

5. Project documentation

The project documentation is available as a separate Appendix. The project appendix contains the top-level documented outputs of the project and is available upon request. Table 3 highlights the documentation within the project appendix and the status of the documentation as of 20/10/2023.

Table 3 Project documents summary

Supporting document	Reference	Status
D1 Site Findings Report	D1 Site Findings Report v1.0.docx	Complete
D2 Sensing Requirement Report	D2 Sensing Requirements Capture.docx	Complete
D3 Specification	D3 PoC Specification v1.4.docx	Complete
D4 Lab Test Report	D4 - Robotic Crawler and PushRod Speaker Simulated Testing.docx	Complete
D5 Simulated Test Report	D5 - Robotic Crawler and PushRod Speaker Simulated Testing.docx	Complete
D6 FMEA	D6 FMEA (Updated).xlsx	Complete
D7 End-to-end Process	D7 - End-to-end Process and Operational Method Statement V1.1.docx	Complete
D8 Closure Report	D8 - Closure Report_v1.0.docx	Complete

6. Conclusion

Synthotech and the University of Sheffield have collaborated with Thames Water, Wessex Water Welsh Water to develop a Proof-of-Concept system that could demonstrate the feasibility of vibroacoustic sensor technology for the detection of defects within sewer rising mains.

A working Proof-of-Concept robotic system, sensor array and data acquisition system were designed, built and tested within this project phase. These were manufactured, assembled, tested, and debugged under laboratory conditions to provide confidence within simulated testing. Simulated testing was able to clearly highlight the different characteristics of in-pipe features, identifying pipe barrel, joint and 1” defect features.

The technology provides the grounding for the inspection of live rising mains, where existing approaches, such as CCTV, are limited. Further development of the system will enable water companies to detect problems within their rising mains assets with minimal excavation, and greater insights through defect identification for cost-effective asset management.

Overall, this project phase has been successful in creating a working prototype system and proving the technology for defect detection within a simulated rising main environment. The scope for future project work would be able to take this development to a higher technology readiness milestone, such that the technology is enhanced and adapted enough for live field trial operations.

7. Appendix A - Detailed Deliverables

Table 4 Review of Deliverables

WP	Aim	Clarifications requested	Deliverables/ Outputs	Due date	Status
1A	**Field Work**	Top-level overview of site reports to be used in final report	**D1 Site Findings Report**	16/09/2022	Complete
			Site Measurements Report	19/12/2022	
1B	**Lab Work**		Exhumed Pipe Testing Report		Complete
1C	**Desktop Study**	Top-level overview requested for end of phase reporting, better explanation to a non-technical audience	COMSOL Simulation Report	19/12/2022	Complete
			D2 Sensing Requirements Capture	16/11/2023	
2A	**Sensor Insertion**	What are the exact methods of insertion to be tested, and what aspects will be in the feasibility study only	**D3 Specification**	03/03/2023	Complete
			D7 End-to-End Process	30/09/2023	Complete
2B	**Robot Platform**	Robot platform to be adapted from existing Synthotech crawler	**D3 Specification**	03/03/2023	Complete
			Robot platform	30/06/2023	Complete
2C	**Sensor Package**	Accelerometers: Programming and attachment to robot crawler 'halo' ring	**D3 Specification**	03/03/2023	Complete
			Sensor package for PoC testing	30/06/2023	Complete
2D	**Field Tests**	Test rig location and layout	**D4 Lab Test Report**	30/09/2023	Complete
			D5 Test Rig Trial Report	30/09/2023	Complete
			D6 FMEA	30/09/2023	Complete
2E	**Additional**	Transient generator	Manufacturing & Assembly	31/07/2023	Complete
			Reported within D4	30/09/2023	Complete
3	**Reporting**	Project reporting & documentation requirements, close out report due date	End of Phase 1 Report	15/11/2022	Complete
			D8 Project Close-Out Report	31/10/2023	Complete

8. Appendix B - Prevailing Concerns, Unknowns and Suggestions

Table 5 Prevailing Concerns, Unknowns and Suggestions

Category	Concerns/Unknowns	Suggestions
Mechanical	How do we deal with launch equipment which are filled with wastewater?	Pump out into isolated containers for specialised waste disposal.
	What is the best way to isolate sensors from the delivery body without impacting the data? Could this be calibrated out?	
	How do we clean/maintain the robot properly post-egress and during service inspections?	Chlorination of all wastewater-contaminated equipment post-egress, followed by contained jet wash and spray down with chlorine on-site.
	How do we launch the robot into 10 Bar and is current equipment up to spec?	Pressure-balanced launch vessel. Umbilical tubing/ cable glanding is currently all ok for 10 bar.
	How do we ensure the sensor ring does not snag in situ?	Potentially use an "inflatable" ring to overcome snags.
	Is the current design suitable outside of 300mm NB pipe?	Long term design to have very different profile/ shape - to also minimise impact on data capture.
Data capture	How do we increase the data rate of the RS485?	
	How do we increase the data rate of the SPI?	
	How do we multitask the read from SPI and write from RS485?	
	Do we need cameras for the final phase? Knowing there will be reduced visibility.	
	Do we switch to full duplex RS485 for better data rate and synchronous comms	
	Can we get away with the analogue version of the sensors	
	Can we overclock PICs by 300%? Or should we find a more suitable PIC that can handle a higher clock and multitasking?	
Electronic	Do we design a separate coiler for this robot? Can it run off of our existing coiler?	
	Do we design a separate controller box for this robot?	

	What do we need in terms of power requirements?	
	Can we change the cabling to better help the twisted pair comms and video?	
Firmware (Controller / Robot)	How do we timestamp the data coming from the sensors? Is it in firmware?	
	Do we need the checks and balances on the sensors, knowing that they slow down transmission? For data validity.	
	What's the fastest and most integral method of transmission?	
	How do we stamp the start of the data so it can be properly ordered by the software	
Software (User Interface)	How do we timestamp the data coming from the sensors? Is it in software?	
	How do we handle the incoming data properly?	
	How do we handle saving that data, so that it doesn't affect incoming data?	
	How do we handle the addressing of data incoming from the firmware?	
	How do we present the data to the user in order to identify if at a defect area or not?	
Regulatory	What wastewater management requirements do we need to know going into field operations?	
	What are the Health & Safety/ health monitoring requirements for wastewater operatives? Frequent respiratory health assessments, BA required?	
	Will safety certification be needed/ impact system design/materials?	
	Do technical operatives and project personnel need to get vaccinated going into the next stage? Vaccine party for Tetanus, Polio, Hepatitis B, Hepatitis A	
	Is there any specific training required for technical operatives and project personnel for the handling of wastewater tooling and equipment? EUSR/ SHEA Water?	
BaU	How do we statistically prove out the technology in the field to support the	

	business case for business-as-usual approval?	
Emergency planning and controls	What is the current approach for emergency equipment recovery in water/ wastewater? How could this be adapted for PipeBots?	
	What is the probability of ragging preventing system recovery - either by building up on system OR around access valve seal thus preventing valve closure? Are there existing methods for valve access into foul rising mains?	
	How might transients impact live operations?	

Appendix 9. D5 - Test Rig Trial Report

Document Name:	L09 PipeBots in Rising Mains				
Document Number:	L09-T-003			Revision:	1
Drawn By:	PS	Checked By:			

L09 – PipeBots in Rising Mains

Test Report Number
L09-T-003
Deliverable – D5

Test Number	L09-T-003
Location	STaRS - Synthotech
Test Description	Robotic Crawler and PushRod Speaker Simulated Testing
Present	PS, CJW, SiL, AKW
Date	August-October 2023
Report completed by	Pravin Smart

Document Name:	L09 PipeBots in Rising Mains				
Document Number:	L09-T-003			Revision:	1
Drawn By:	PS	Checked By:			

Contents

Figures

1 Introduction

Up to this point, a submersible crawler, sensor array and sound generator had been designed, built, tested, and refined for simulated testing of the proof-of-concept rising main inspection system. With a high degree of assurance in the system's performance, the next phase of testing concentrated on critical factors that would define the system's viability for inspecting water-based pipework. Operational testing of the system's deployment, functionality, and its ability to gather insightful data will be critical for the future development of this system for low impact, detailed inspections of rising mains. This report covers the testing processes and their outcomes.

1.1 Aims

The purpose of this deliverable is to document the system testing of the whole system within a simulated rising main environment. This aims to demonstrate the feasibility of the current configuration for asset inspection in situ, and to optimise what the end-to-end approach might look like using this system for field inspections.

1.2 Objectives

The objectives of the simulated tests were to demonstrate that the system could be deployed within a simulated rising main, move throughout the length of pipe to collect data, identify where areas of interest were. Based on the objectives defined in Deliverable 3, the main objectives have been focused around key areas of investigation:

The delivery of sensors to locations within a pipe:

- Crawler functionality under 100 – 200 mbarg static head and pressurised conditions
- Movement of crawler over test rig distance (> 8 m)
- Assessment of meterage accuracy
- Feasibility of sensor mounting and locations for in-pipe sensing

The measurement accuracy of the sensor system within the rising main pipe:

- Assessment of the sensors for measurements on:
    - New ductile iron pipe (control section)
    - Ductile iron pipes with machine defects
    - Corroded ductile iron pipes with real defects (partly covered in ICAIR tests – see D4)
- Assessment of measurement system repeatability over multiple measurements
- Assessment of sensor to detect common in-pipe features
- Assessment of sensors to detect changes in the rising main system

The operational approach to deployment, inspection, and retrieval of the whole system:

- Access, deployment, and retrieval of crawler into and from rising mains
- Process inspection times – measurements per metre X time per measurement

Simulated Testing at STaRs

Test site

Synthotech's Test and Research site (STaRs) is located in Ripon, North Yorkshire, just off junction 50 on the A1(M). This location has been used for several gas and water inspection products and projects, as well as providing a suitable training location for operatives to get to grips with new products and inspection processes.

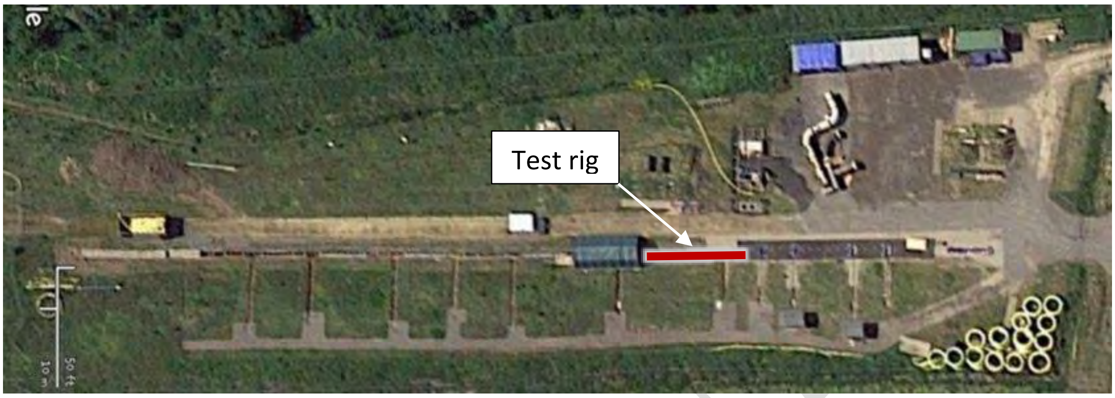

Figure 1 Google Maps image of STaRS test site with reference to the location of PipeBots test rig.

Test rig

The test rig was composed of DN300 Ductile Iron pipe with PN16 flange connections. A diagram of the test rig is presented in Figure 2. Two potable water (blue) equal tees and four 2m sections of non-potable (red/cement lined) pipe were lowered into an existing trench, bolted together according to the manufacturer's torque settings, and covered in sand and gravel to simulate a buried pipe environment. Two additional 750 mm non-potable sections were bolted to the vertical sections of the equal tees to provide access points for test equipment. Mild steel endplates with 2" BSP fittings enclosed on either side of the test rig. The 2" fittings were connected to external pipework which was connected to nearby IBCs and acted as a water reservoir for the test rig, as shown in Figure 3. These IBCs were stacked to facilitate greater static pressures within the test rig itself without the need for a large pump unit to provide additional pressure.

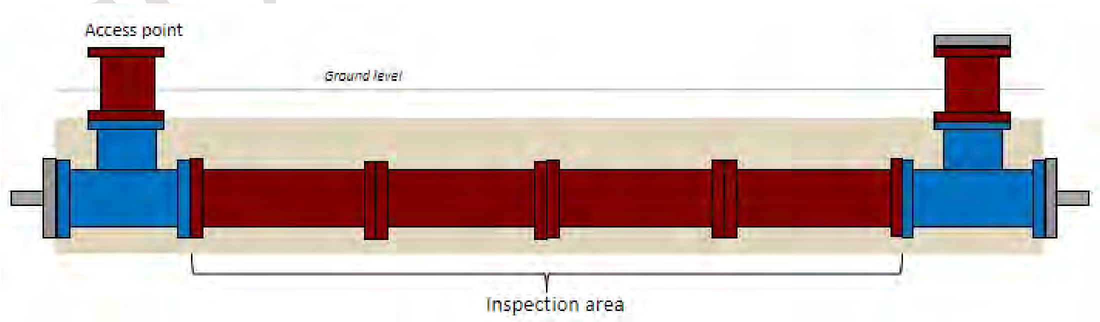

Figure 2 Diagram of PipeBots Test Rig.

Figure 3 Test rig connected to stacked water IBCs via 2" pipework

End plates were also machined to enable pressurisation of the test rig through push fit connections – see L09-T-001 in Appendix 1 to see how the system was pressure tested to 1 Barg prior to crawler and access testing. These fitting also made it possible to trial live access of the system into a pressurised environment. For this, two addition components to rig were required for testing: an access valve and live access launch vessel, shown in Figure 4.

a) b)

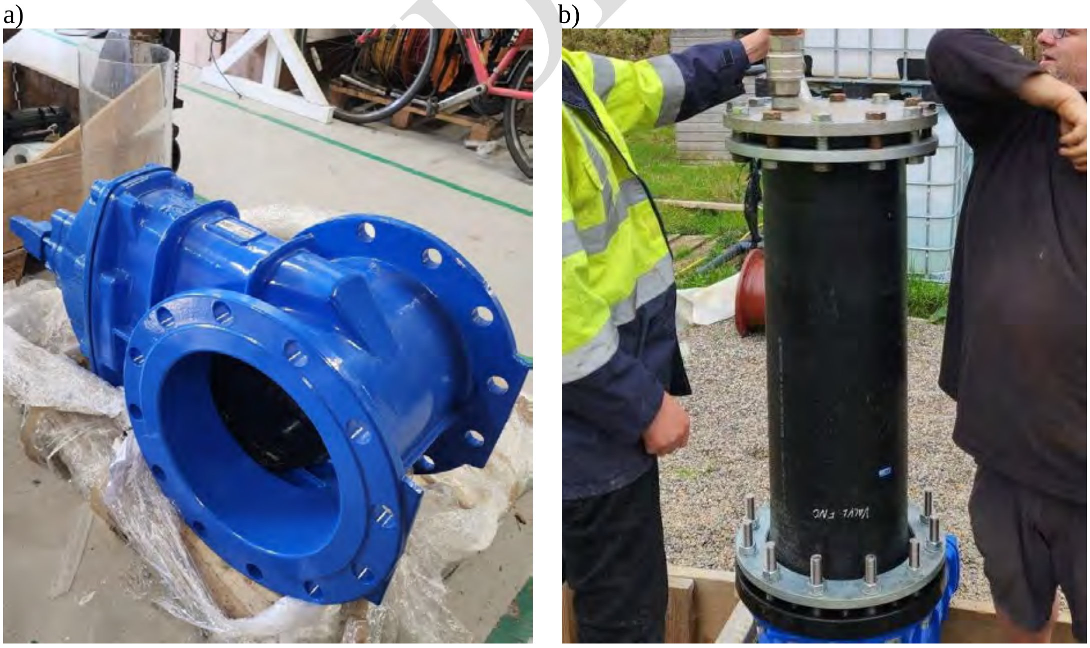

Figure 4 Live access equipment for pressurised tests showing a) the DN300 Donkin gate valve and b) the launch tube assembly connected to the Donkin valve on site.

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System Testing Apparatus

The equipment used for testing on site are list below:

- PoC Robot Assembly
- Robot Specific 40 m Umbilical Tether
- Visual display and control unit
- Additional visual display unit
- Power cables
- Bike pump
- 6 mm tubing and push fitting
- Digital Manometer (<2Barg)
- Acoustic signal generator
- Transient Speaker push rod assembly
- 15 & 60W Speaker attachments for above assembly
- 30W underwater speaker
- Tape measure
- Synthotech H2O Camera kit

Phase 1 Testing – Non-Defective Pipe

Test arrangements and methodology

The first phase of testing aimed to cover the safe insertion, operation, and retrieval of the robot crawler within the DN300 pipework, and to test the sensors on new, non-defective pipe as a benchmark. The arrangements and test methods are detailed below:

1. **Insertion and robot specific**

Figure 5 shows the general test arrangement for majority of tests within this phase. The transient generator would be statically position on the far side of the pipe, whereas the crawler would access the pipe from the opposing end. It was important to understand how the design of the crawler and sensor arrangement would access and navigate the pipe, having to overcome an initial 90° bend from the vertical access. Tests were broken down into the following:

a) Robot deployment, operations, and retrieval in a dry test pipe
b) Robot deployment, operations, and retrieval in a water filled test pipe under static head (approx. 100 mBarg)
c) Robot deployment, operations, and retrieval in a water-filled test pipe under Pressurised scenario with launch equipment.

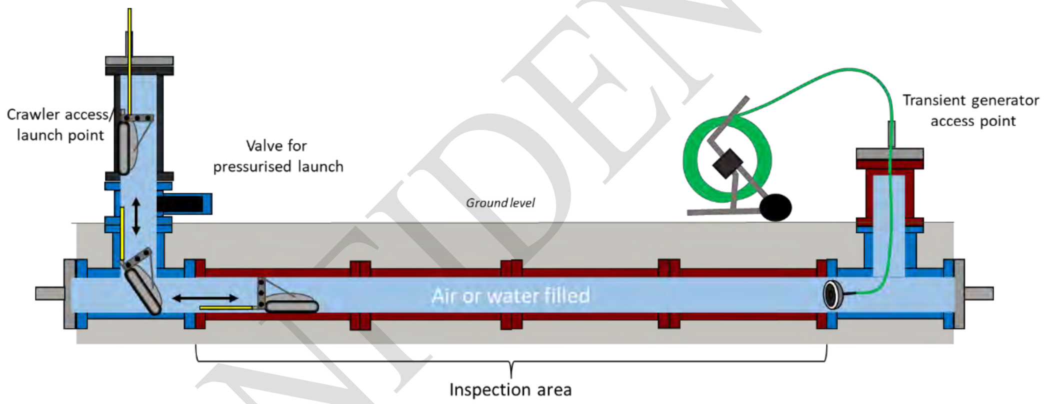


Figure 5 Test arrangement for insertion and crawler operation testing. Vertical section on the left is swapped out and replace with valve/ launch apparatus for pressurised tests.

2. **Sensor specific testing**

Using the same test arrangement as above, sensor specific testing aim to understand if the signal produced by the transient speaker could be captured by the sensor configuration within the pipe environment. Tests were broken down into the following:

a) To assess sensor output within water-filled test pipe w.r.t various robot operations
b) To assess sensor output within pressurised water-filled test pipe w.r.t various robot operations
c) To understand the optimum approach to sensing with the PoC system
d) To understand the sensor's baseline measurements with a non-defective test pipe configuration

Results

Deployment, operation, and retrieval (Dry Ops)

The crawler design and sensor array design were validated during dry testing. It was able to be vertically deployed into a dry pipe without hindrance, cover the full 8 meters of inspectable pipe without cable or halo snagging, and it was easily retrieved, with no noticeable impact on crawler controls and output visuals on the display units. Figure 6 shows an example of the dry testing, deployment, and internal visuals.

a) b) c)

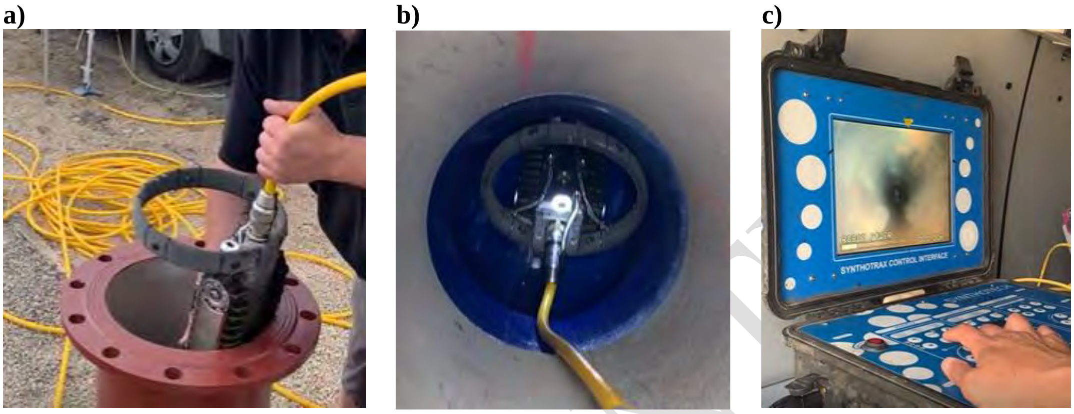


Figure 6 Dry deployment and operational test. a) Crawler Insertion to the vertical pipe, b) Crawler driving into the pipe, c) Crawler camera feed from within the pipe.

Deployment, operation, and retrieval (Wet Ops)

Additional tests were conducted with the rig filled with water to approximately 100 mBarg static head. The crawler consistently maintained an internal pressure of 489 mBarg without any pressure drop during these tests. Deployment, operation, and retrieval of the system remained effective. However, to reduce stress on the umbilical/crawler connection during vertical insertions, additional holding fixtures were introduced to improve crawler handling.

a) b)

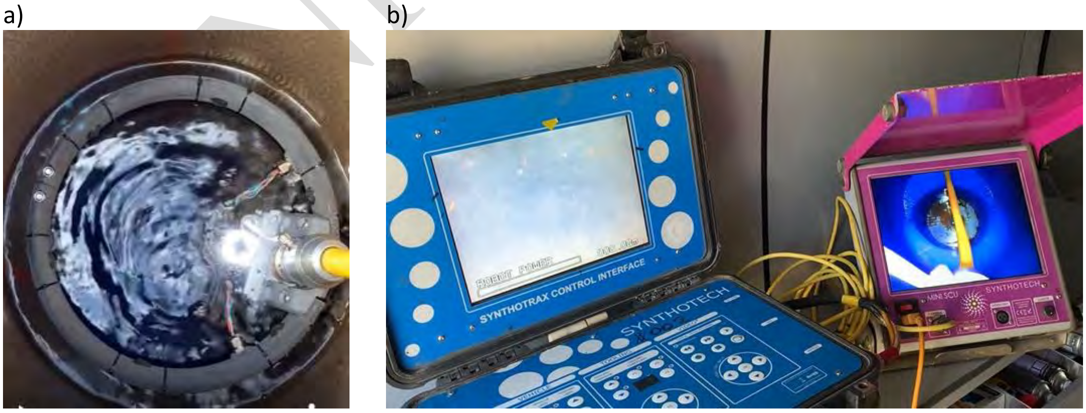


Figure 7 Wet deployment and operational test. a) Crawler insertion into the wet vertical section, b) Crawler camera feeds from within the water-filled pipe.

Deployment, operation, and retrieval (approach to pressurised operations)

The test rig was adapted to include a DN300 through-bore gate valve and a launching system for introducing the crawler into a pressurised environment. The launching system consisted of a 1-meter 315mm SDR 17 PE pipe section with flange fittings at both ends, allowing for a secure connection to the gate valve. The launch tube itself had passed a 3 barg pressure test. On the opposite end of the launch tube, there was an endplate with a welded glanding system and a camera entry point. The glanding system ensured controlled movement of a tether in and out of the pressurised pipe environment, using seals and gaskets to prevent any leaks at the cable insertion location. While the current setup validates the concept, it's advisable to consider adding a flush chamber at the top of the gland stack to cleanse the cable with a chlorinated solution as it's withdrawn from the foul water system.

The extra camera port was a helpful addition as this enabled the simultaneous deployment of a water specific camera. This camera was used to observe the robot inside the pipe, aid in positioning during tests, and confirm the robot's location during both launch and retrieval operations from the launch point. While a camera might not be feasible to use within live rising mains, it might be essential for launch and retrieval operations to confirm the crawler's presence at the launch point.

a) b)

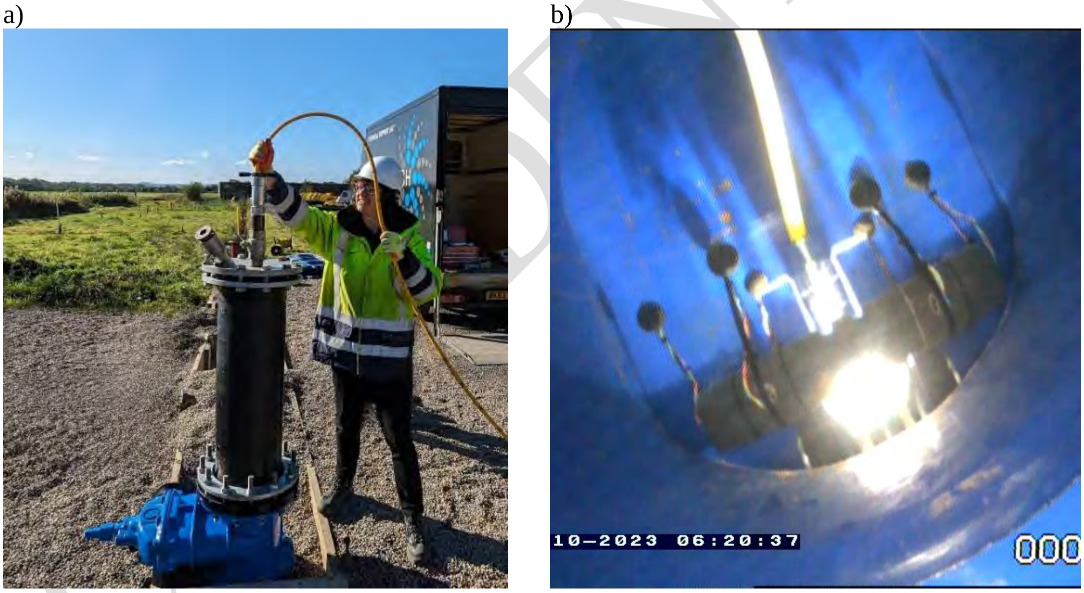


Figure 8 a) Test insertion and cable management of crawler through access assembly and b) H2O camera view from vertical launch point.

Test deployment and retrieval of the crawler through the launch apparatus and valve were successful with no issues around the technique or the sensor's array geometry. The next stage of tests should look to test out the end-to-end approach under a pressurised system. This is something that Synthotech are in the process of testing, and will update on progress going forward.

In-Pipe Data acquisition from STaRS test rig

After refining the data capture process, data was able to be captured within the water filled pipe under static head pressure. Figure 9a) shows an example of what a sensor captures during a single accelerometer scan. A 6 second scan starts with a sound check, followed by 1 second of background noise, and then less than 5 seconds of sound at a given frequency, in this case 100 Hz. In Figure 9b) the data quality is evident as it displays approximately 10 cycles of a sinusoidal response within 0.1 second, indicating the system's accurate reception and capture of the 100 Hz sound wave under static head conditions in a buried, water filled pipe.

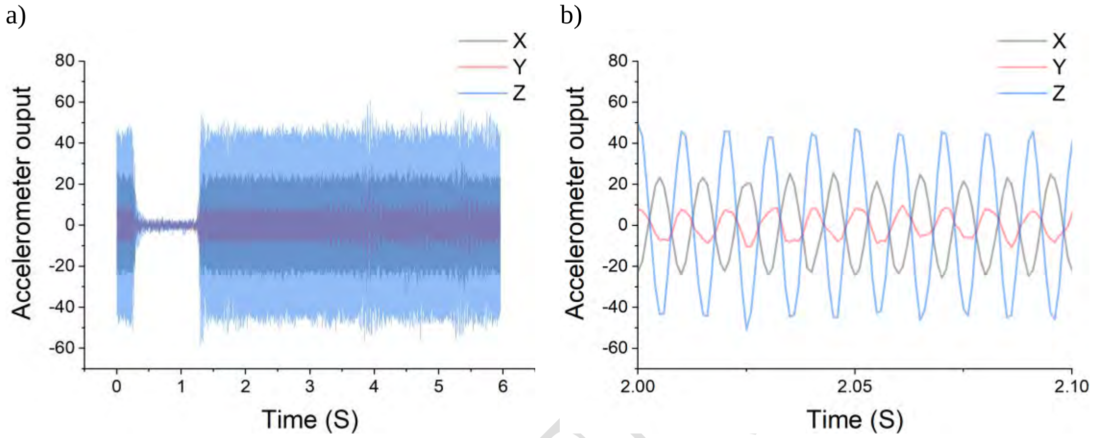


Figure 9 Example of data captured during a scan within test rig under static head condition for a) the full scan and b) a zoomed in section of the data.

Variability of repeated measurements from the STaRS test rig

Control tests were conducted to assess the consistency of accelerometers across consecutive measurements at specific scan locations within the pipe's barrel, away from joint features. These repeated scans were compared within the scan series to ensure a consistent response. In Figure 10, an example with three repeat scans is shown from accelerometers 2 to 5, with their XY, XZ, and YZ data plotted to evaluate acceleration changes along each axis. The investigation determined that the repeated scans exhibited good similarity in relation to individual accelerometers, with minimal changes in the data across multiple scans. This finding implies that valuable time can be saved in operational processes and testing, as reliable data can be obtained from a single scan. Differences between different accelerometers were linked to a few things, including individual sensor orientation in the potted housing (ball) and sensor position on the halo (impacting distance from pipe surface).

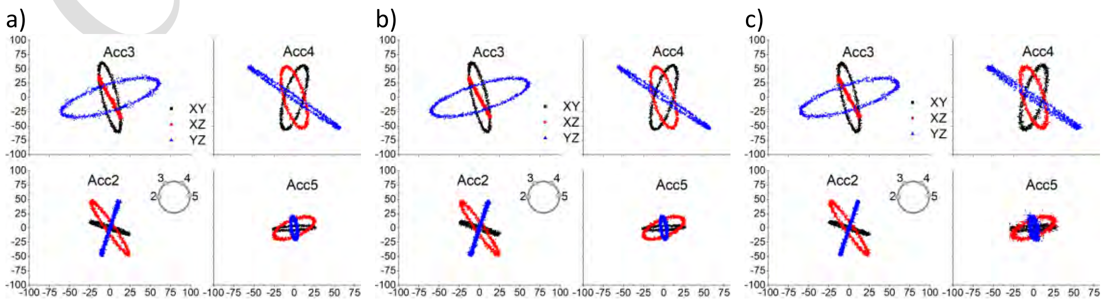


Figure 10 Repeats at single point in the barrel of the first pipe a) repeat 1, b) repeat 2, and c) repeat 3.

Pipe barrel and Pipe joint confirmation with smaller drive increments

Additional measurements of the control pipe and joint sections were conducted, assisted by a potable water pipe inspection camera to align the sensors at the areas of interest. The sensor halo was initially positioned directly over the inspection area, followed by nudging the crawler backward five times (a "nudge" representing a brief press on the crawler's controls to move it a short distance). Once back at this starting position, the crawler was nudged forward, and scans were taken after each nudge. This approach was chosen to enable the sensor to pass through and scan the area, providing insights into the vibrations associated with the pipe barrel and joint features.

Figure 11 present the results from scans over the pipe barrel section, while Figure 12 presents the same for scans over a joint area, with additional side graphs. Looking at the pipe barrel there are no major changes as the crawler moves past this location. This is to be as expected as this is the control section of pipe in good condition. Similarly, when the crawler moves past a joint, there is not much of a change in the Y amplitude, with minor increases closer to the joint area.

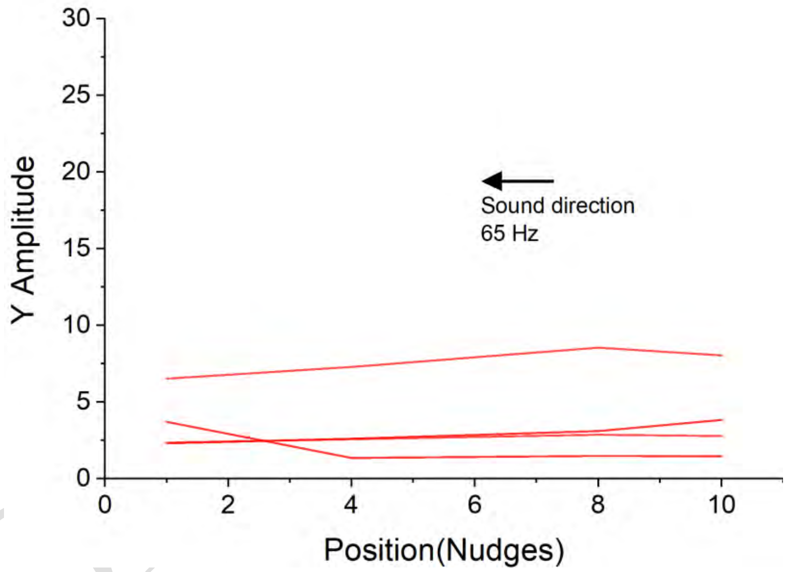


Figure 11 Changes in Y amplitude from accelerometers within pipe barrel (control) section over 10 crawler nudges.

What helps to differentiate the two features in the data is the relationship between XY, XZ and YZ accelerometer when plotted together. The side graphs in Figure 12 show the differences between a pipe barrel, an area of the pipe approaching a joint and around the joint itself. There is a clear change in the XZ and XY data, with the shape of the accelerometer data becoming more circular towards and on the joint, itself compared to the pipe barrel. This outlines how this data could be interpreted in the field, by knowing what different features present themselves as. The next phase of tests will examine how these changes across small and larger defects. Again, there are differences in the amplitude across different accelerometers, which are linked to the system's design, but it is important to note the variation over the individual accelerometer provides more of an indication of the pipe's condition. With sensor development, orientation refinements and a suitable calibration procedure before measurements, all accelerometer readings can be presented with a similar baseline output that is scaled appropriately.

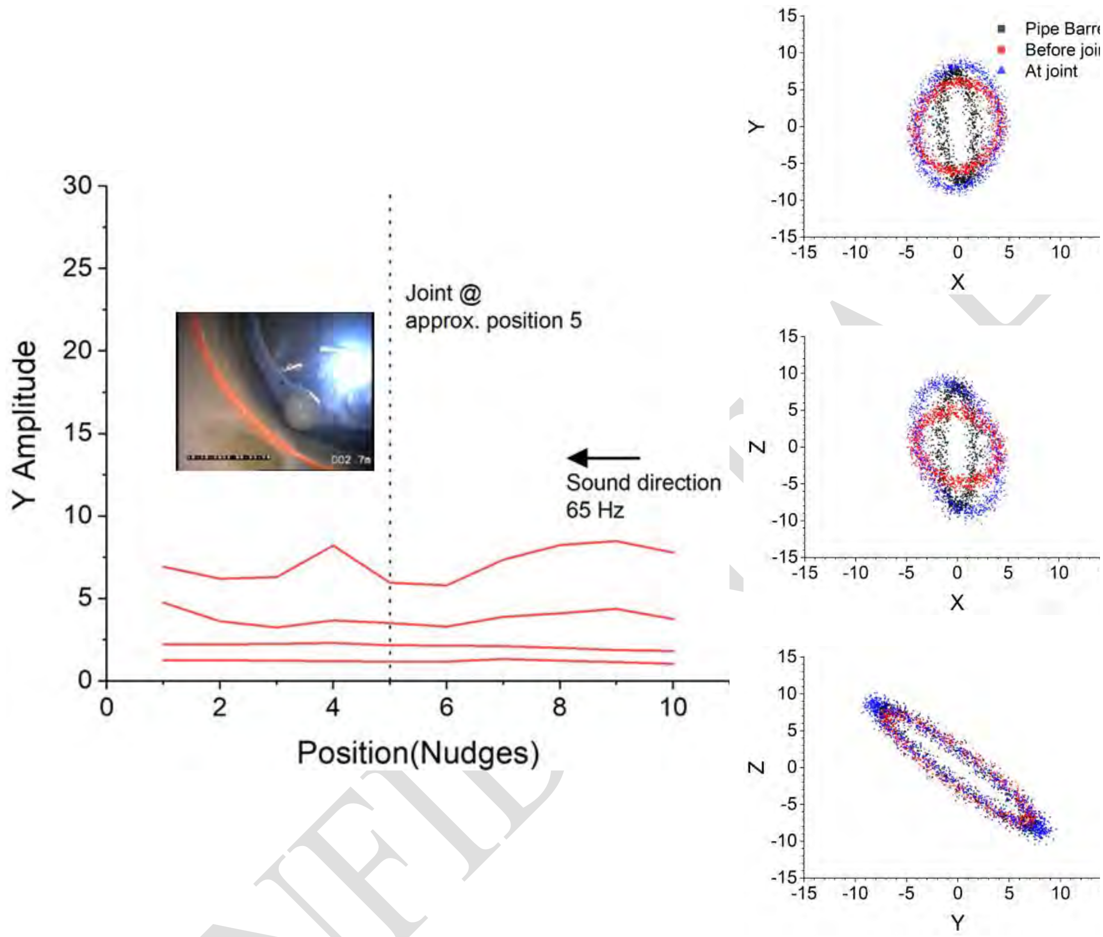


Figure 12 Joint detection with accelerometer data, showing amplitude changes over position and comparing XYZ position data of the pipe barrel (black), pipe section before the joint (red), and the joint itself (blue).

Conclusions

- The Robot crawler can be launched into a water-filled pipe through an open access point, drive forwards and backwards within 300mm nominal bore pipework, and transmit visual data to display units without failure.
- The PoC design can detect a known sound frequency within a water-filled pipe through an open access point and drive forwards and backwards within 300mm nominal bore pipework.
- The collected data is of good quality, with minimal variation between repeat measurements.
- The relationship between accelerometer data on each axis is able to differentiate between a control pipe section and joint.

Phase 2 Testing – Defective Pipe

Test arrangement and defect locations

To validate the concept, two defects were introduced to the STaRS test rig: a small ¼” hole and a larger 1” defect. These holes were precisely created using a mag drill, threaded, and equipped with plugs to allow for adjustments in the depth of the internal defects during subsequent testing. These are presented in Figure 13. The defects were intentionally positioned on separate pipes, with the 1” defect situated at a distance of 2750 mm from the beginning of the inspection area (in pipe section 2), and the ¼” defect placed 5000 mm from the start of this area (in pipe section 3). In relation to the clockface orientation from the access point towards the speaker, these defects were located at the 10 o’clock position, making Accelerometer 4 the primary sensor for detecting the most significant changes in measurements.

a) b)

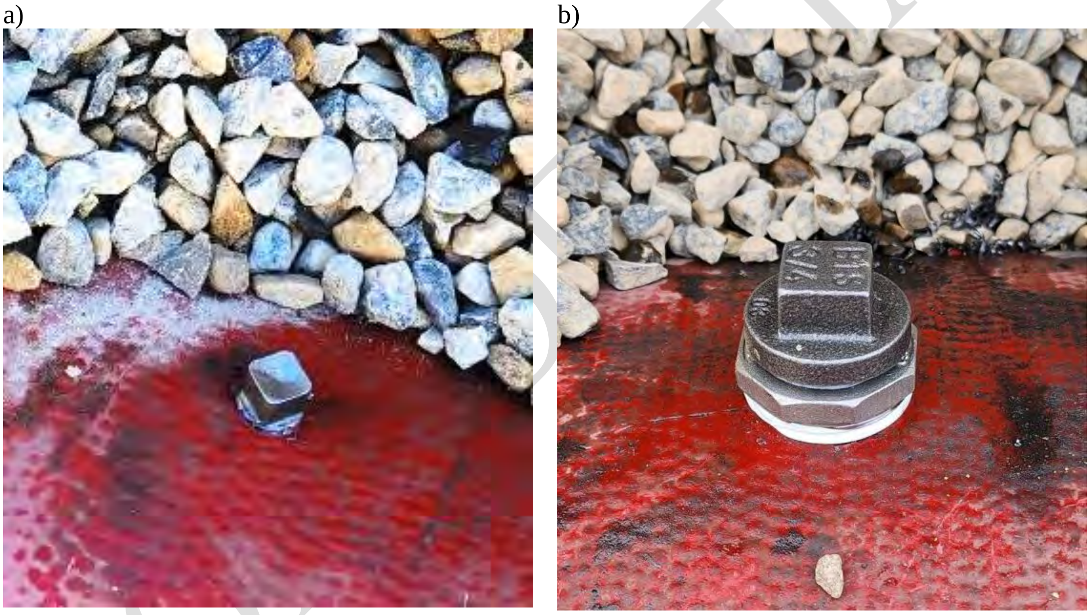
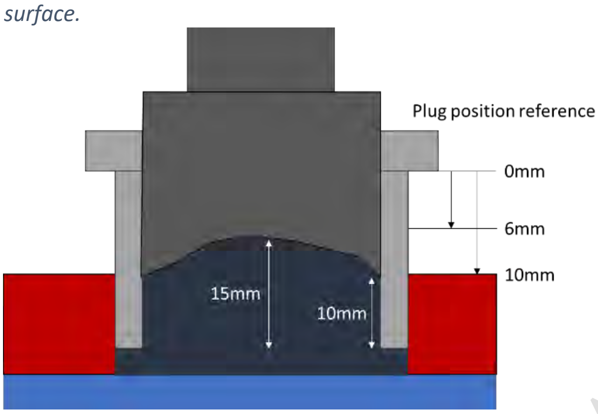


Figure 13 Defects on STaRS test rig showing a) the small ¼” defect and b) the large 1” defect.

A 1/4" solid plug addressed the small defect, while a 1" hollowed plug was used for the larger defect. Table 1 illustrates the defect cross-section in the pipe and explores how adjusting the plug's distance from the external surface affects the defect dimensions, simulating various levels of localised wall thinning. The initial position was with the plug fully inside the pipe (0mm reference), followed by exposing 6mm of thread externally, and then 10mm.

Table 1 1" Plug schematic currently showing the 10mm out configuration and approximated internal defect depths from internal pipe surface.



Plug position reference in relation to external pipe surface	Defect depth from internal surface (edge)	Defect depth from internal surface (centre)
0 mm	-2 mm	-7 mm
6 mm	-8 mm	-13 mm
10 mm	-12 mm	-17 mm

Results

Figure 14, Figure 15, Figure 16 and Figure 17 present the results from scans over the smaller ¼" plug defect, the larger 1" plug defect in the 0mm out position, the 1" plug in the 6mm out position and the 1" plug in the 10mm out position respectively. These are presented in a similar way as Figure 12, however the main focus is on Accelerometer 4 as the closest sensor to the defect and Accelerometer 1 to show the response on the opposite side of the pipe's circumference.

Joint vs defects

Comparison between the joint sweep and the defect sweeps has revealed significant distinctions in feature characteristics, particularly in the XY and XZ dimensions, with larger changes in the Y and Z direction. Notably, while joints exhibit a tendency to become more circular with minor amplitude changes, the defects display subtle angle adjustments and increased Y-axis amplitude. While further testing and in-depth data analysis are required to validate these observations across a broader range of internal pipe features, this provides a foundation to develop a portfolio of feature characteristics that can be used by operators on site.

Small vs large defect

Subtle differences become apparent when comparing the 1/4" defect shown in Figure 14 to the larger 1" defect in Figure 15. Notably, the larger defect exhibits more significant changes in the Y and Z directions compared to the smaller defect. The alterations in the angle are somewhat more pronounced in the XYZ data of the 1/4" defect, although it's worth noting that some of these distinctions may be attributed to the smaller plug being a solid bulk fitting, as opposed to the hollowed 1-inch plug. Despite these nuances, significant differences exist between both plug defects and the pipe barrel, allowing for the distinction of these features from a pipe in good condition. Further research is required to pinpoint the specific aspects of a feature that influence the accelerometer's output response.

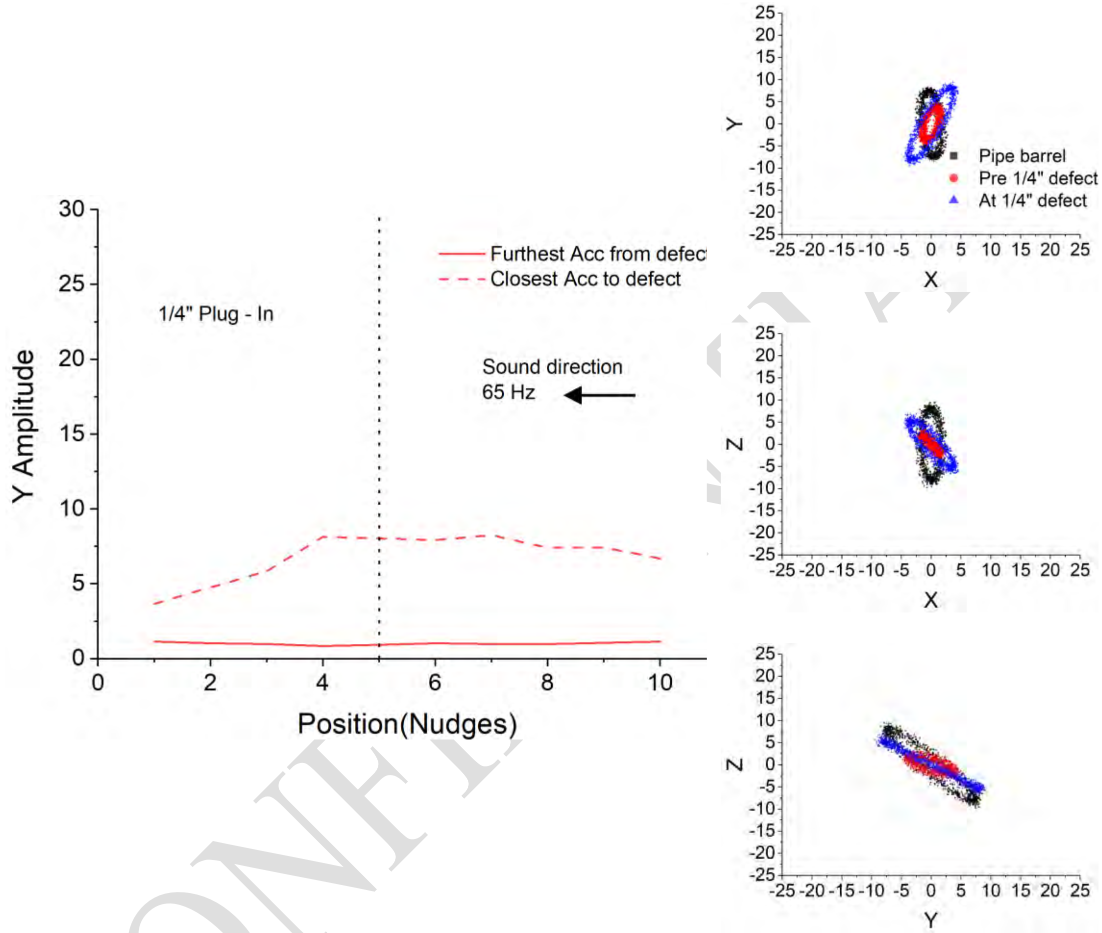


Figure 14 Defect detection of 1/4" defect position with accelerometer data, showing amplitude changes over position and comparing XYZ position data of the pipe barrel (black), pipe section before the defect (red), and the defect itself (blue).

Depth changes to large defect

Increasing the depth of the defects yielded noticeable results in terms of Y-amplitude and shifts in the Y and Z axes within the accelerometer data. The most significant changes occurred when the plug was unscrewed by 10mm. This observation suggests that accelerometers can detect subtle variations influenced by the depth of a feature. Nevertheless, further systematic testing in the next phase is essential to comprehend the precise relationship between accelerometer data and wall thickness measurements, in addition to other degradation features.

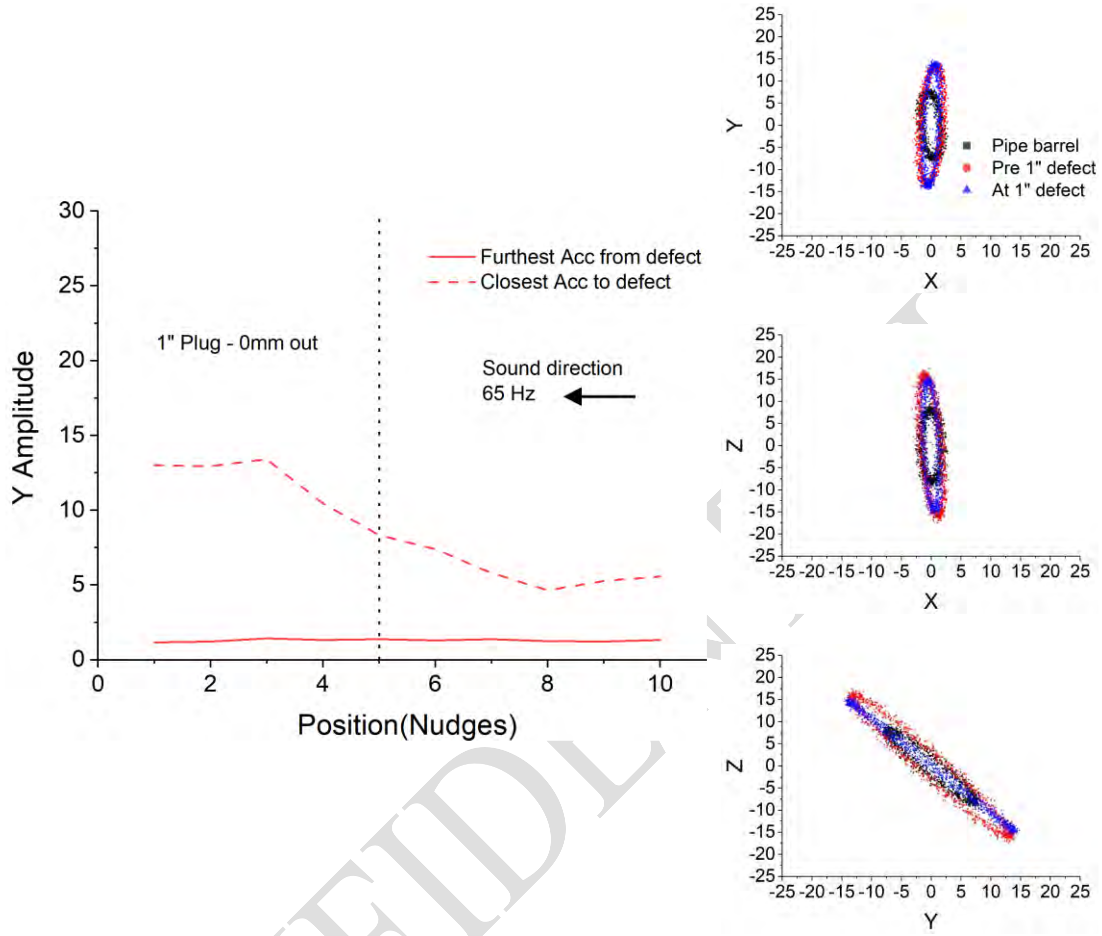


Figure 15 Defect detection of 1" defect in 0mm out position with accelerometer data, showing amplitude changes over position and comparing XYZ position data of the pipe barrel (black), pipe section before the defect (red), and the defect itself (blue).

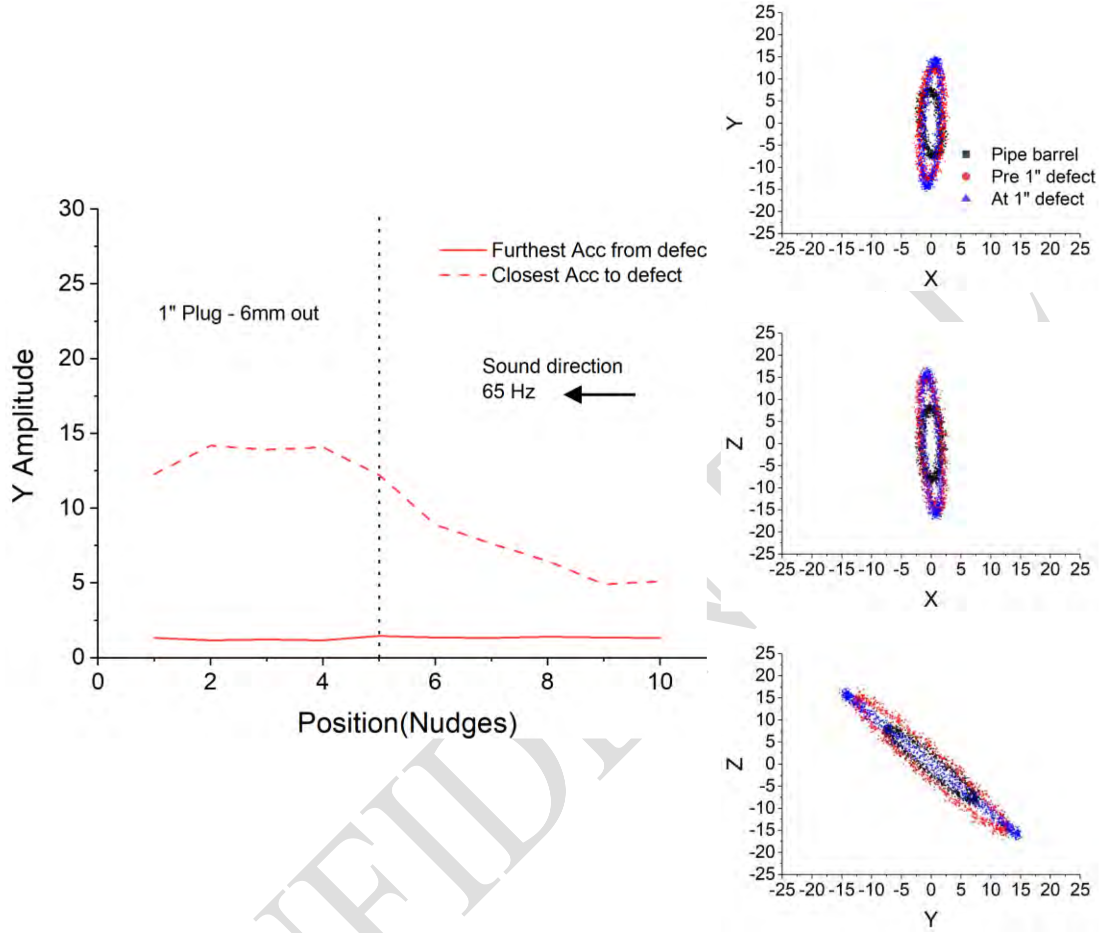


Figure 16 Defect detection of 1" defect in 6mm out position with accelerometer data, showing amplitude changes over position and comparing XYZ position data of the pipe barrel (black), pipe section before the defect (red), and the defect itself (blue).

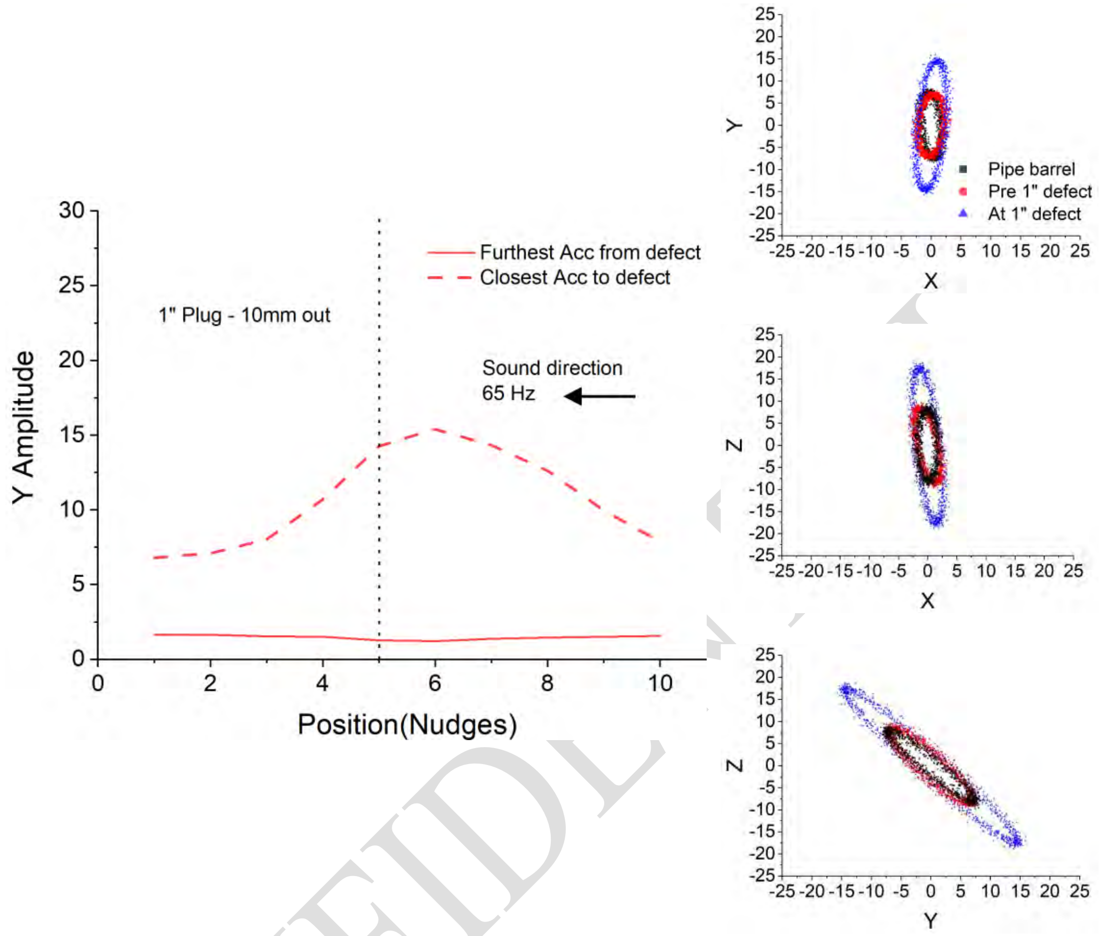


Figure 17 Defect detection of 1" defect in 10mm position with accelerometer data, showing amplitude changes over position and comparing XYZ position data of the pipe barrel (black), pipe section before the defect (red), and the defect itself (blue).

Conclusions

- Significant distinctions have been made in feature characteristics, especially between the baseline pipe barrel and joint scans vs defect scans.
- There is potential in the sensor system for indicating defect size and depth with the recorded data – to be further inspected within the next phase.

Outcomes and Recommendations

In summary, the tests successfully demonstrated that the system could be deployed into a buried pipe through a suitable access point, collect data on the pipe's condition using the Proof-of-Concept sensing system, and exit the pipe. The data quality was good, and analysis showed the system's ability to identify specific features within the pipe environment. The key findings are as follows:

The delivery of sensors to locations within a pipe:

- The crawler proved to be waterproof and functional under static head pressures and effectively traversed the 10m test rig.
- The halo configuration did not hinder access and egress, ensuring sensors could capture data.

The measurement accuracy of the sensor system within the rising main pipe:

- The system could distinguish between features in the pipe, such as the pipe barrel, joints, and machined defects.
- Repeated scans of the same locations yielded consistent results in the current data capture setup.

The operational approach to deployment, inspection, and retrieval of the whole system:

- Vertical launch for system access and egress is a feasible method.
- Upgraded hardware has the potential to significantly expedite the inspection process.

Although this work showcased the potential of the pipe condition sensing approach, further development is needed to advance this TRL3-4 system to a state suitable for deployment in an operational rising main environment. Identified areas for system refinement have been identified for development within the next project phase, and recommendations for achieving these improvements are discussed below.

Data contextualisation with asset condition – The existing Proof-of-Concept system has successfully demonstrated its ability to capture data and infer feature detection by the analysis of distinct vibrational signatures within a static flow pipe environment. In the upcoming phase, the focus should shift towards identifying the crucial data outputs that are relevant for asset condition monitoring, such as measurements of wall thickness and how accelerometer data reflects changes in this aspect. Efforts should be directed towards data processing and comprehending how data output correlates with the actual physical condition of assets. Validation should be carried out in laboratory settings and on a section of simulated pipework to ensure accuracy and reliability.

Sensor orientation and calibration – Misalignment of the accelerometers resulted in varying outcomes during both control and defect inspections. To address this, improvements in the manufacturing process should ensure proper orientation of the accelerometers. This would, in turn, enhance the clarity of amplitude changes in the specified X, Y, and Z axes during data processing. Furthermore, it is crucial to explore the necessity of a calibration process before taking pipe measurements. Such a process would involve offsetting control readings to establish a benchmark position for subsequent measurements. This would allow for a comparative analysis of amplitude changes throughout an inspection, relative to the benchmark position. However, a thorough investigation is required to determine the feasibility and effectiveness of this approach.

Data processing workflow and key outputs - In this phase, we have explored the partial processing of accelerometer data to gain insights into the sensor's capability in detecting changes within the pipe's internal environment. In the next phase, it will be essential to allocate dedicated time and resources to determine the most effective approach for data processing. This involves identifying the optimal data processing method, the ideal processing location, and scripting it into an automated process. This automation will enable the direct input of output data into the processing algorithm, resulting in a concise summary report with key metrics for the entire pipe survey. By fine-tuning the sensor's orientation and gaining a deeper understanding of how accelerometer data can be processed for condition monitoring, the reporting process can be streamlined to only output critical information and minimise processing time.

Proof-of-Concept measurement limitations: spatial resolution - During the testing iteration, several limitations were identified in the system's ability to scan a location. The method of nudging the robot proved to be relatively imprecise. This imprecision affected both the spatial resolution and, consequently, the scan resolution across the sweep area. It resulted in potential data points being missed over the nudge distance. Prior work in D4 has already shown that the noise generated by the crawler in motion can be effectively filtered from the data. Therefore, future testing should focus on refining the data collection process during motion to ensure no locations are overlooked during operational scans of rising mains. This development is critical in the next phase to optimise inspection times and enhance scan resolution.

Appendix 1. L09-T-001 – Pressure/ Leak Testing

Introduction

As part of the commissioning of the PipeBots In Rising Mains (PBIRM) test rig, pressure and leak tests were performed to ensure joints were secured and leak-tight ahead of Phase 1 Proof of Concept (PoC) testing. Testing was performed at STaRs on 300 mm Ductile Iron pipes that had been placed, bolted, and capped off with standard and modified blank plates. All bolts were tightened to 120 Nm of torque in line with the pipe manufacturer's instructions for this size and type of pipe.

Test Rig and Equipment

Figure 18 presents the pressure and leak test arrangement. A mixture of water and dish soap was used to make up the leak detection fluid to determine if and where leaks occurred on the test rig.

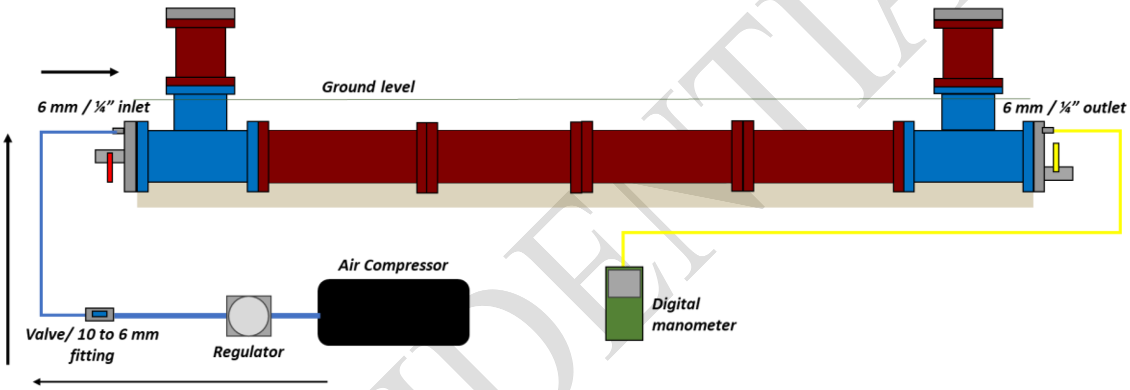


Figure 18 Schematic of the pressure test arrangement for the ductile iron test rig. 10 Bar rated compressor was used with a regulator to achieve test pressures and fed into the 1/4" BSP inlet to the test rig via 10 and 6 mm tubes. The pressure was monitored with a digital manometer which was connected to the far side ¼" BSP outlet with 6 mm tubing.

Methodology

All ball valves were closed on the test rig before testing. The manometer was set to zero as our reference baseline before running the compressor and pressurising the test rig. The rig was then gradually pressurised until it reached a pre-determined pressure for leak testing. The chosen pressures for testing are listed in Table 2.

Table 2 Pressure Test Parameters

Test	Pressure (mBarg)
1	120
2	250
3	500
4	1000

The compressor was cut off when close to the desired pressure, where an initial reading from the manometer was taken. After 5 minutes a second manometer reading was taken to see if the rig held pressure. Where it didn't hold pressure, leak detection solution was sprayed over all joints, bolts, end plate fittings and fitting along the tubing to locate where on the rig air was escaping. These were noted before continuing to the next test pressure.

Results

Tests were performed at 1422 DST on the 26th of July 2023. Conditions were fair with an ambient temperature of approximately 19-20 °C and sun shining on the exposed surfaces of the test rig. Results are presented in

Table 3 Pressure and Leak Testing Results

Test	Initial Pressure (mBarg)	End Pressure (mBarg)	Pressure Drop (mBarg)	Leak?	Leak Observations
1	119	110	9	Y	• 2" BSP Outlet fitting – 12 O'clock
2	251	239	12	Y	• Same as Test 1 • 2" BSP Inlet fitting – 10 O'clock
3	501	480	21	Y	• Same as Test 2
4	1003	970	33	Y	• Same as Test 2 • 10/6mm valve

Outcomes and Recommendations

- All flange joints between pipes and endplates were shown to be leak-tight at 1000 mBarg.
- Leak points were observed to be located on both 2" end plate fittings on the flow inlet and outlet of the test rig.
- Audible sound from the 10 to 6 mm connector/valve during the 1000 mBarg test, along with soap bubbles, indicating greater pressure loss at this location compared to other leaks on the test rig – which may have accounted for the larger pressure drop at this test.
- Once the 2" fittings have been amended, then the test rig will be ready for PoC trials.

Follow up outcomes

- 08/08/2023 - Fittings were resealed and the test rig was repressurised up to 1000 mBarg without observed leaks.

Appendix 10. U3 - Final Report

U3 Report on Sheffield University rising mains work: January- October 2023

Modelling of the effect of a defects in pipe on low-frequency acoustic field

The effect of a loss of wall thickness on low frequency (i.e. when the wavelength of sound is much greater than the pipe diameter) acoustic pressure in a fluid-filled pipe is relatively small so that it is difficult or impossible to measure with traditional sensors such as hydrophone or other type of pressure transducer. However, the use of low frequency acoustic waves to detect wall thickness losses is attractive because these waves can propagate considerable distance with little attenuation and relatively unaffected by the presence of gas or impurities in the fluid. In many cases, low frequency sounds in a rising main are generated by pumps, valves or leaks to be used as a naturally present acoustic stimulus. This part of the report is focused on modelling the propagation of low frequency acoustic waves in the presence of a defect to illustrate that acoustic velocity sensors can be used to detect the onset of wall damage with a relatively high fidelity.

Multiple types of pipe wall defect

It was assumed that small defects in rising mains can be grouped into 4 main categories:

a) Internal pitting
b) External pitting
c) Internal reduction of pipe wall thickness
d) External reduction of pipe wall thickness

The effect of these defects on the acoustic pressure and velocity were all modelled in Comsol MultiPhysics™ for a cast iron pipe with a 100 mm internal diameter and 10 mm thick wall, as shown in Figure 1. From these models the behaviour of the acoustic velocity vector defined as $\boldsymbol{v} = \frac{\nabla p}{i\omega\rho}$ was predicted, analysed and compared with that of the typically measured acoustic pressure, p. In this equation ω is the acoustic frequency, ρ is the fluid density and $i = \sqrt{-1}$. In a pipe the acoustic velocity vector is usually described as a vector that depends on the axial, z, and radial, r, directions and azimuth angle θ. The acoustic velocity component in the axial direction, v_z, is highly correlated with the acoustic pressure and it is usually predicted as $v_z = \frac{p}{Z}$, where $Z = \rho c$ is the acoustic impedance of the medium, c being the speed of sound in the fluid. The model also predicted the wall acceleration to compare the results of this simulation with field measurements.

The results of the Comsol simulation are shown in Figure 2 for a range of distances to the internal pitting defect and 300 Hz acoustic excitation. The absolute value of the radial component of the acoustic velocity is uniform across the pipe cross-section and small in comparison with the axial component if the pipe wall is continuous and without any defects, i.e. $|v_r| \ll |v_z|$. When the frequency of sound is low, then the acoustic pressure and axial component of the acoustic velocity are relatively unaffected by the presence of a defect as shown in Figure 2. Therefore, these quantities do not change noticeably along the length of cross-section of the pipe and cannot be used as an indication of pipe damage. The axial velocity data are omitted from Figure 2 and only the acoustic pressure data are shown instead as an illustration. The acceleration of the pipe wall is not affected by the presence of the defect either (see Figure 2).

When the thickness of the pipe wall reduces locally, e.g. because of corrosion, graphitisation or structural damage, the amplitude of the radial component increases and varies significantly across the pipe as illustrated in Figure 2 for distances to the defect of 0.05 m or less. At these distances the behaviour of the radial component of the acoustic velocity becomes complex and its absolute value is relatively large and measurable. This effect is also demonstrated in more detail for internal pitting and other types of defects in Figure 3. There is a clear difference between the behaviour of the radial component of the acoustic velocity for the no defect case, local internal pitting, local external pitting and overall thinning in the pipe diameter.

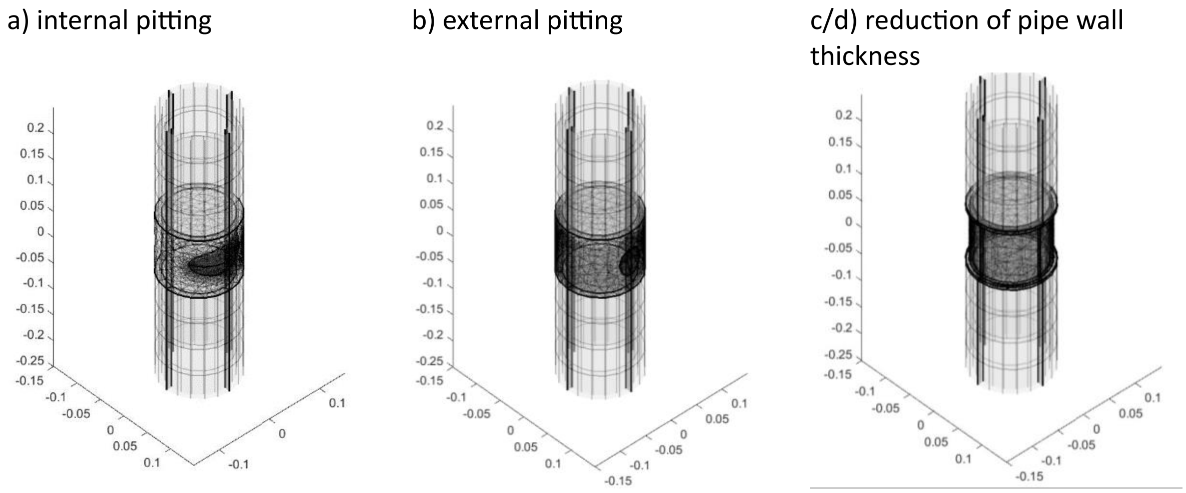


Figure 1: models of each defect, here showing a portion of the mesh used for the model, focussing on the defect itself. The type of defect for a reduced wall thickness is determined by changing the materials of the two concentric cylinders making up the pipe wall.

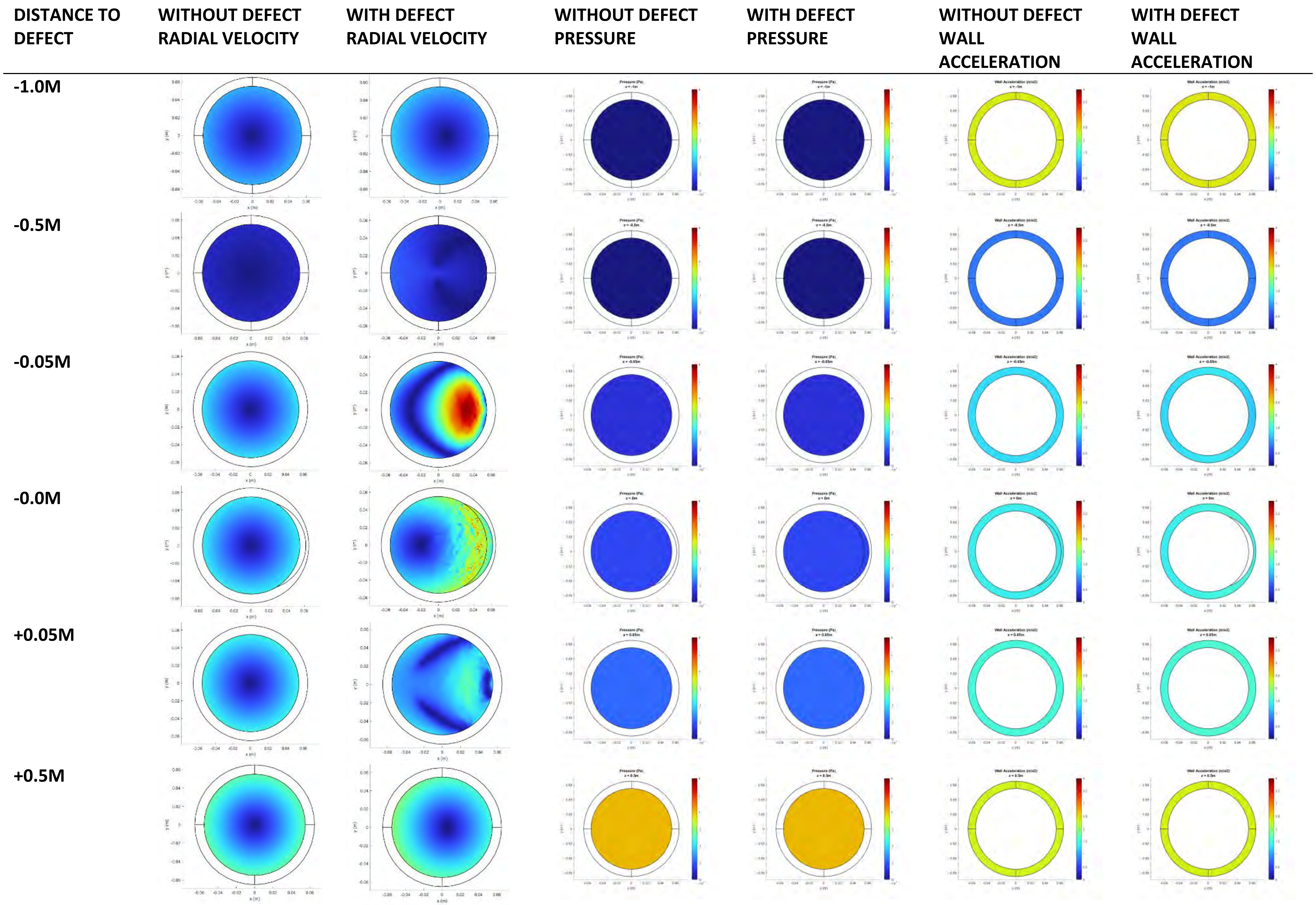


Figure 2: Comparison of cross-sectional planes at different distances from the defect, for metrics of interest. A 300Hz planar source located 2m from the defects. The unit of colourmap is m/s.

WITHOUT DEFECT (0.0M) **WITH DEFECT (0.0M)**

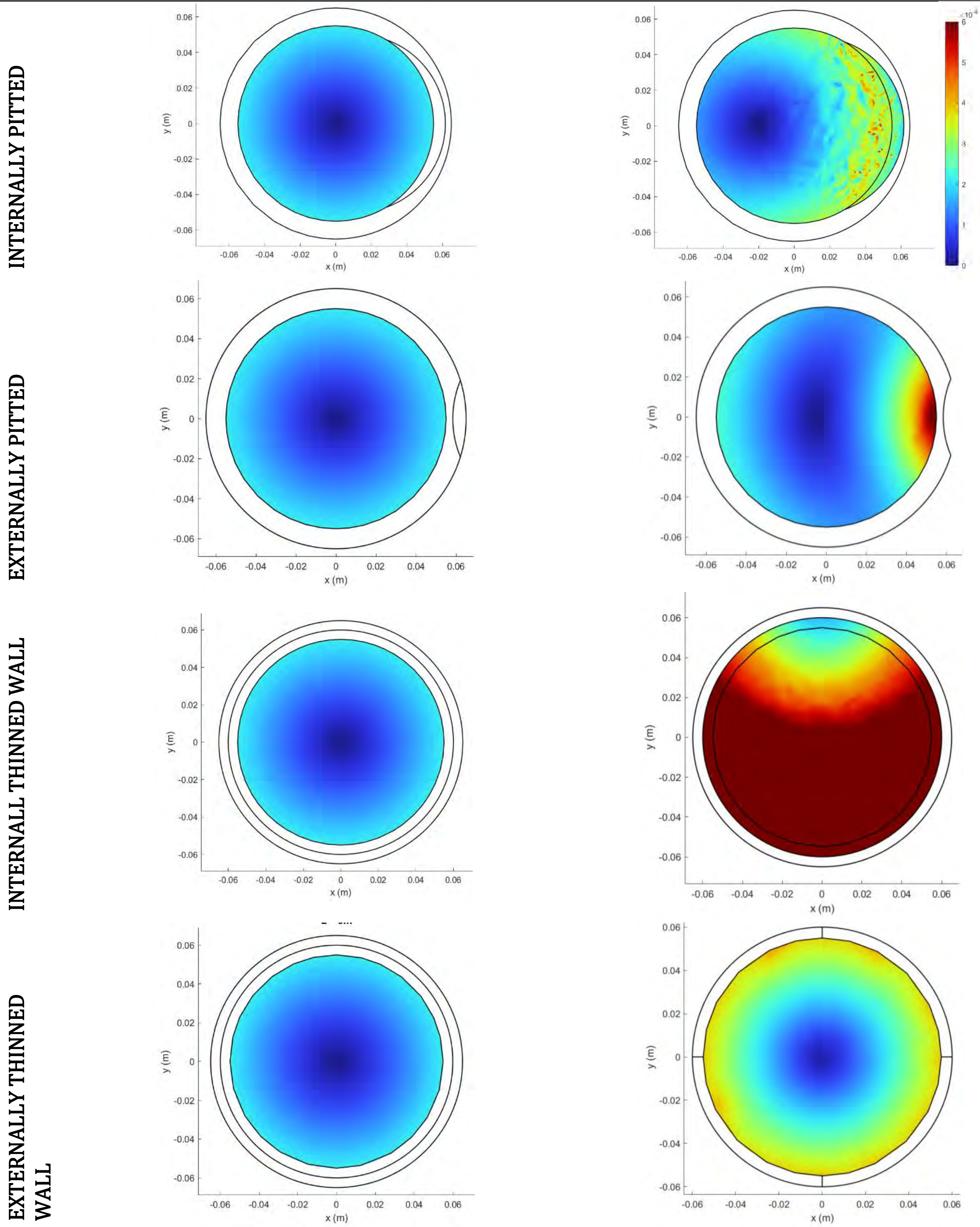


Figure 3: A comparison of the radial velocity in a 100 mm cast iron pipe with and without the defect for a 300Hz planar source located 2 m from the defect. The unit of colourmap is m/s.

Increasing size of pipe

The simulations above consider a 100 mm diameter pipe. This diameter is smaller than might be considered typical for a rising main. A similar analysis was conducted for a 300mm diameter cast iron pipe with 10 mm thick wall, local internal pitting and source frequency of 65 Hz. This frequency is close to the spectrum of typical pump noise measured in a rising main. This noise can potentially be used as a stimulus to determine defects in a rising main.

The results of this simulation for the radial and axial components of the acoustic velocity are shown in Figure 4. The results shown in this figure suggest that there is a relatively small change in the axial velocity and it is almost uniform in the vicinity of the defect. In contrast, the radial component of the acoustic velocity in the vicinity of the defect has a very pronounced cross-sectional variation and shows a significant increase in comparison with that expected at a distance away from the defect (see Figure 2). This cross-sectional pattern is still detectable 0.5 m away from the defect as shown in the bottom part of Figure 4.

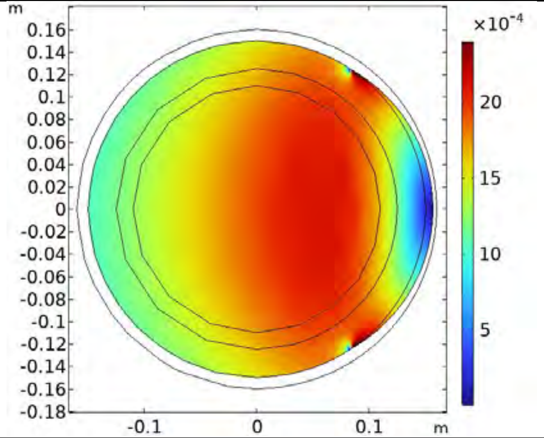
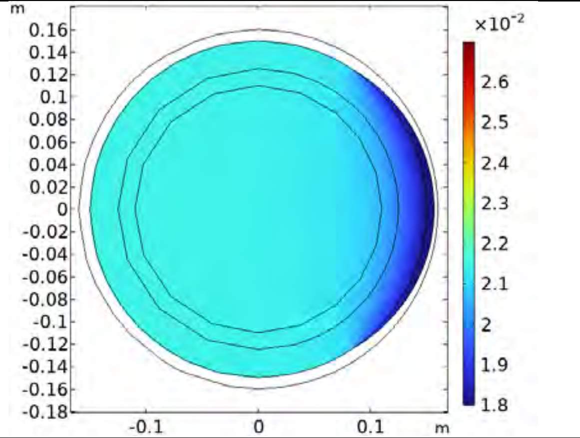
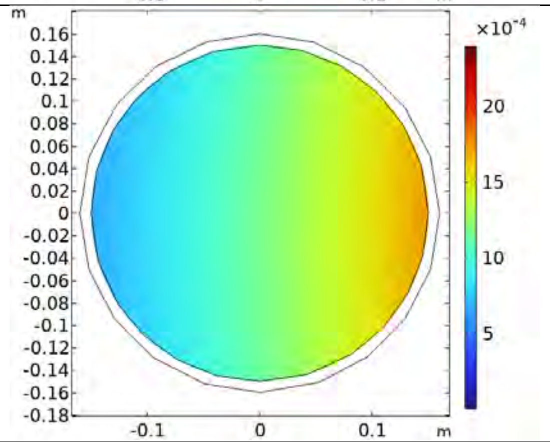
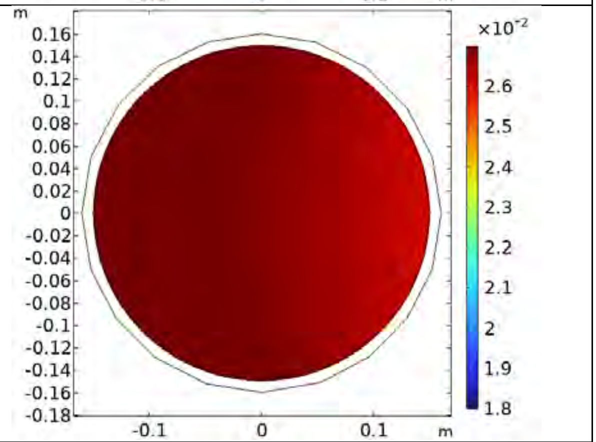
	Radial velocity	Axial velocity
At defect		
0.5m from defect		

Figure 4: The radial and axial acoustic velocities close to the defect in a 300mm diameter cast iron pipe. Source frequency 65Hz.

Effect of robot on measurements

The proposed deployment technique to measure the acoustic velocity vector is to mount triaxial accelerometers on a 'halo' attached to a crawler robot (see figures 1. & 2. of the Overview Report). Adding such a robot to the pipe will inevitably change the acoustic field the very robot is deployed to measure. Accordingly, the Comsol model was modified to include such a robot in order to estimate the severity of the effect and to suggest recommendations to compensate for the presence of robot. The dimensions of the robot and halo were provided by Synthotech. The robot's body was assumed to be steel. The halo's material was assumed to be PVC. This model was used to evaluate the effect of the robot the presence and absence of a defect as illustrated in Figure 5. The defect was simulated with its centre at 0 degrees (crown of the pipe). It was a sphere of 95% of the radius of the pipe, cut into the pipe by 2/3 of the pipe thickness. The simulation was performed for a tonal signal at 65 and 130 Hz.

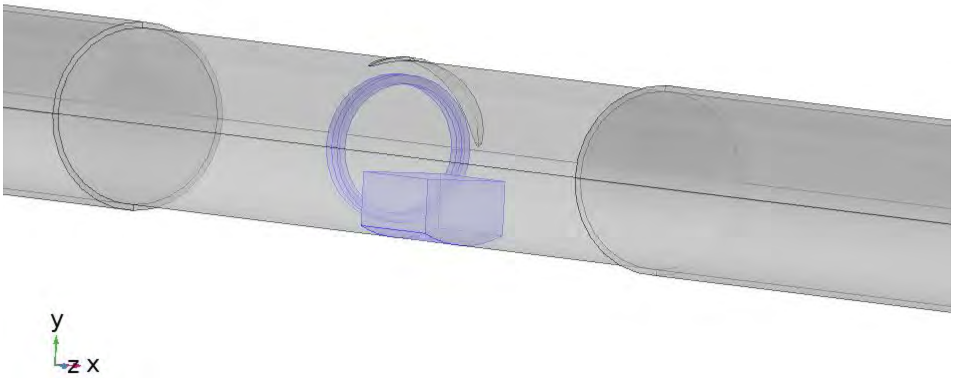


Figure 5: An acoustic Comsol model of a robot with a halo and defect in a 300 mm cast iron pipe.

The absolute values of the radial and axial acoustic velocities were predicted for the case where there was and was not a robot with a sensor halo in the pipe (see Figure 5), and in the cases where there was and was not the defect in combinations. The receiver points were placed around the circumference of the halo at 5 degree intervals with 0 degrees corresponding to the crown of the pipe. The amplitudes of the axial, v_z, and radial, v_r, components of the acoustic velocity were plotted as a polar diagram in Figures 6-8. The acoustic effect of inserting a robot in a pipe without any defects is shown in Figure 6. The effect of an internal wall pitting defect on the acoustic velocity in the pipe without the robot is shown in Figure 7. The effect of the robot on the acoustic velocity in the presence of the pitting defect is shown in Figure 8.

The results presented in Figure 6 illustrate that the robot has a significant impact on both the radial and axial components of the acoustic velocities. In the absence of the robot the radial component of the acoustic velocity is relatively small whereas its axial component is relatively large as expected from the simulation the results of which are also shown in Figures 2-4. The two velocity components are independent of the angle read from the crown of the pipe. When the robot is introduced, this symmetry is broken and there is some oscillation in the velocity components as a function of the angle. The presence of the robot causes a considerable increase in the amplitude of the radial component of the acoustic velocity and decrease in the amplitude of its axial component. Conversely, without a robot the fluid is free to move in the z-direction, and the presence of a robot significantly reduces this because of a large contrast between the sound speed and densities in water and steel.

In the presence of the defect and absence of the robot the radial component of the acoustic velocity increases significantly as illustrated in Figure 7. The effect of the defect on the axial component is relatively small as expected from the results also presented in Figures 2-4. The presence of the robot changes considerably the behaviour of the two acoustic velocity components scattered by the defect as shown in Figure 8. The axial component remains relatively insensitive to the presence of the defect, but it now becomes angle-dependent as illustrated in Figure 8. The radial component is sensitive to the presence of the defect, but its behaviour is very different to that predicted for the case when the robot was absent (compare Figure 7 against Figure 8). There is a significant change in the direction of the maximum in the polar diagram for the radial component due to increased scattering from the robot's body. This maximum shifts from 180 degrees (without the robot, Figure 7) to 90 degrees (with the robot, Figure 8).

The same simulation was repeated for 130 Hz to understand the effect of the source frequency on the behaviour of the acoustic velocity around the halo in the presence of the robot and pipe defect. A significant increase in the complexity of the halo oscillation was observed as demonstrated with the polar diagram in Figure 9. For this frequency the axial and radial velocity components are sensitive to the presence of the defect, but their behaviour is very complex. In general, there is some increase in the amplitude of the two components at particular set of angles when the defect is present (see Figure 9). Some of this complex behaviour can be explained by the vibration of the halo the amplitude of which becomes more pronounced as the frequency of sound increases.

A modal analysis of halo vibration was carried out using Comsol in the frequency range between 1 and 1000 Hz. The material of the halo was initially set to PVC and then change to steel. The results from this analysis are shown in

Table 1. These results suggest that there are multiple resonances in the halo that frequencies are close to the range adopted for the simulation and subsequent experiments. In the case of PVC halo the lowest frequency was 72 Hz. In the case of the steel halo the lowest frequency was 303 Hz.

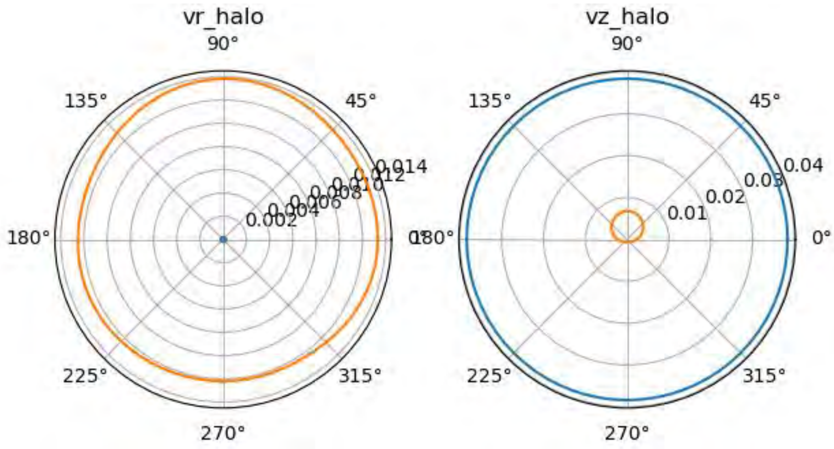


Figure 6: Effect of robot on axial (z) and radial velocity in absense of defect. Orange: with robot, blue: without robot. Velocity in m/s. Source frequency: 65Hz.

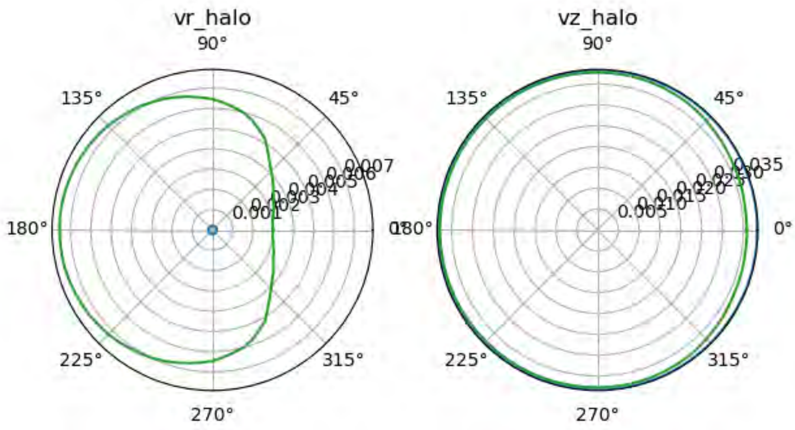


Figure 7: The effect of the defect on the acoustic velocity in the absence of the robot in the pipe. Blue: without defect, green: with defect. Velocity in m/s. Source frequency: 65Hz.

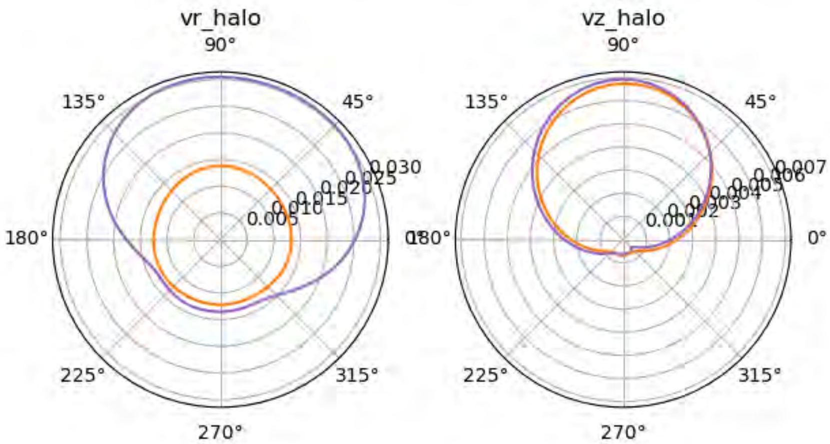


Figure 8: The effect of the defect on the acoustic velocity in the presence of the robot in the pipe. Orange: without defect, purple: with defect. Velocity in m/s. Source frequency: 65Hz.

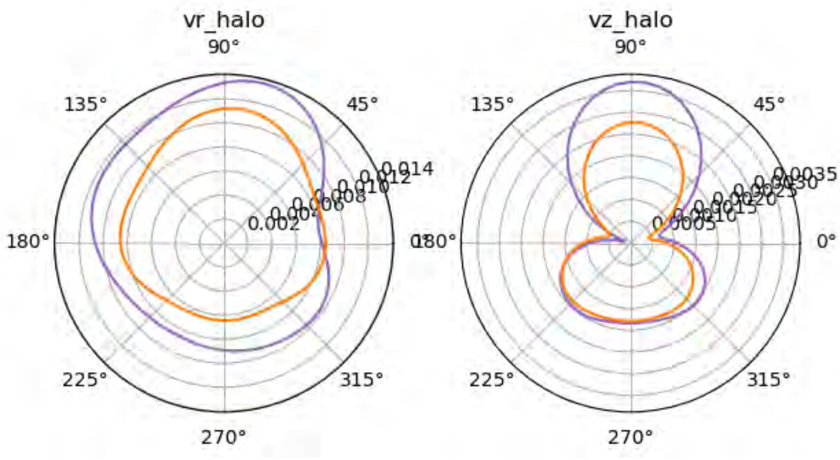


Figure 9: The effect of the defect on the acoustic velocity in the presence of the robot in the pipe. Orange: without defect, purple: with defect. Velocity in m/s. Source frequency: 130Hz.

Table 1: The first few modal frequencies for the sensor halo made of steel and PVC.

	Mode frequency (Hz)								
Steel	302.89	367.78	739.93	811.22					
PVC	72.222	77.24	185.07	206.25	361.25	443.69	574.65	770.56	827.68

Experimental investigations of defects in pipe

In order to validate the Comsol simulations experiments were carried out on an exhumed section of ductile iron pipe provided by Thames Water. This was a 2m long, 300mm diameter ex-rising main displaying clear signs of abrasive wear along its bottom edge, it is shown (upside down, as used for testing) in **Error! Reference source not found.**. The pipe was placed in a PVC container that was filled with water. An underwater speaker was installed at one end of the pipe.

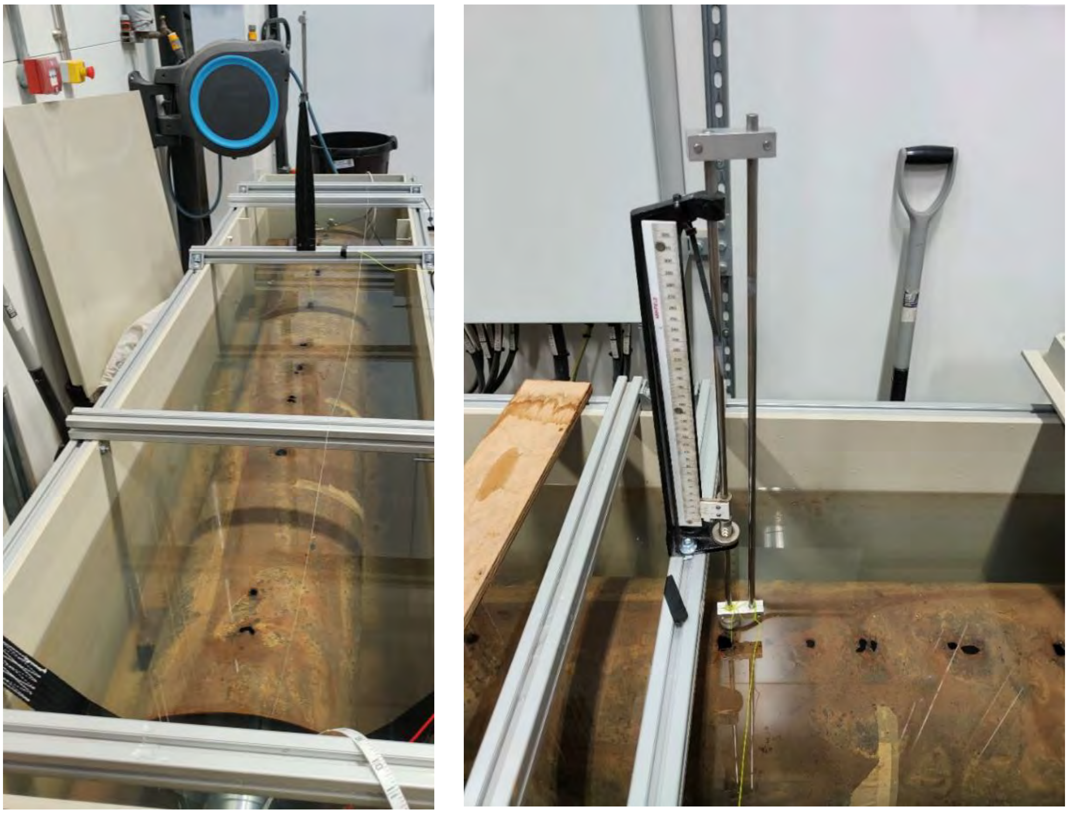


Figure 10: The rising main section used for testing the new sensing method. Lef: full pipe length, with speaker visible in foreground. Right: deployment method for sensor.

A triaxial accelerometer shown in **Error! Reference source not found.** was inserted into the pipe by suspending it through a hole in the crest of the pipe. The frequency of tonal sound was set to 65 Hz. The acoustic pressure was approximately 30 Pa. In order to investigate whether it could detect regions of abraded material measurements were taken at 75mm from the top of the perforated pipe section, middle and at 75mm from the bottom of the undamaged pipe section. This measurement was repeated several times for three different perforations in the pipe approximately 25 mm in size (see Figure 10).

Figure 11: Triaxial accelerometer. York G-Link-200.

As an initial check of the accuracy of the sensor, the acceleration recorded with the sensor was compared with the pressure recorded by a hydrophone. It is expected that the pressure is related to the velocity of a fluid by the relation $v = \frac{p}{Z}$ where Z = 1.48 MPa s/m for water, and the acceleration component j recorded in the time domain can be converted to velocity by moving to the frequency domain and dividing by $2\pi f$, where f is the frequency, i.e. $a_j(\omega) = 2\pi f v_j\,(\omega)$. A plot of this data is shown in Figure 12, where it can be seen the pressure is approximately 30Pa, so the expected velocity is $2x10^{-5}$m/s. Converting this to acceleration, the expected acceleration is 0.066m/s^2=0.0067g, which is of the same order of magnitude as the acceleration recorded.

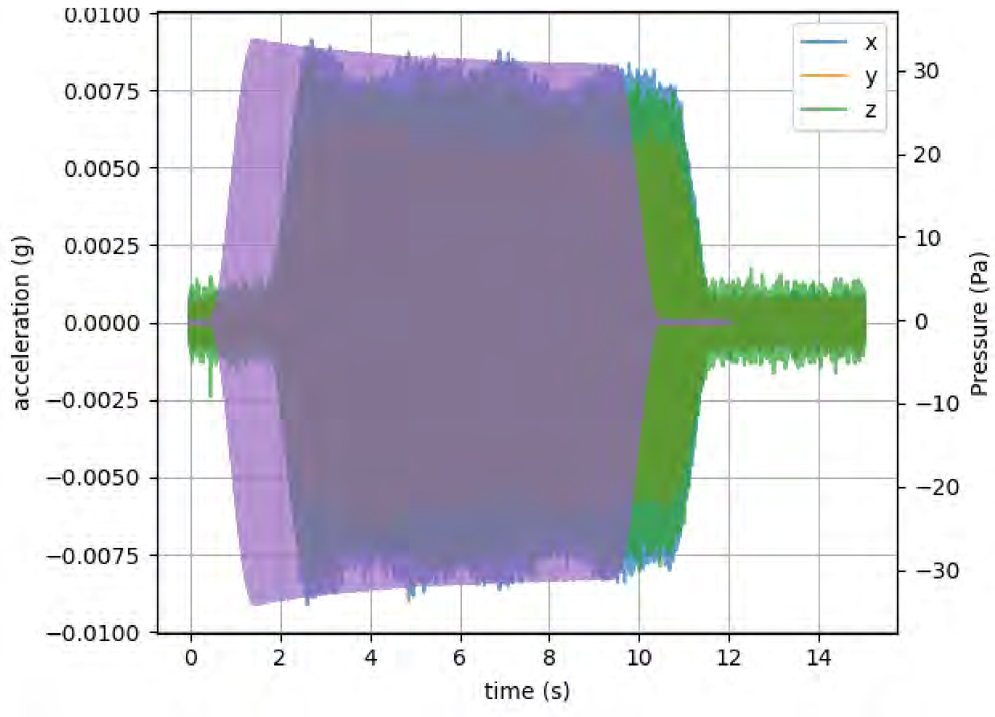


Figure 12: Comparison of the acceleration and pressure measured simultaneously, with the acceleration for each of the three axes plotted with respect to the left hand axis, and the pressure plotted with respect to the left hand axis. Source frequency: 65 Hz.

Due to the design of the accelerometer sensor used in the experiment, the accelerometer was able to rotate about its y (upwards) radial axis, making it difficult to determine which in direction the other two acceleration components x and z were pointing. However, running the measurements with the accelerometer constrained in the axial direction it was determined that the axial acceleration dominates the $x - z$ plane by an order of magnitude. As such the x and z components of the recorded acceleration were combined to form an estimate for the axial acceleration. The amplitude of the acoustic velocity recorded on the accelerometer was estimated by taking the absolute value of the Hilbert transform, $|H(v_j)|$.

The ratio of the radial to axial amplitudes of the acoustic velocity components for each of the three defects is shown in Figure 13 for several repeats at each location. It can be seen that while there is some variation between measurements at the same location there is also a clearly visible and consistent distinction between measurements close to and far away from a defect. For comparison, this ratio of the amplitudes of the axial to radial velocity components predicted with the model for the pipe with a similar defect was similar and equal to approximately 0.1.

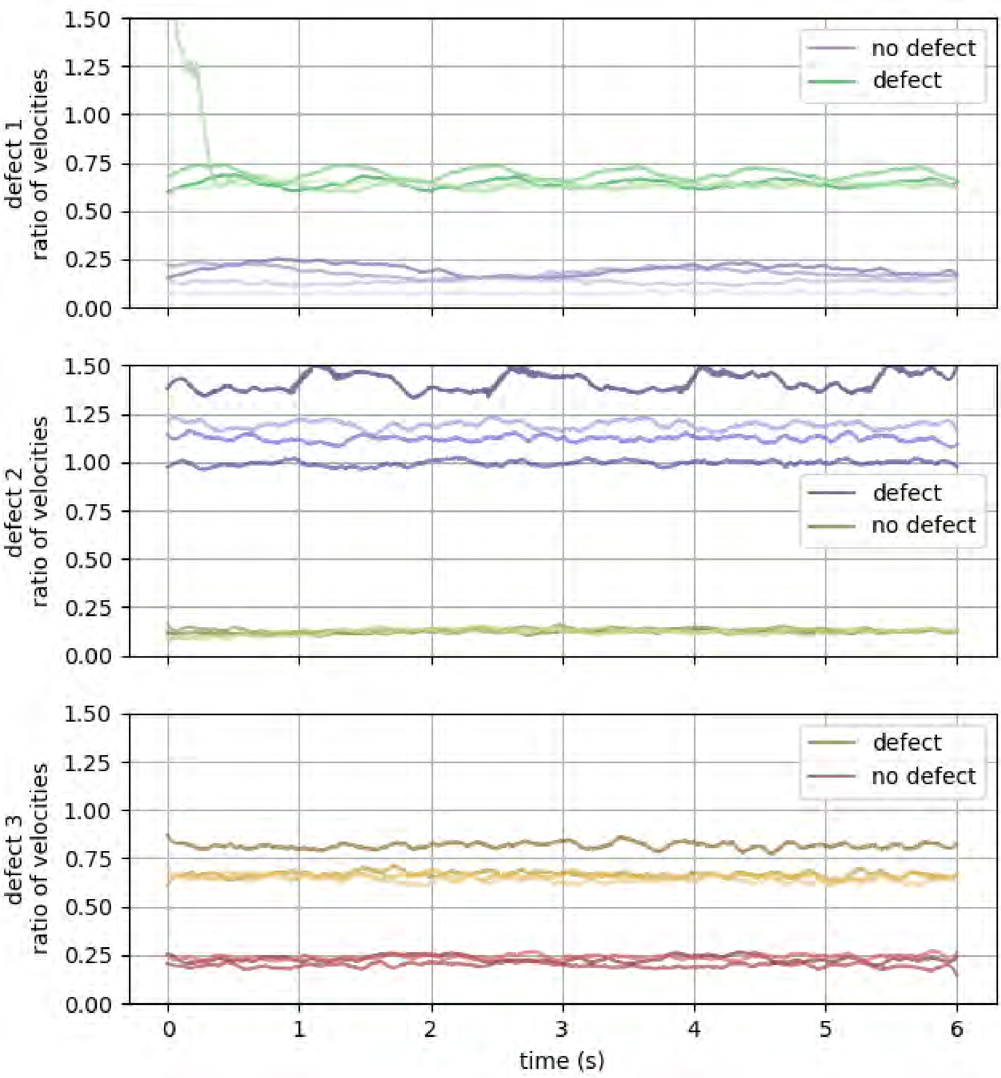


Figure 13: Ratio of radial to axial velocities for each of three positions, with and without a defect. The ratio was calculated by taking the envelope of each accelerometer direction's recording using the Hilbert transform, $H(x)$, and combining the x and z axes, such that the ratio is given by: $\frac{|H(v_y)|}{|v_{xz}|} = \frac{H(v_y)}{\sqrt{|H(v_x)|^2 + |H(v_y)|^2}}$. Source frequency: 65Hz.

Figure 14 demonstrates the influence of the defect on the behaviour of the axial and radial components of the acoustic acceleration with the $a_r = f(a_z)$ graphs, $\dot{v}_j = a_j$. This figure presents three graphs taken with the sensor being in the vicinity of a perforation, in the middle of the pipe and at the opposite wall of the pipe that was undamaged.

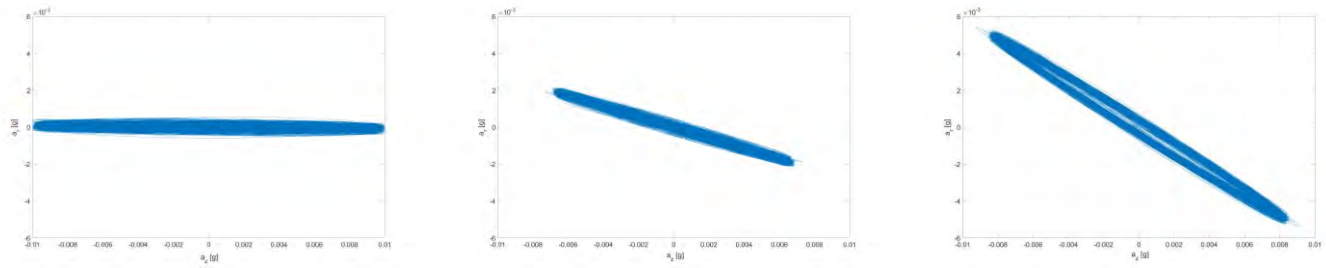


Figure 14: The relative behaviour of the acoustic acceleration measured in the radial, a_z, and axial, a_r, direction in the 300 mm ductile iron pipe. Left: near the undamaged pipe wall. Middle: in the middle of the pipe cross-section. Right: near a wall perforation. Source frequency: 65 Hz.

Conclusions

The results of an acoustic simulation performed using Comsol Multiphysics suggest that the radial component of the acoustic velocity is highly sensitive to internal and external wall damage even if it is measured at a frequency with the wavelength that is much greater than the pipe diameter and characteristic damage dimension. In this way a structural damage, wall corrosion and perforations can be detected with a suitable sensor that can measure the sound pressure gradient in a continuous sine wave excited in a pipe. This sensor can be an array of potted accelerometers plus a speaker adapted to work underwater. On the contrary, the acoustic pressure and axial component of the acoustic velocity are not very sensitive to the presence of damage. Further simulations with Comsol suggest that the effect of the robot's body on the quality of acoustic velocity data can be significant. The robot causes a noticeable distortion of the acoustic velocity field that can mask the effect of wall damage. Further, the vibration resonance in the halo accelerometer array can also affect the measured acoustic velocity components. These findings suggest the need to minimise the effects of the robot body and accelerometer array halo on the measured radial component of the acoustic velocity.

The results of a laboratory experiment on an exhumed section of a ductile iron pipe in the absence of a robot suggest that the proposed method is sensitive to the presence of a small pipe perforations. This experiment was carried out using a relatively low frequency of sound, e.g. 65 Hz at which the wavelength was significantly greater than the diameter of the pipe and the size of the defect, i.e. $\lambda \approx 23$ m vs 0.3 m pipe diameter and 0.025 m diameter of perforation. A relatively simple method to detect a wall loss is to measure the ratio of the amplitude of the radial to axial acoustic velocity components. A substantial increase in this ratio was observed when the sensor was in the vicinity of the defect, e.g. 75 mm from it. This ratio remained relatively constant and small (e.g. below 10%) when the sensor was near the undamaged wall section of the pipe.

See further technical background for finding defects with radial and axial acoustic velocity components in Appendix 1.

Appendix 1.

Finding defects with radial and axial acoustic velocity components

Finding defects with radial and axial acoustic velocity components

Basic acoustics

We define sound pressure of a harmonic sound wave as

$$p(x,t) = \tilde{p}(\omega)e^{ikx-i\omega t} \quad \text{[Pa]}$$

angular frequency

wavenumber

$$i = \sqrt{-1}$$

$p(t) \Rightarrow$ Fourier transform

time

$\tilde{p}(\omega) = \int_{-\infty}^{\infty} p(t) e^{-i\omega t} dt$

$i = \sqrt{-1}$

ω - freq.

$k = \frac{\omega}{c}$ ← sound speed

measure with microphone or hydrophone

Basic acoustics

We define wavenumber as

$$k = \frac{\omega}{c(\omega)} \qquad [1/\mathrm{m}]$$

sound speed

It is a complex quantity

$$k(\omega) = k_{\mathrm{Re}}(\omega) + i k_{\mathrm{Im}}(\omega)$$

how fast sound propagates

how fast sound attenuates

$K = \frac{2\pi}{\lambda}$

$\uparrow$ wavelength

$\uparrow$ slower travel

$\uparrow$ → faster attenuate

Basic acoustics

$\bar{u} \sim u_0 \cdot \cos(\omega \cdot t)$ (ampl.)

P_1 P_2 m_1 m_2 Δ x

We define the acoustic (particle) velocity as

is not the speed of sound!

$$\mathbf{u} = \frac{1}{i\omega\rho_0}\frac{\partial p}{\partial \mathbf{n}} \quad \text{[m/s]}$$

$$\frac{\partial p}{\partial x} \approx \frac{p_2 - p_1}{\Delta}, \quad \Delta \to 0$$

$\bar{u} = (u_x, u_y, u_z)$

density of fluid

density of fluid, $\rho_0 \approx 1\,T/m^3$

normal $\bar{n}$

$i = \sqrt{-1}$

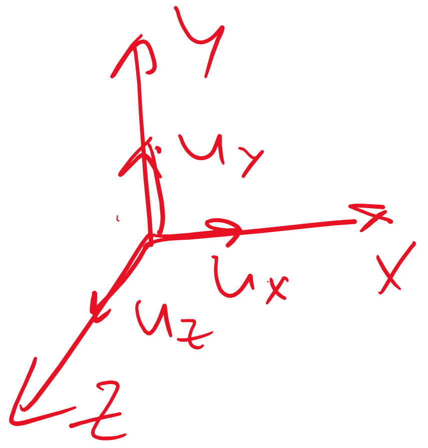
Basic acoustics

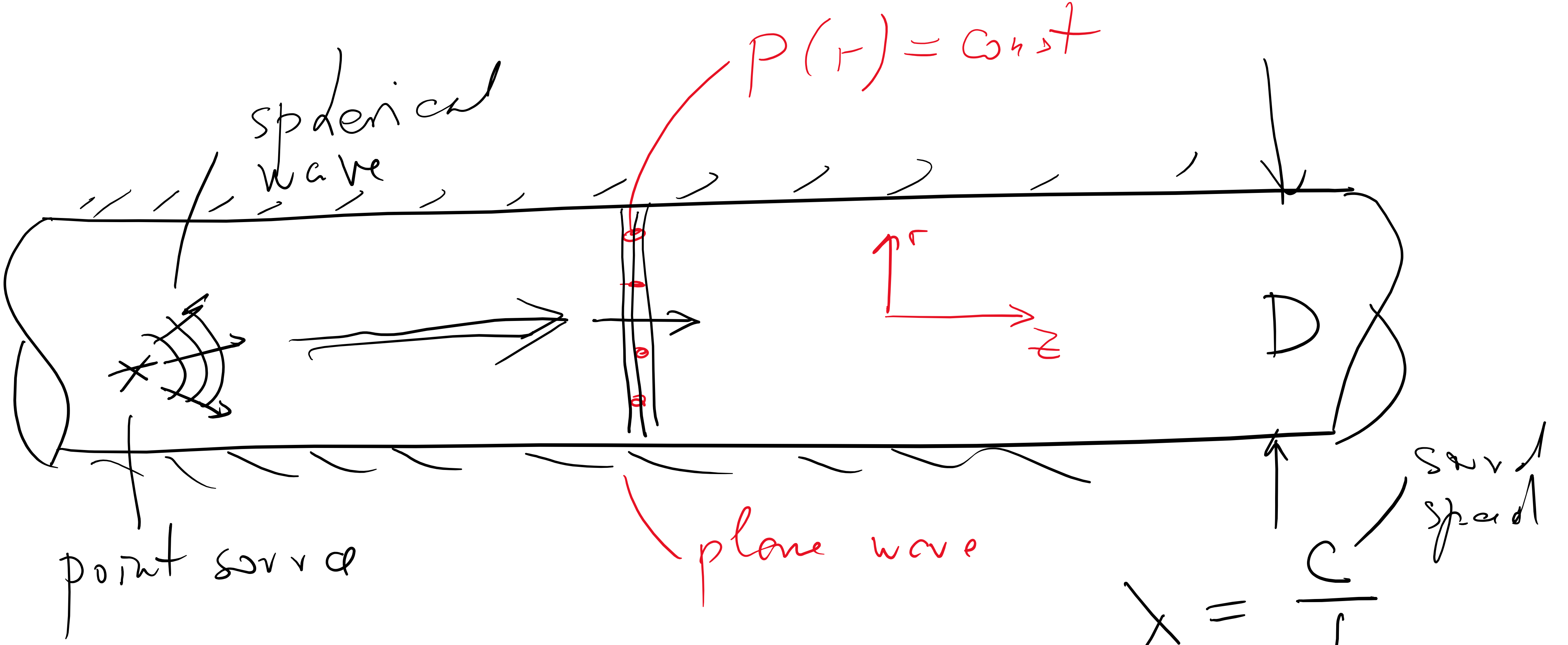
For a harmonic sound wave in an elastic medium the acoustic velocity is

$$u = \tilde{u}_0(\omega) e^{ikx - i\omega t}$$

amplitude
freq.-depend.

u_x
u_y
u_z





$\lambda = \frac{c}{f}$ ← freq. in Hz

$C_w = 1500\,m/s$

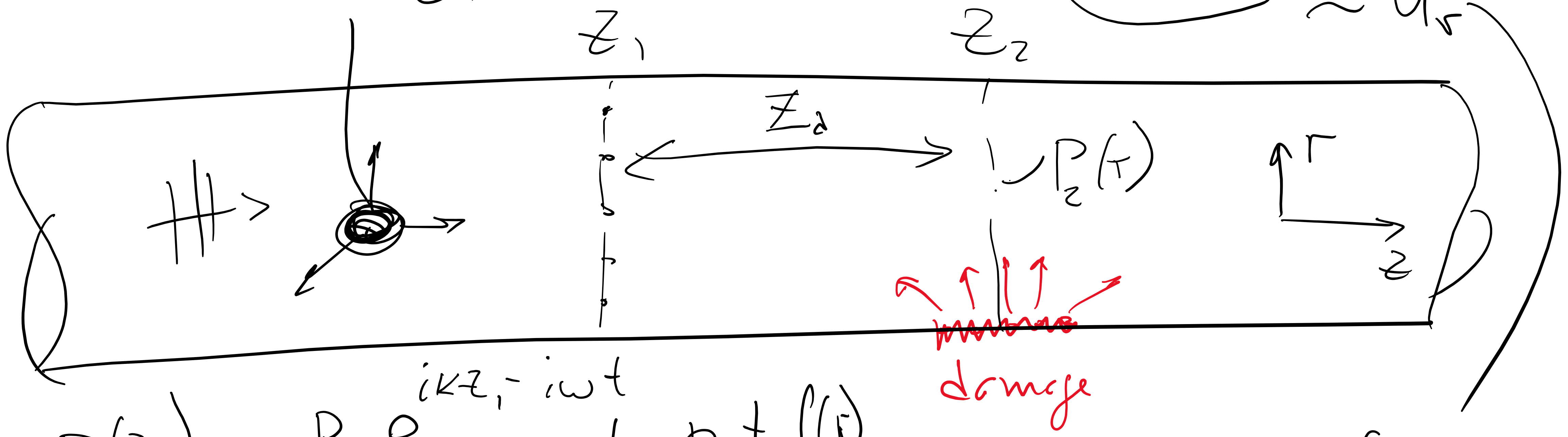
$f = 100\,Hz$ $\Rightarrow \lambda \sim 15\,m$ $\quad \lambda \gg D\ (300\,mm)$

$p(z) \sim e^{ikz}, \quad k = k_R + ik_I, \quad p(z) \sim e^{-k_I z}$ ↓

$$\frac{\partial P_2}{\partial r} \approx \frac{\partial P_s}{\partial r}, \quad \frac{\partial \bar{P}}{\partial r} \approx 0$$

relatively large $\sim U_r$

3-axial accel.



$$p(z_1) = P_1 e^{ikz_1 - i\omega t}$$ const, $p_1 \neq f(r)$

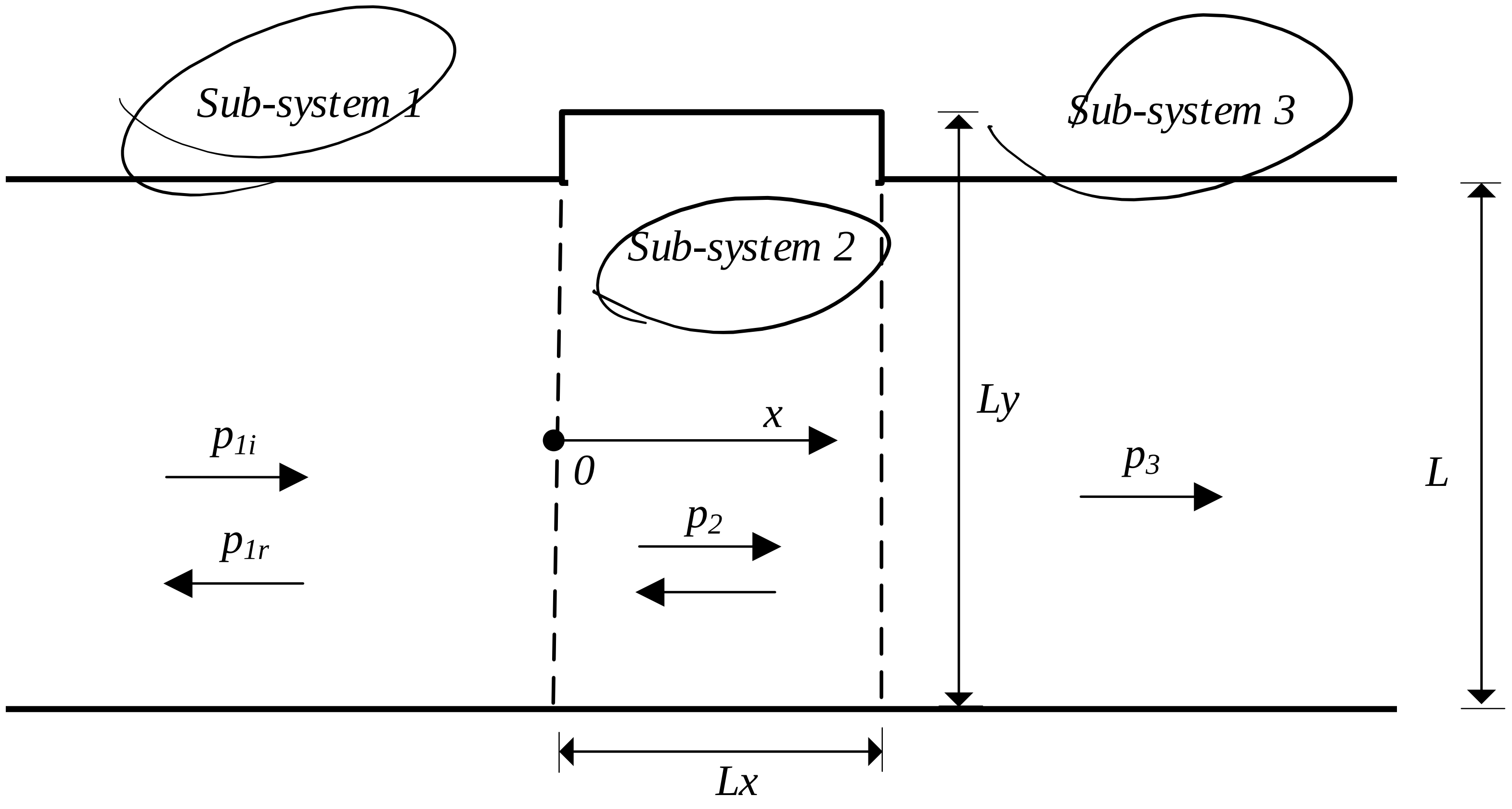
$$p(z_2) = P_2(r) e^{ikz_2 - i\omega t}$$

$P_2(r)$ – variable

$$p(z_2) = \bar{P} + P_s(z), \quad \bar{P} \approx P_1, \quad |P_s| \ll \bar{P}$$

can measure with accel.

Theory (1)



Theory (2)

reflection coefficient from excitation at mode (*m'*, *n'*) to reflection at mode (*m, n*):

$$r_{mn,m'n'} = -\delta_{mm'}\delta_{nn'} - 2i\boldsymbol{\chi}_{mn}(\mathbf{H} - k_0^2\boldsymbol{I})^{-1}\gamma_{m'n'}\boldsymbol{\chi}_{m'n'} \tag{1}$$

The transmission coefficient from excitation at mode (*m'*, *n'*) to transmission at mode (*m, n*):

$$t_{mn,m'n'} = -2idiag[(-1)^{l}]\boldsymbol{\chi}_{mn}(\mathbf{H} - k_0^2\boldsymbol{I})^{-1}\gamma_{m'n'}\boldsymbol{\chi}_{m'n'} \tag{2}$$

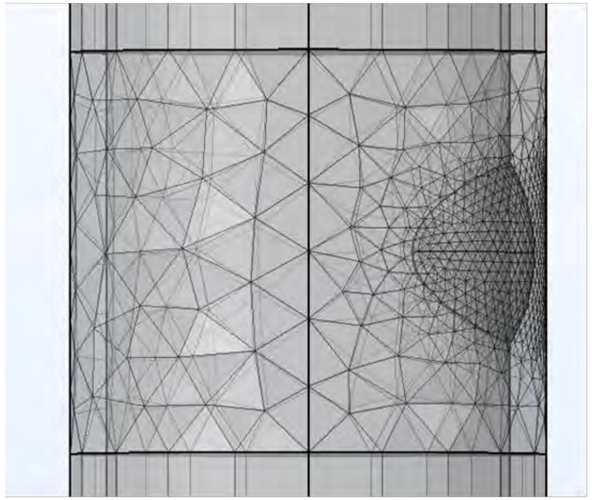
where $\mathbf{H}$ is the effective non-Hermitian Hamiltonian matrix,

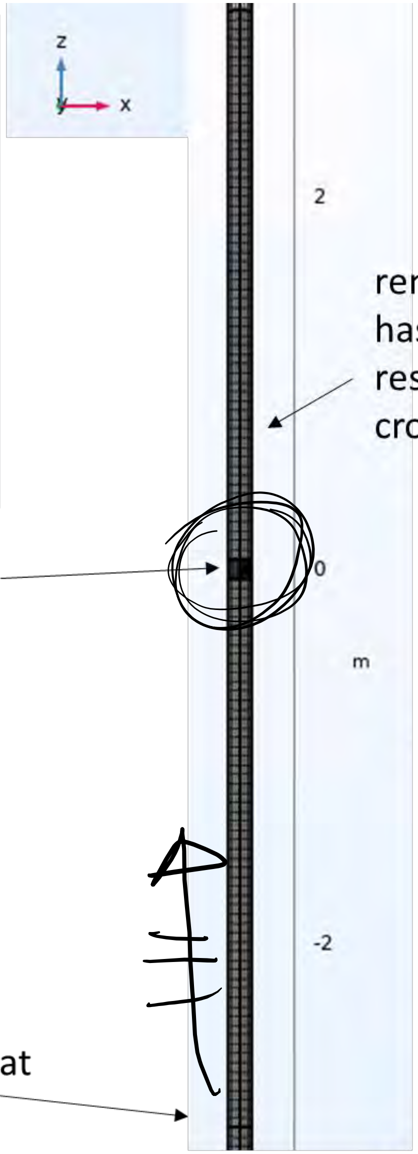
$$\mathbf{H} = diag\left[k_{\mu l}^2\right] - i\boldsymbol{\chi}diag[\boldsymbol{\gamma}]\boldsymbol{\chi}^{\mathcal{T}} - idiag\left[(-1)^{\boldsymbol{l}}\right]\boldsymbol{\chi}diag[\boldsymbol{\gamma}]\boldsymbol{\chi}^{\mathcal{T}}diag\left[(-1)^{\boldsymbol{l}}\right] \tag{3}$$

$\boldsymbol{\gamma}$ is the wavenumber of the waveguide at each mode, $\boldsymbol{\chi}_{mn}$ denotes the coupling between the waveguide and the cavity (subsystem 2) with $\chi_{\mu,mn} = \iint_S \frac{1}{\phi}\varphi_\mu(x,y)\Psi_{mn}(r,\theta)dS$.

From Eqs. (1)(2), the reflection and transmission coefficients can be calculated.

Model

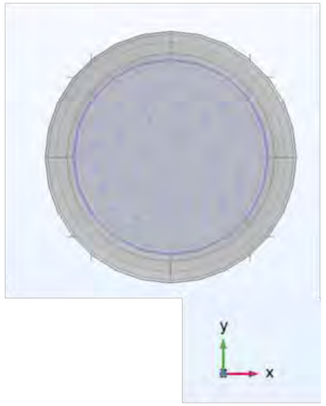




defect at 0.0m, surrounded by 0.11m of high density mesh.

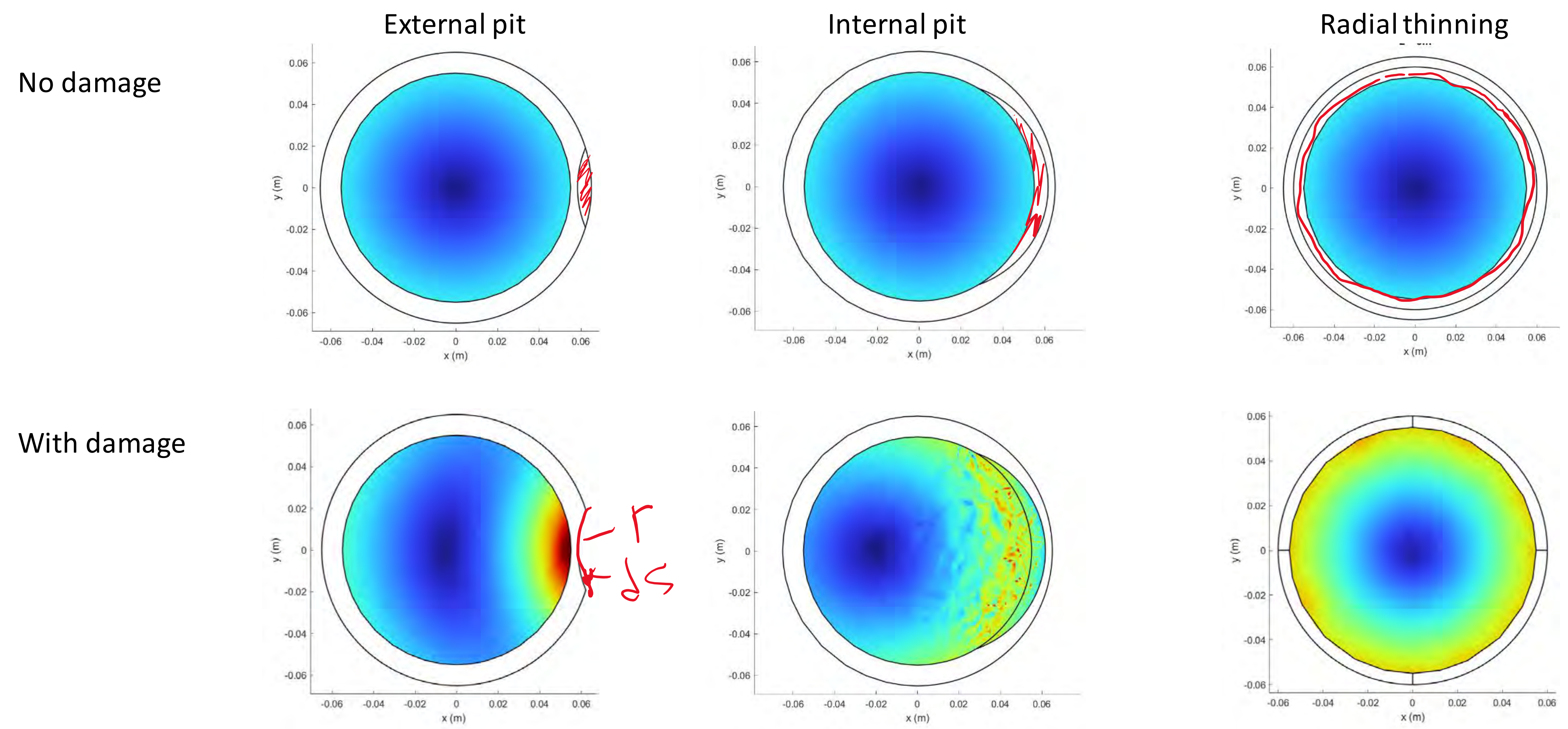
source at -3.0m

remainder of mesh has 0.05m axial resolution with cross section:

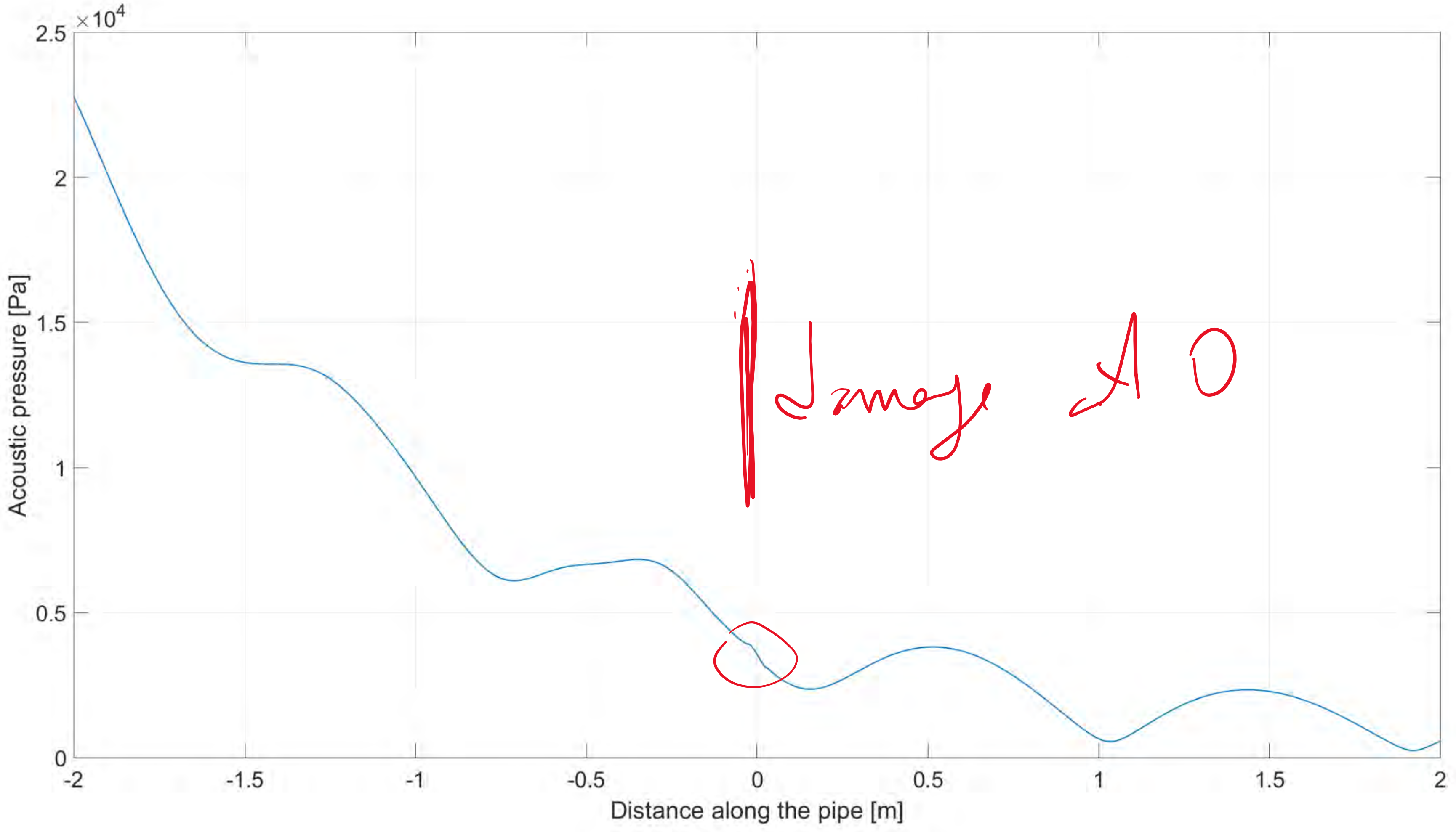


Predicted radial velocity

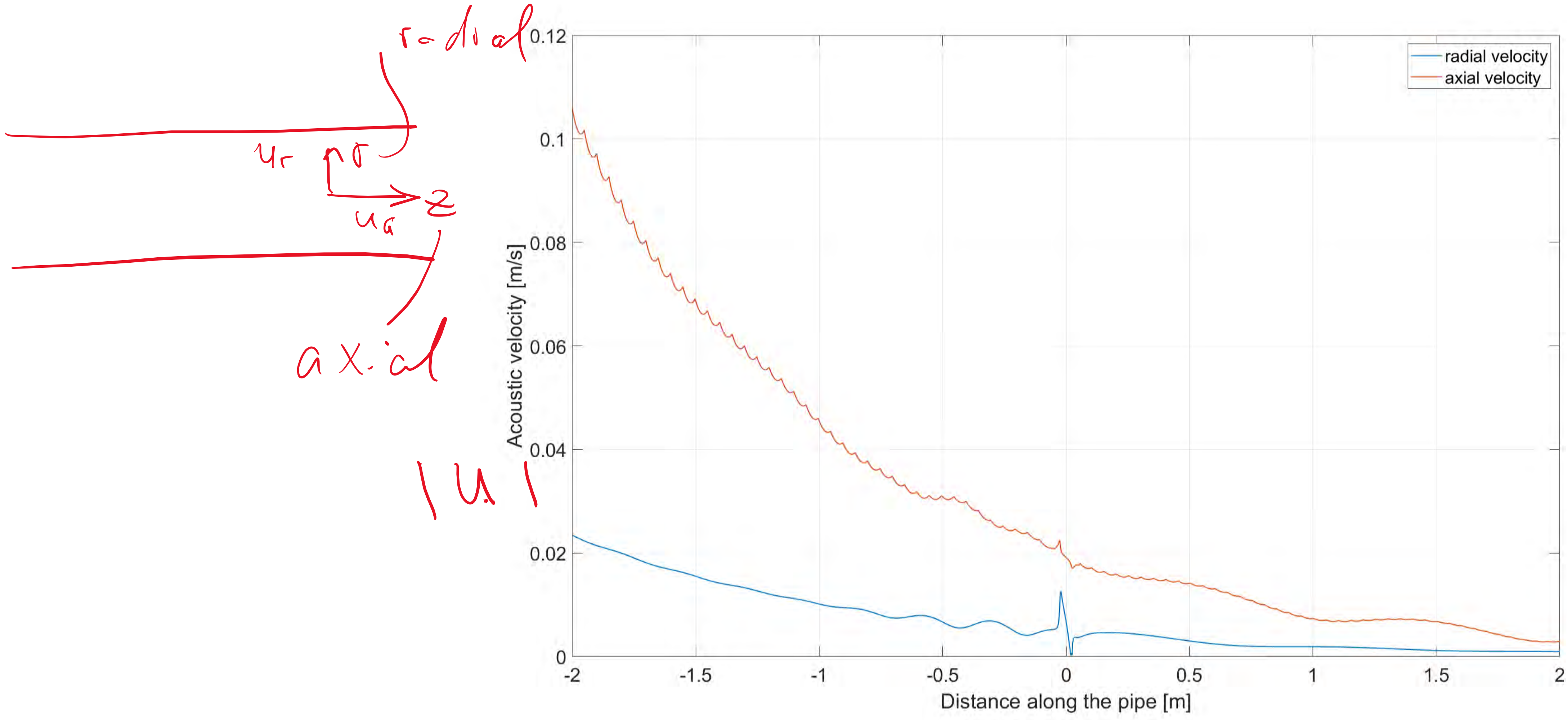
$$P_s \sim -\bar{P}\int_{\Gamma} \frac{\partial}{\partial n}\left(\frac{e^{ik|\bar{x}-\bar{x}_s|}}{k|\bar{x}-\bar{x}_s|}\right) ds$$



Model – pressure - amplitude



Model – fluid vibration velocity - amplitude

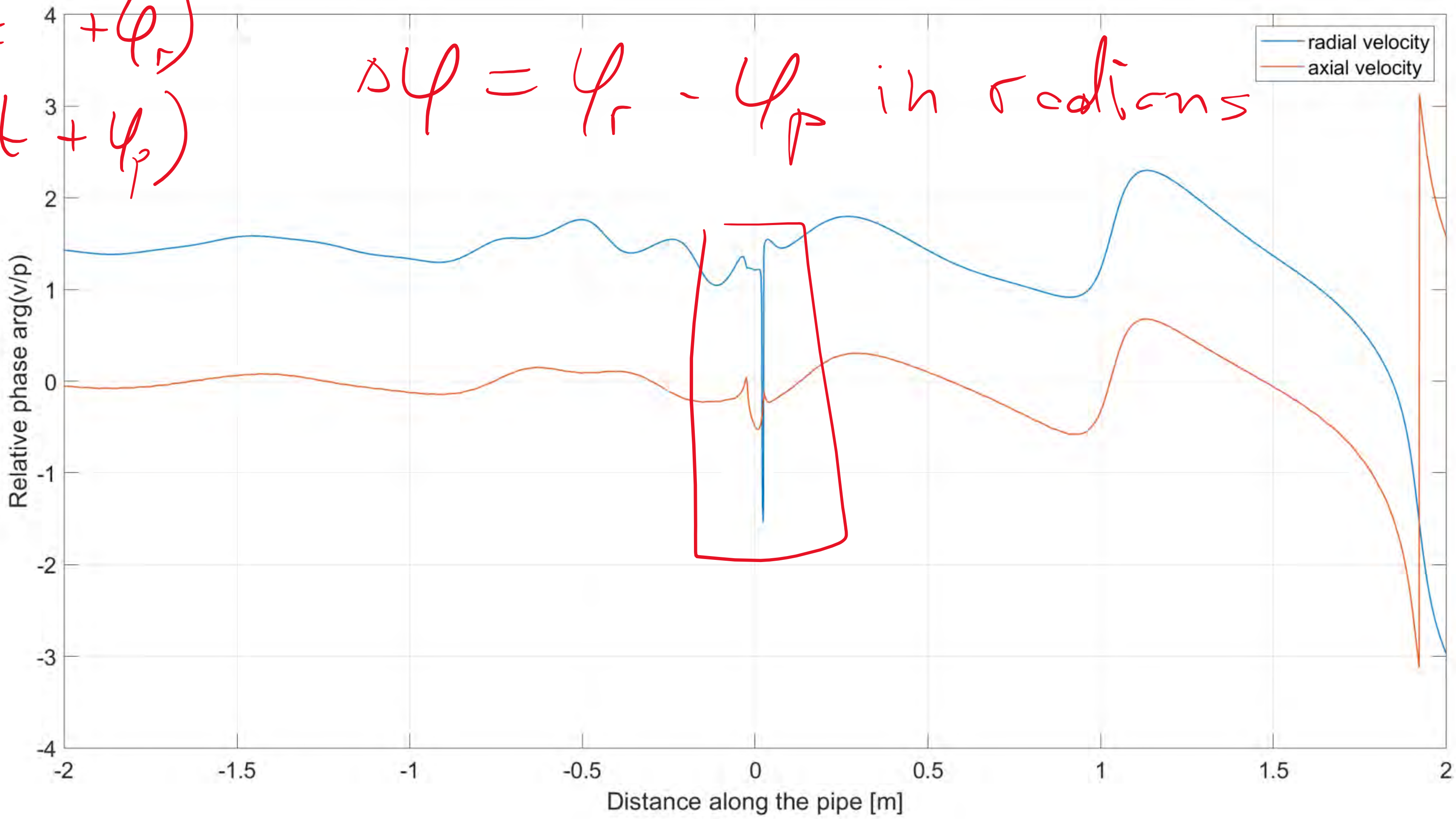


Model – fluid vibration velocity - phase

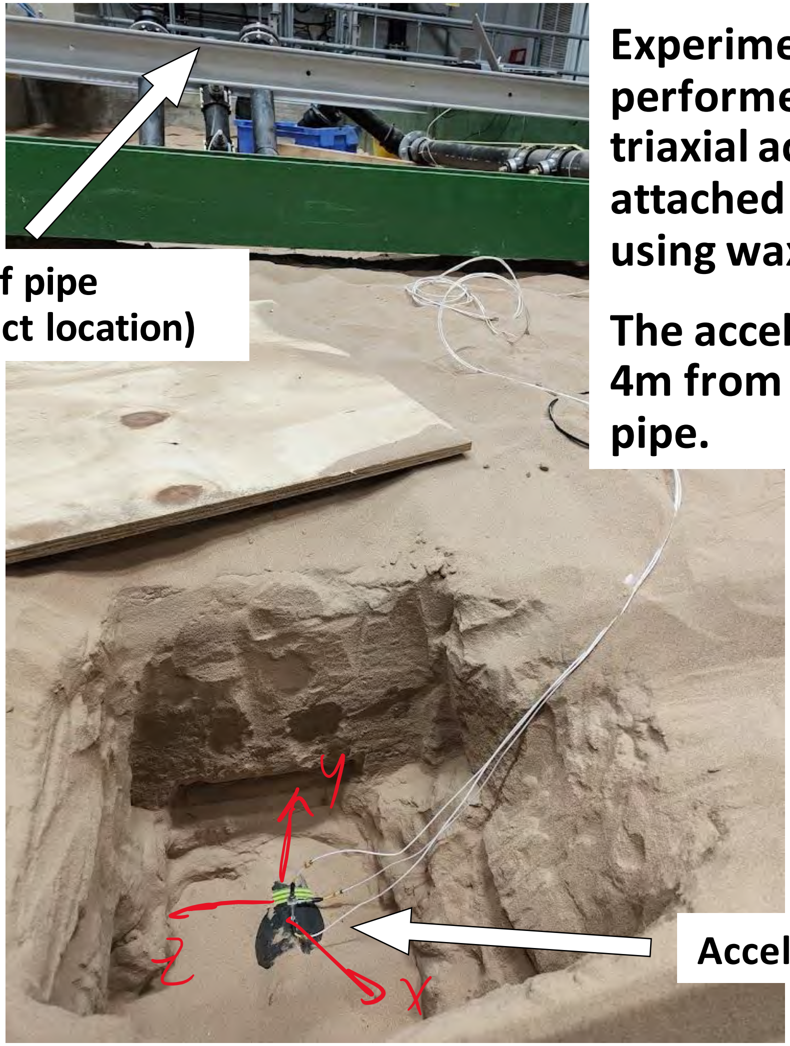
$u_r = |u_r| \cdot \cos(\omega t + \varphi_r)$

$p = |p| \cdot \cos(\omega t + \varphi_p)$

$\Delta\varphi = \varphi_r - \varphi_p$ in radians



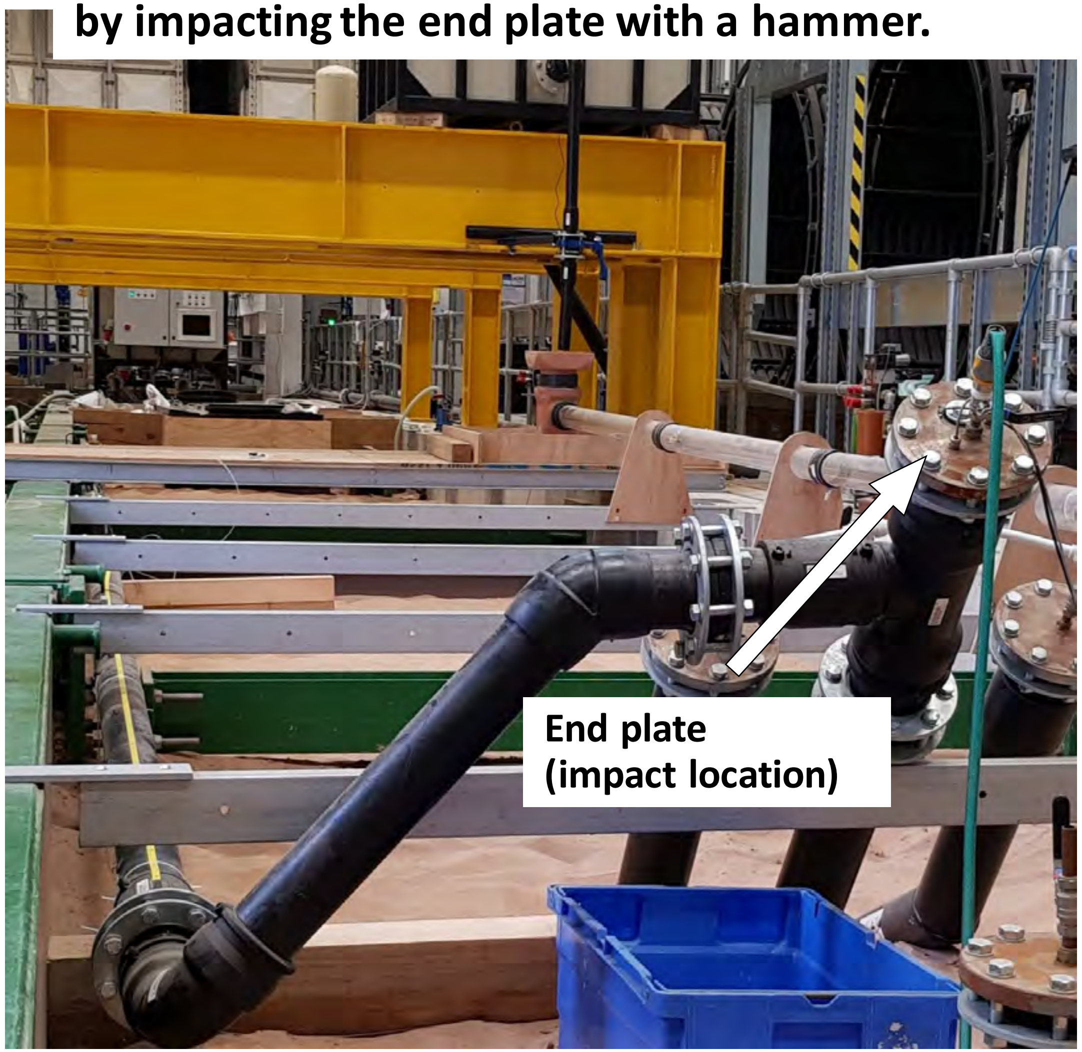
Experimental setup



Experiments were performed using a triaxial accelerometer attached to the pipe using wax.

The accelerometer is 4m from the end of the pipe.

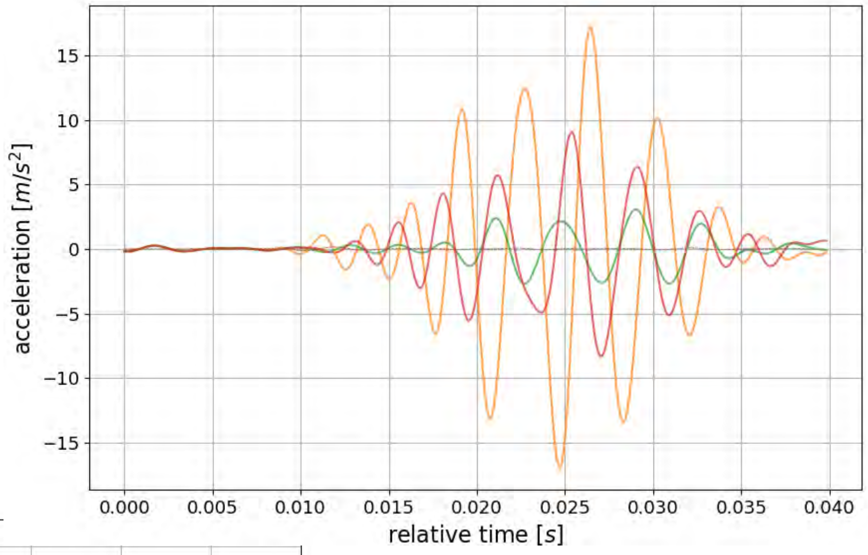
The pipe was pressurised using an elevated water tank to ~1bar, and a wave was excited in the pipe by impacting the end plate with a hammer.

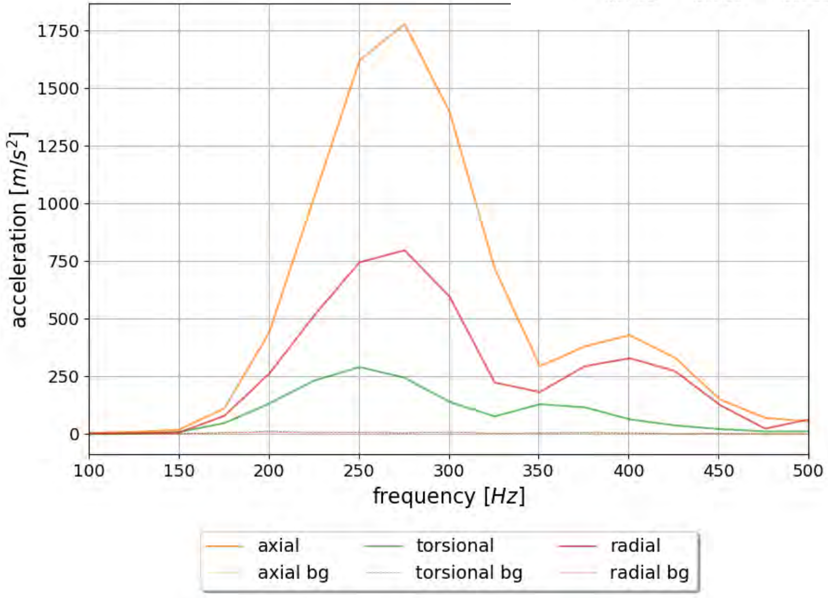


Experimental results

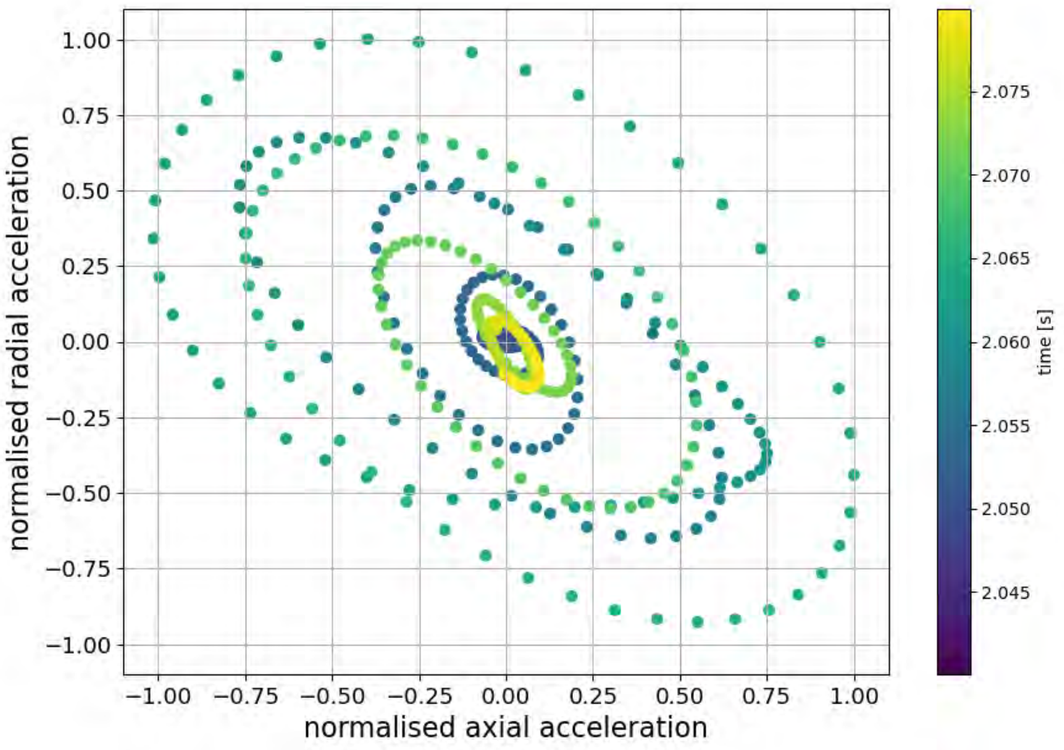
A conventional analysis would consider the time series and spectrum of the data.

Shown here filtered between 200 and 400Hz with a 4th order Butterworth filter.

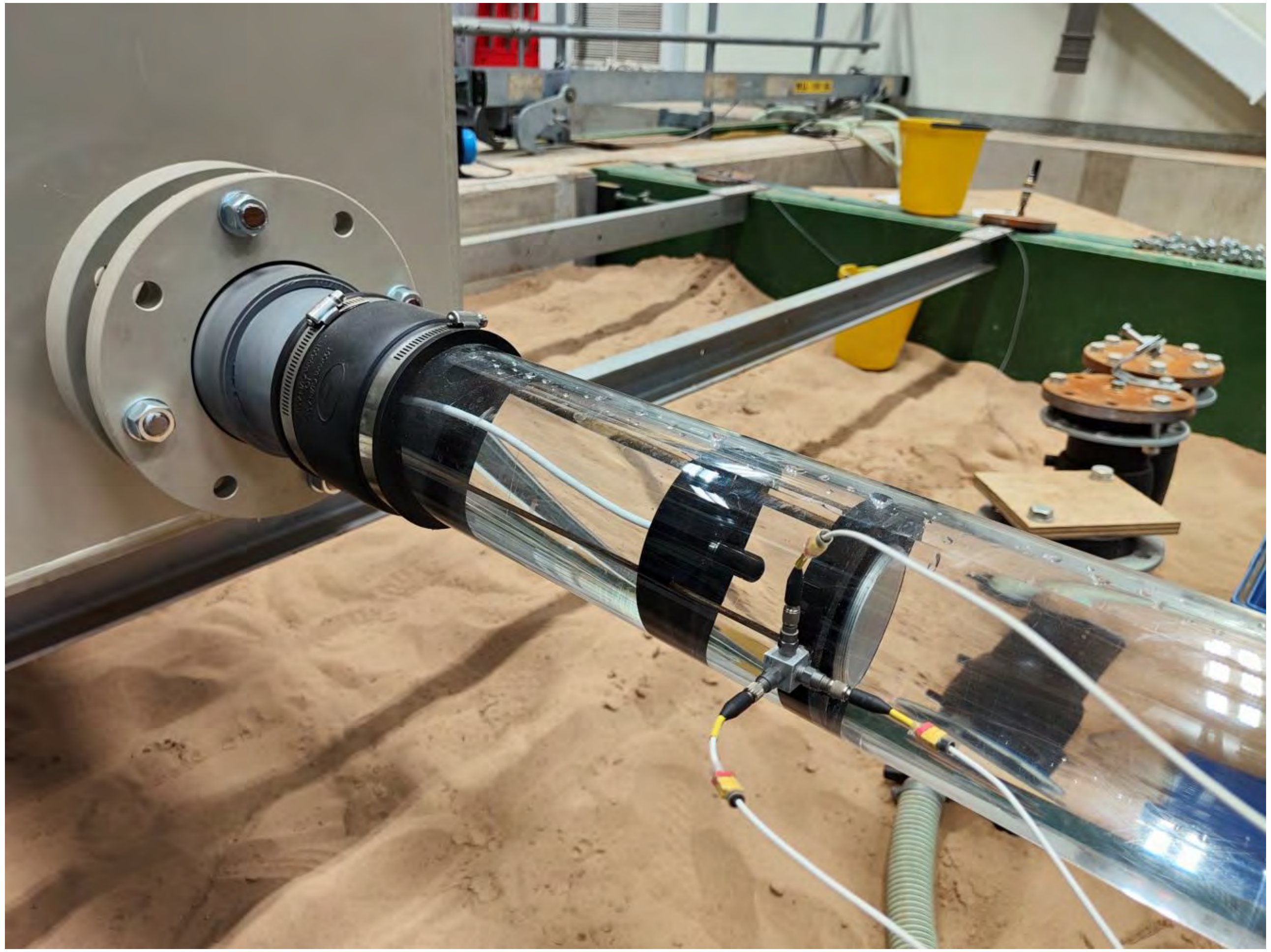




We are more interested in the relationship between the axial and radial components.



Future work (1)

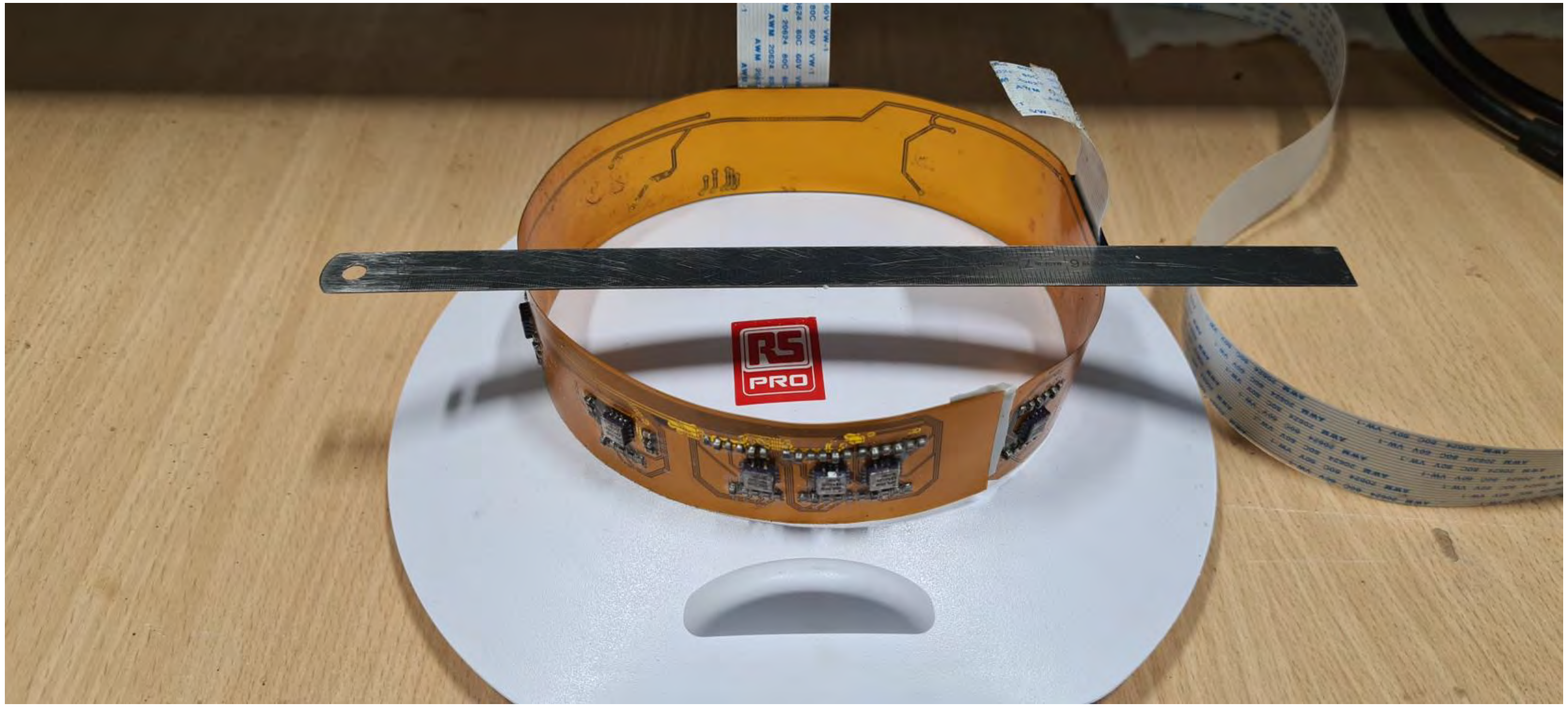


https://www.fido.tech/

Future work (2)

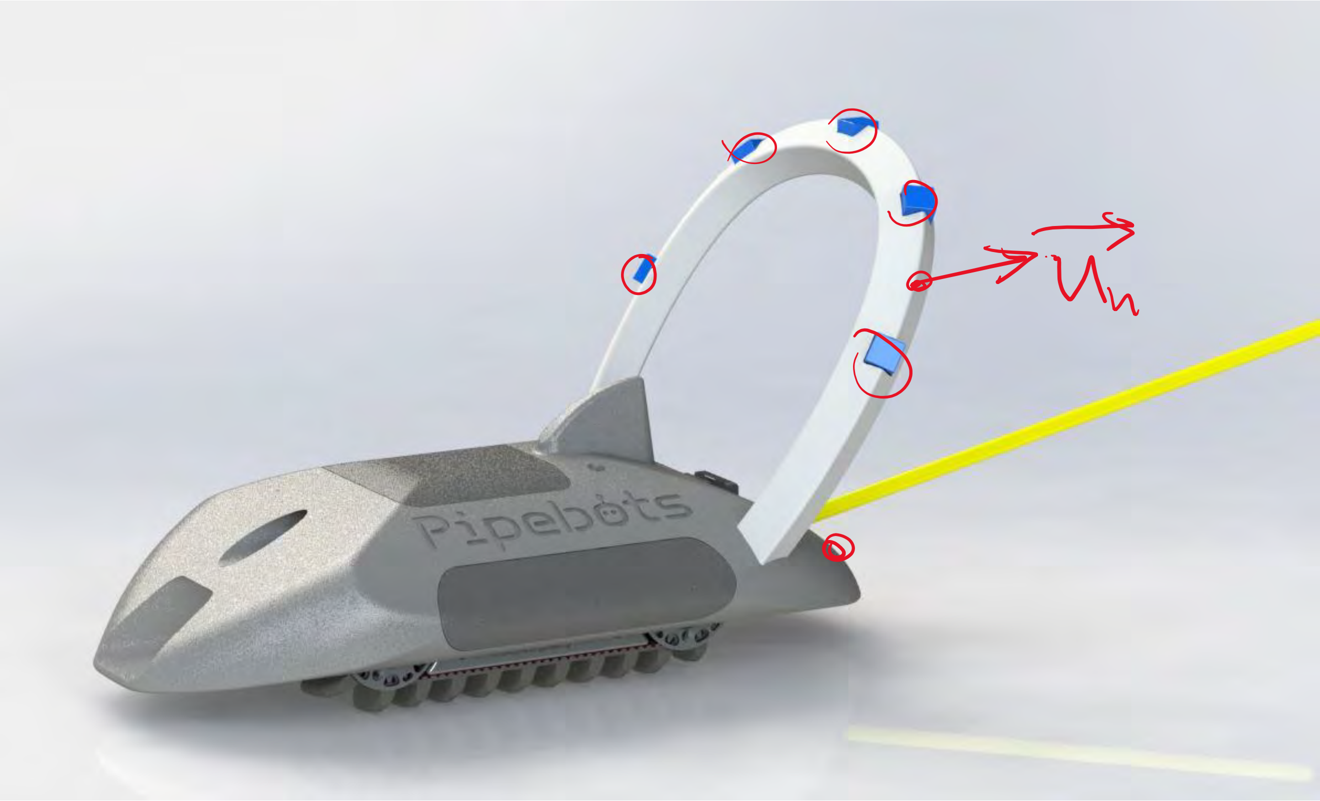
$\zeta_p \approx \zeta_w$!

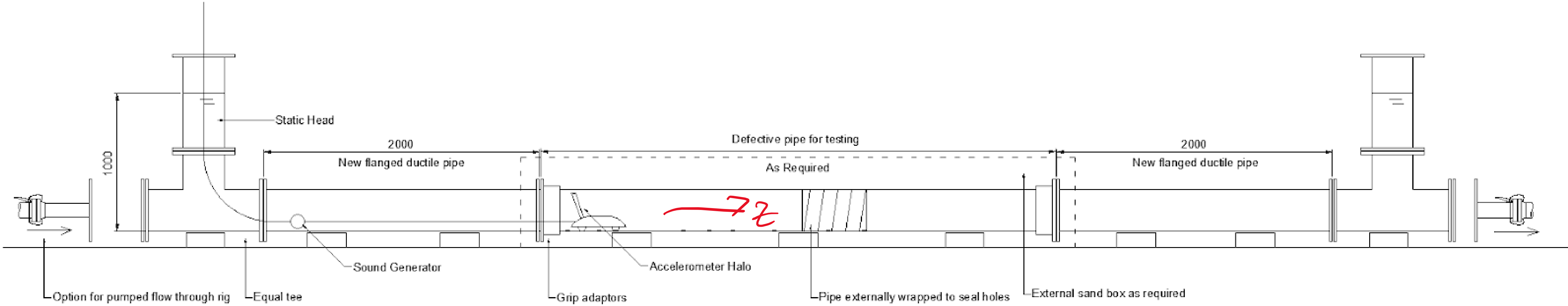
$\zeta = \rho_m \cdot c_m$, $\zeta_w \approx 1.5 \times 10^6 \ Pa \cdot s \cdot m^{-1}$



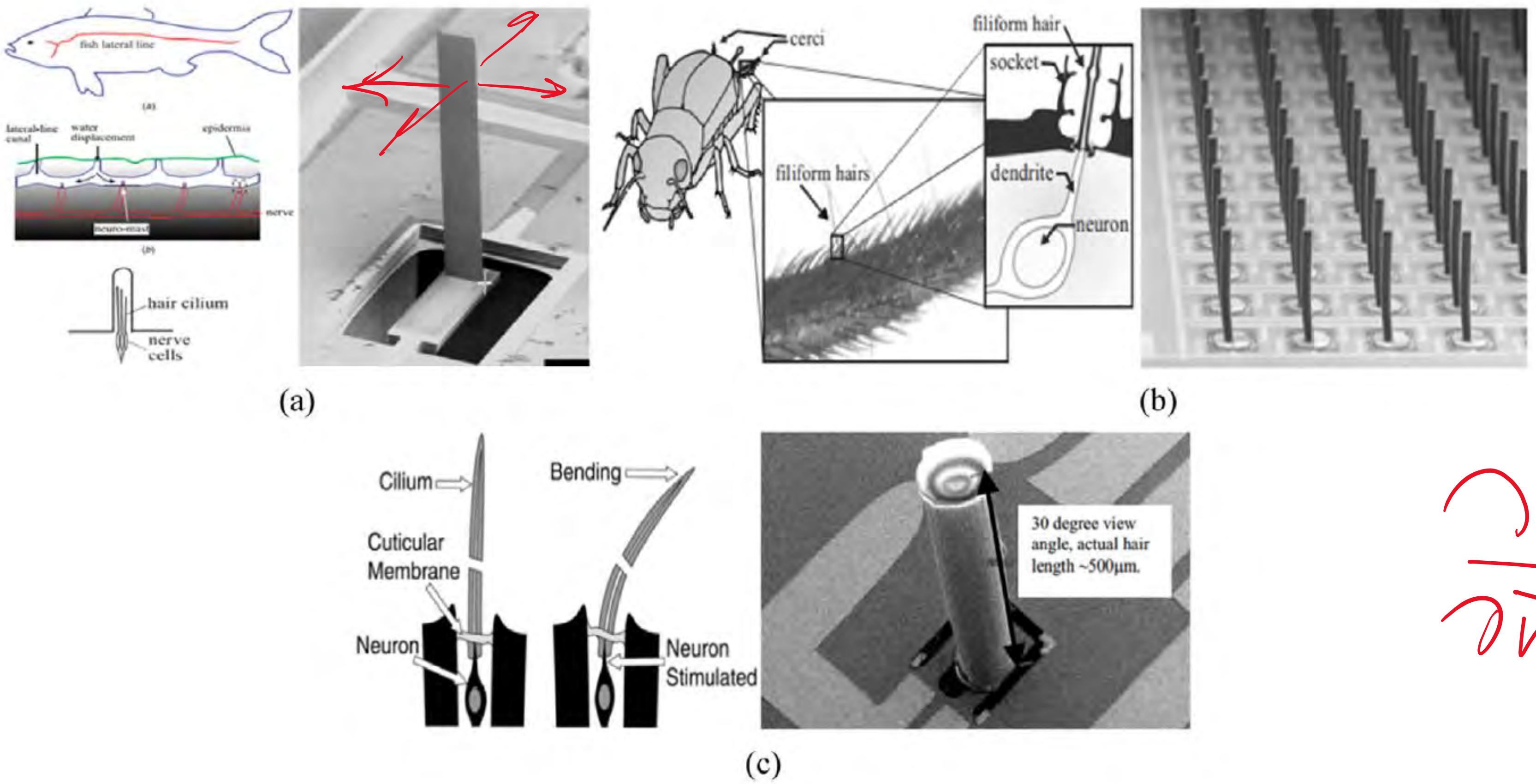
Future work (3)

$$u_r(z) = |u_r| e^{ikz + i\varphi}$$





Sensors - MEMS vector hydrophone



$$\frac{\partial p}{\partial n} \quad \frac{\partial^m p}{\partial^m n}$$

https://doi.org/10.1016/j.ymssp.2017.11.027

Appendix 11. D7 - End to End Process

Document Name:	L09 PipeBots in Rising Mains				
Document Number:	D7 – End-to-end Process			Revision:	1.1
Drawn By:	PS	Checked By:	MT	Issue Date:	20.10.23

L09 – PipeBots in Rising Mains

End-to-end Process / Operational Method Statement Overview

Deliverable – D7

Document Name:	L09 PipeBots in Rising Mains				
Document Number:	D7 – End-to-end Process			Revision:	1.1
Drawn By:	PS	Checked By:	MT	Issue Date:	20.10.23

1 Contents

2 Figures

3 Tables

1 Introduction and Process Overview

The purpose of this document is to outline what the operational process could look like. This aims to cover:

- Preparation upon site arrival,
- Access procedure for sewer rising main
- Operational use of the system and transient generator for data capture
- Egress from sewer rising main
- Options for sewer water purge and pre-sanitisation
- System removal, cleaning, sanitisation, and waste fluid management

The processes outlined in the document have been formulated based on several assumptions on the access point type, size of asset and current configuration of the system.

This document serves as a comprehensive resource detailing the current functionalities of the Proof-of-Concept (PoC) rising main inspection system in its current form. It is important to consider the information herein as the manufacturer's prescribed guidelines for the utilisation of the system for metallic mains with a nominal diameter of 300 mm. This will inevitably expand to other materials and sizes with future system developments.

The focus of this document is to outline and construct what will be referred to as a Technical and Operational Reference Manual (TORM), an essential reference for all operatives involved in the practical application of this equipment in the field. This manual is designed to be thoroughly reviewed upon receipt and subsequently employed as a dependable reference guide during field operations, encompassing all activities related to the surveying of live foul rising mains.

In the final segment of this document, additional insights are provided to refine the future end-to-end process. Subsequent editions of this manual will need to align with the specifications required for field deployment, which necessitate approvals from relevant UK Engineering Policy departments for use on live metallic foul rising main assets up to expected operational pressures.

It is important to note that the operation of this equipment strictly adheres to the Water Network Procedures for foul rising mains going forward and that the reference manual is updated in accordance with these procedures. Additionally, only individuals who have received training and registration from Synthotech Limited are authorised to operate this equipment.

2 Safety, Risks and Risk Control

Examples of the potential risks associated with using robotics and pushrod systems on 'live' foul rising mains/ pipes include ***but are not limited to***:

Risk	Control
Trip Hazard on cables	There are several lead cables used for robotic surveying with vibroacoustic technology. These must be set out neatly on site, avoiding areas of footfall or in a public area. Signage should be used where appropriate.
Personal injury due to stored energy in a pressurised system	Ensure all equipment is suitably maintained and, operators must not place any part of their body above/over/in front of pressurised parts.
Release of foul gas	The foam gland must be replaced after each survey (usually this involves 2 directions from one excavation point). Personal H2S monitors should be considered as standard PPE for operatives.
Release of foul wastewater	Purge, access, and egress procedures must be followed to minimise site contamination of foul wastewater. All equipment must be pressure-checked before entry into the foul water system. Spill kits and cleaning stations must also be available to operatives on site.
Lifting launch equipment, and heavy objects on site	Launch tube apparatus should only be handled when two people are present. Heavy equipment over 20 kg must not be handled by one person only. Appropriate manual handling processes should be followed.

3 Components and Parts

This system in its current state can only be used under the following circumstances:

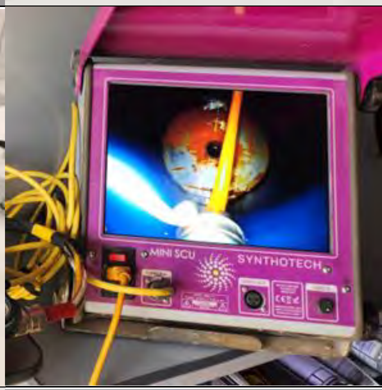
- In DN300 live metallic mains operating at pressures below 1 Barg. (potentially PE, but only tested on Iron to date)
- In Decommissioned /exhumed mains for research and test purposes
- Operated by Synthotech personnel or trained network representatives
- Vertical (or horizontal / end on) launch required, through a minimum of 300mm access point
- Suitable with PN16 through-bore (or similar) valves through under pressure launch tube

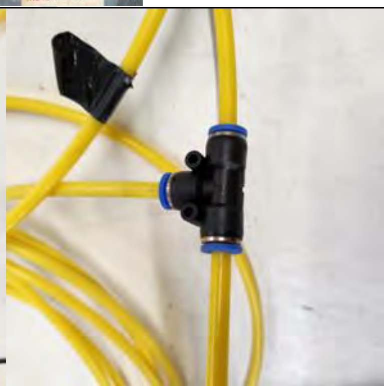
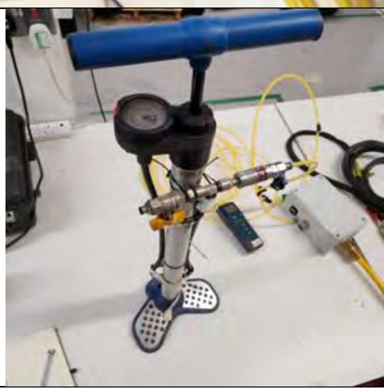
The system comprises of 3 main subsystems:

- The robotic crawler (Table 1)
- The transient generator (Table 2), and
- The access insertion kit (Table 3)

The next few tables provide a visual reference of the required equipment to carry out inspections within the foul rising main.

Table 1 PoC Robot Assembly equipment

Item	Reference	
Robot crawler: - Twin tracked robotic vehicle - Front and rear cameras - Replaceable tracks - Sensing halo with built-in accelerometers		
Umbilical tether/connection box - 40-metre cable - Physical meterage marking - Internal tubing for internal pressurisation		
Synthotech Control Unit (SCU) / Rear camera display - Controls all robot functions - On-screen playback, SD card screenshots,		
Power cables - Powers control unit and additional display (230v and 110v available)		

Display cables - Connects the controller to connection box and optional rear camera display.	 
Digital Manometer - Monitoring internal pressure of system	
6 mm tubing assembly - Manometer offtake connection - Valve connection	 
Hand pump - Pressuring internal cavity in crawler	

Ethernet/ USB cables - Connects between laptop and connection box for data acquisition.	
Data acquisition Laptop - Capturing and displaying accelerometer data	 DaQ Laptop

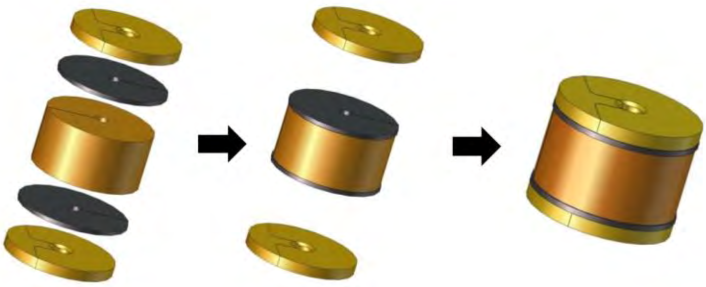
Table 2 PoC Transient generator equipment

Item	Reference
Transient speaker - 60W submarinised speaker - Spring connector	
Pushrod cable and reel - Fibreglass cobra - Audio connections to amplifier	

Amplifier/ cabling - Amplifies signal/power to the speaker	
Signal Generator/ audio cabling to laptop - Produces signal at set frequency for transient speaker	

Table 3 PoC Access equipment

Item	Reference
Vertical Launch assembly (Crawler) - Site tested to 3 barg - Cable gland and management system - PN16 DN300 flange - Push fit valves for pressure monitoring and purging procedures.	

M24 Bolts/nuts/ washer set - for access valve connection to the launch tube	
Cable gland plastic (P)/ foam (F)/gasket(G) seals - to provide a seal around cabling under pressure - order: PGFGP	
6/8mm tubing - to assist purge processes	
Vented container (example only) - hazardous waste container to limit contamination during purge procedures - 110 L bowser type system easier to move about on site. - Alternative: static black water holding tank in van.	
Chlorinated water tank - to assist in decontamination of equipment	Same as above

- Similar to above – bowser type to help position around site.	
Clean down brushes/tooling/ consumables (example only) - specific to clean down operations and sterilisation - - absorbent pads/spill kits	

4 Operational Process

4.1 Before arrival to site

1. Review site location, pipe material/size, collate documentation for the system (Risk Assessment, Technical Operation and Reference Manual, other Site required documents etc.)
2. Complete preflight checks on the robot crawler & transient generator, check sensor data acquisition and capture quality (workshop)
3. Sign out the required equipment and complete the checklist
4. Load transport with equipment, fastening any loose containers and equipment to the body of the vehicle to prevent damage during transit
5. Head to site

4.2 On-site preparation

1. Arrive to site
2. Sign in & completion of site documentation (Water company and site specific)
3. Completion of site documentation (Synthotech)
4. Wait for a clear go-ahead from Water Company Operations Manager (Competent Person or Site Manager) to begin operations.
5. Complete preflight checks on the robot crawler & transient generator, check sensor data acquisition and capture quality (On site)

4.3 Access Fitting

To outline the potential access process, a vertical launch procedure is presented. This does not implicitly mean that this is the only way to launch as there could be many configurations depending on the site access requirements and the design of the robot going forward. Synthotech has experience in both vertical, horizontal, and angled launches so adapting the launch system is within future project capabilities. The section highlights the process and what is required for safe access into a rising main in its current configuration.

1. The access fitting should be checked for compatibility with the access system and insertion devices before arrival at site. When at site, this must be confirmed.
2. The access fitting must be fitted and the main drilled in accordance with the manufacturer's instructions and network policies.
3. For the purposes of the PoC system, this is a DN300 through-bore gate valve bolted onto the vertical PN16 flange of the DN300 Ductile Iron Equal tee.

4.4 Preparation: Crawler

1. Set up the control unit and display unit in a position that enables the pilot/operator to see both screens.
2. Feed the umbilical cable through the gland box on the launch tube flange.
3. Align the arrow on the umbilical connector with the crawler's connector socket to ensure the pins are aligned before connecting.
4. Connect the umbilical and hand tighten the burred brass ring.
5. At the base of the connector, tighten the retaining bolt with an Allen key to complete the connection.
6. Connect the internal pressurisation line on the crawler to the protruding connection point on the umbilical, position the retaining fitting and tighten with a spanner to seal the line (Figure 1).

a) b) c) d)

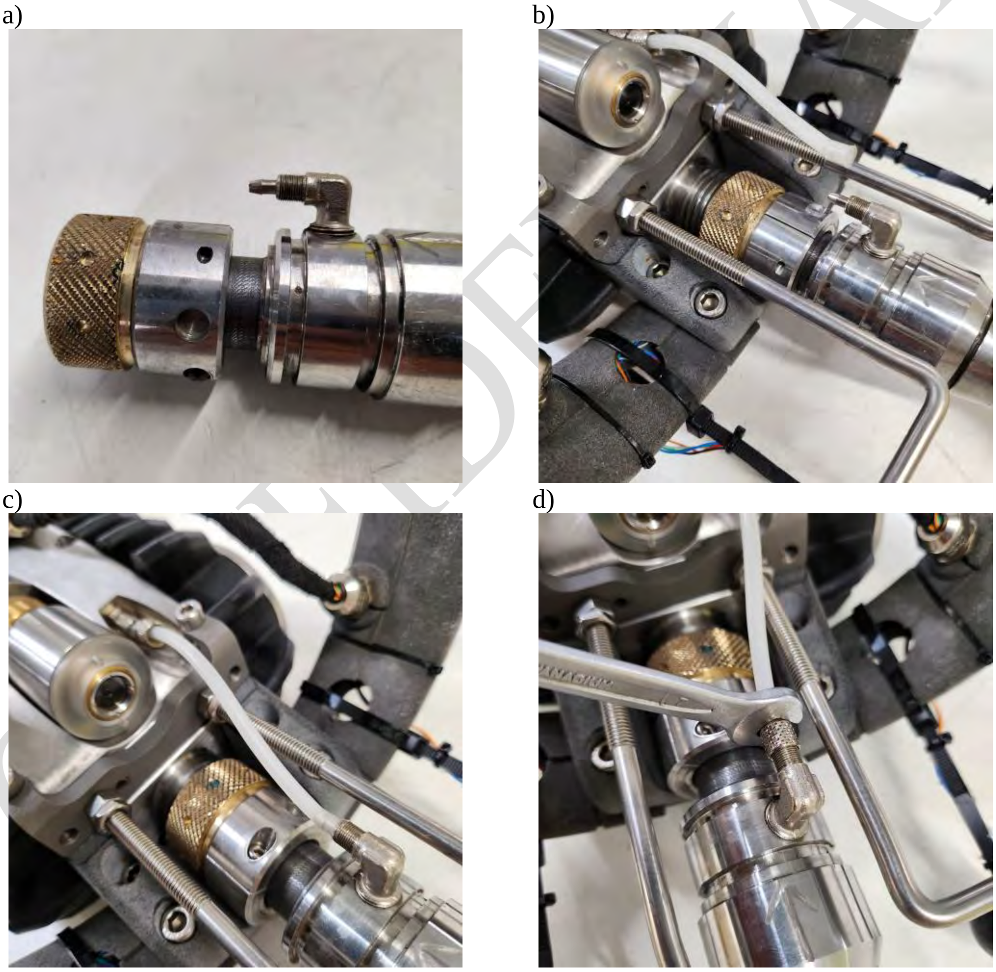


Figure 1 Internal pressurisation connections on crawler - a) Umbilical connector and tube connection point, b) umbilical connected to crawler, c) crawler pressurisation line connected to the umbilical connection point, d) compression fitting positioned and tightened with a spanner at the umbilical connection point to achieve internal seal.

4.5 Preparation: Umbilical connections

Internal pressurisation system and checks

1. Arrange the 6 mm tubing, connections, manometer, and hand pump as presented in Figure 2, and connect everything up (these are quick-release push fittings)
2. Turn the manometer on to get a baseline reading of the internal pressure.
3. Ensure the valves are open and pump up the internal crawler pressure to a minimum of 500 mbarg, monitored by the manometer. (If the system is operating up to 1 Bar then the internal pressure will need to be increased proportionally.)
4. Close the control valve when at pressure and prepare the other system while waiting.
5. Check the internal pressure after 10 minutes to check that it has been maintained, accounting for any temperature changes over this time i.e. the sun came out and warmed the crawler = increase in pressure.

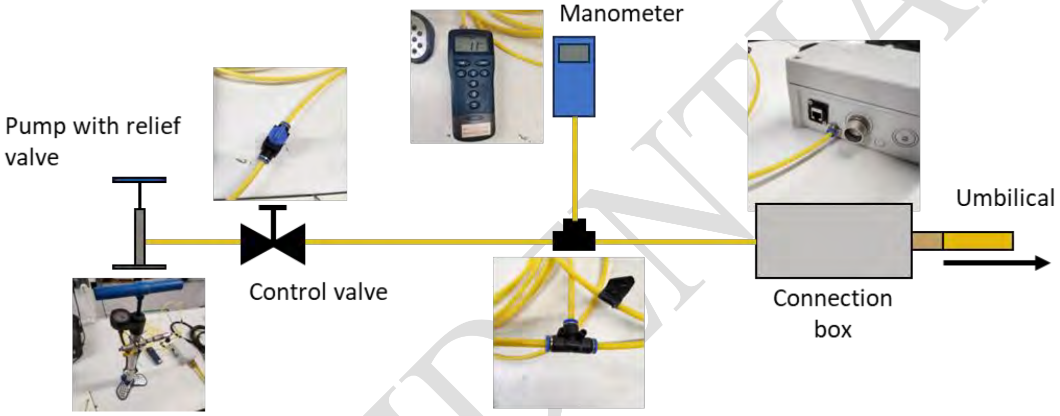


Figure 2 Internal pressurisation system and pressure monitoring arrangement.

Control, display and functionality checks

1. Arrange the control and display unit power cables and connectors as shown in Figure 3, and connect everything up to the connection box. Note, like the umbilical connector and crawler connector socket, there are alignment arrows on the black cable to align the pins accordingly. Tighten the retaining ring by hand.
2. Power up the control unit and display unit.
3. Check the crawler vision and functionality using a pre-flight checklist
4. Once checks are complete, keep equipment powered up for data acquisition checks.

Sensor and data acquisition checks

1. Position the data acquisition device alongside the control and display units so that they are in view of the pilot/operator.
2. Arrange the device and cabling as shown in Figure 4, connecting the red ethernet cable from the laptop to the connection box.
3. Power on the device and open the PipeBots GUI to check communications with all accelerometers on the crawler's sensor halo.
4. Completed sensor specific preflight check to confirm data quality and response.
5. Power down equipment connected to the connection box.

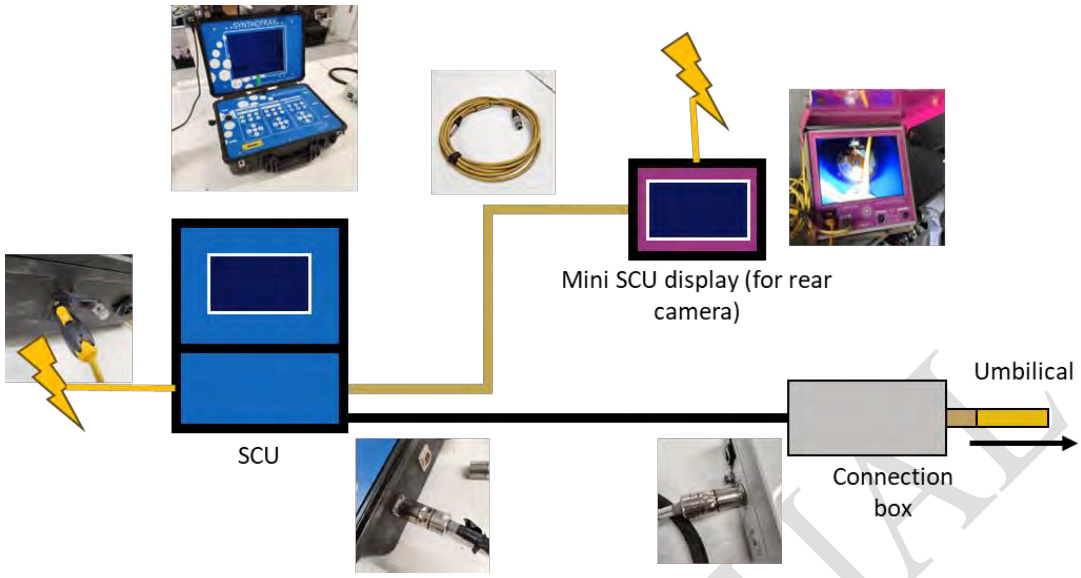


Figure 3 Synthotech Control Unit (SCU) arrangement for crawler power, control, and visuals.

Figure 4 DaQ arrangement for sensor data collection.

4.6 Preparation: Transient Generator

1. Feed the cobra connector through the launch fitting gland stack and connect the spring connector of the transient speaker to the cobra connector socket.
2. Arrange the cobra reel, signal amplifier, signal generator, and cables according to Figure 5, and connect everything together.
3. DO NOT CHANGE the settings on the amplifier – increasing either volume or bass volume has the potential to blow out the speaker. The settings should be checked prior to site arrival. Spare speakers should always be brought to the site for on-site replacement.
4. Signals can either be generated through the signal generator via an audio jack, or directly connected to the data acquisition device to produce the right sound frequencies for surveys. A phone with a signal generator app can be used for initial transient speaker checks.

5. Power up the amplifier and sound a test tone of 100 Hz to check speaker functionality – frequency can be confirmed if coupled to accelerometers on the crawler as part of pre-flight checks.

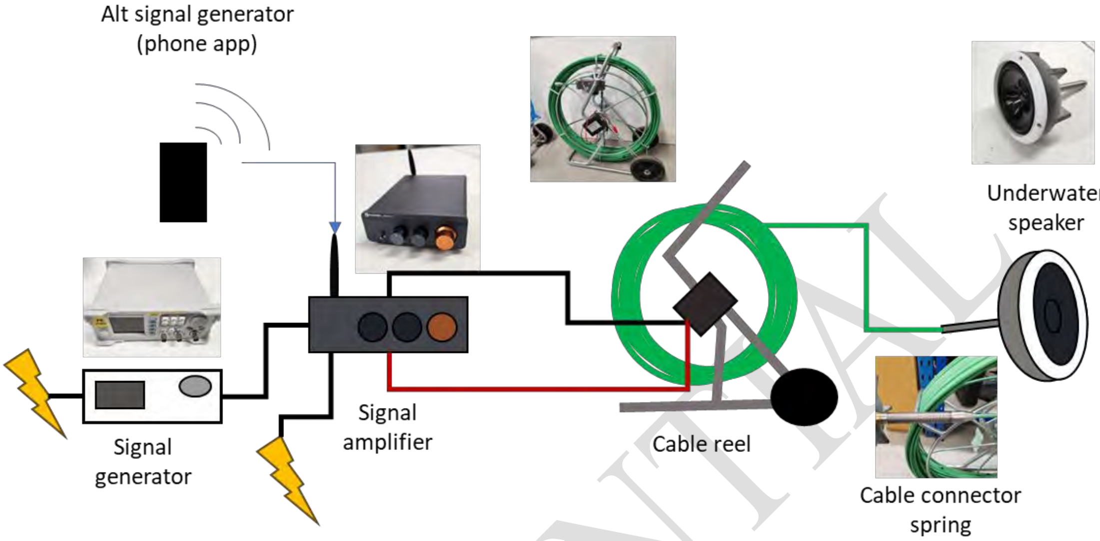


Figure 5 Sound generator arrangement

4.7 Crawler access (Vertical Launch)

1. Once the access fitting is in place the launch tube flange can be fitted. Bolt the tube to the valve with an appropriately sized gasket and bolts – tighten to specified torque settings (Figure 6).
2. Double check the PipeBot's launch orientation. Crawler Tracks to the left, launches to the right.

Figure 6 DN300 Gate valve on vertical flange of equal tee, launch tube attached.

3. Purge the launch tube assembly with chlorinated water while feeding air out to a vented container (container for hazardous waste fluids during ops) – see Figure 7.
4. Close the launch tube flange valves and pressure test the launch vessel assembly to the expected rising main pressure. After a successful pressure test, operations can continue. An equal pressure must be attained to operate and open the gate valve as a larger pressure differential will increase resistance in the valve mechanism. *For higher pressures, a bypass fitting may be required for this diameter of pipe.*
5. Switch on the crawler at this point.
6. Open the rising main valve slowly and monitor pressure in the launch tube.
7. Once the valve is fully opened, lower the system into the main, operating crawler controls to position the base in line with the main – see Figure 8.
8. Once the crawler has touched the bottom of the main, drive forward while continuing to lower the system and cable fully.
9. Pipe pressure should be monitored to understand pressure trends during operation.
10. Drive the crawler forward and begin the internal survey.

a) b)

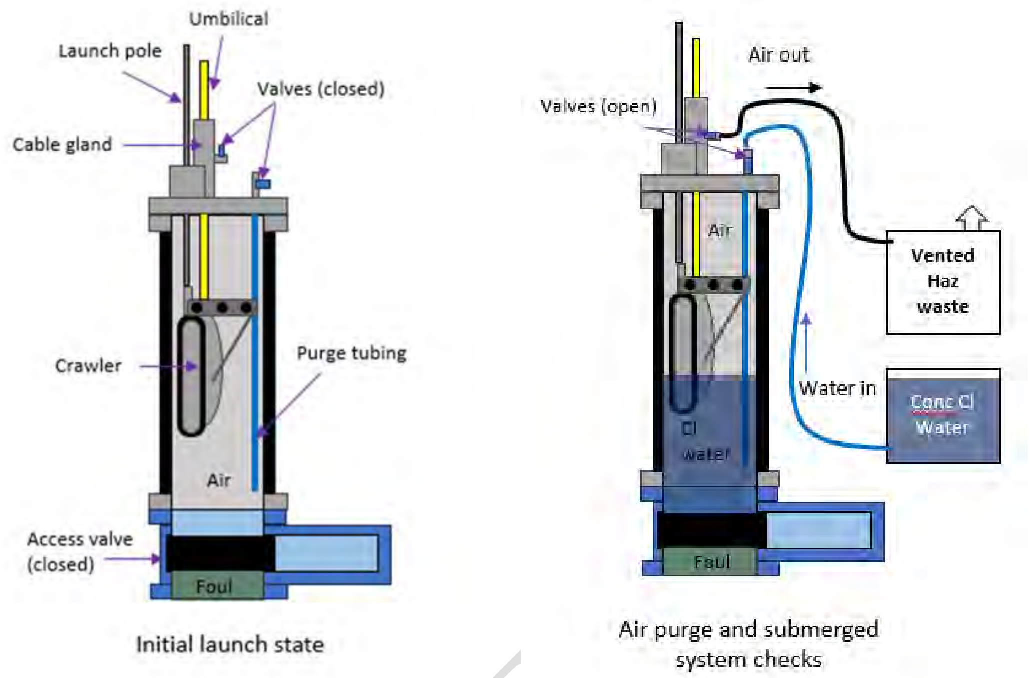


Figure 7 a) Initial state of launch tube with robot crawler mounted onto access valve. b) air purged and replaced with chlorinated water for submerged system checks and launch pressure test.

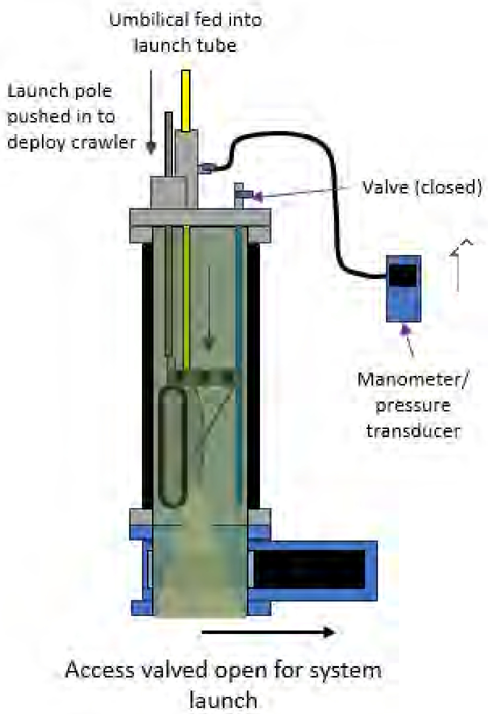


Figure 8 Access valve opened for the deployment of the system using the launch pole.

4.8 Speaker Launch

1. Connect the Speaker Launch tube flange to the launch tube.
2. Once the access fitting is in place the Speaker Launch tube flange can be fitted.
3. Bolt the tube to the valve with an appropriately sized gasket and bolts – tighten to specified torque settings (Figure 6).
4. Purge the Speaker launch tube assembly with chlorinated water while feeding air out to a vented container (container for hazardous waste fluids during ops).
5. Close the speaker launch tube flange valves and pressure test the speaker launch vessel assembly to the expected rising main pressure. After a successful pressure test, operations can continue. An equal pressure must be attained to operate and open the gate valve as a larger pressure differential will increase resistance in the valve mechanism. *For higher pressures, a bypass fitting may be required for this diameter of pipe.*
6. Open the rising main valve slowly and monitor pressure in the launch tube.
7. Once the valve is fully opened, lower the speaker system into the main.
8. Switch on the speaker at this point.

4.9 Inspection, data capture

1. Once in the live main, use the control unit to move the crawler forward and backward in the pipe.
2. When moving forward, ensure the umbilical cable is fed and pushed into the gland stack so as not to restrict forward progress.
3. When reversing ensure that the slack in the cable is pulled back.
4. A survey can now be carried out

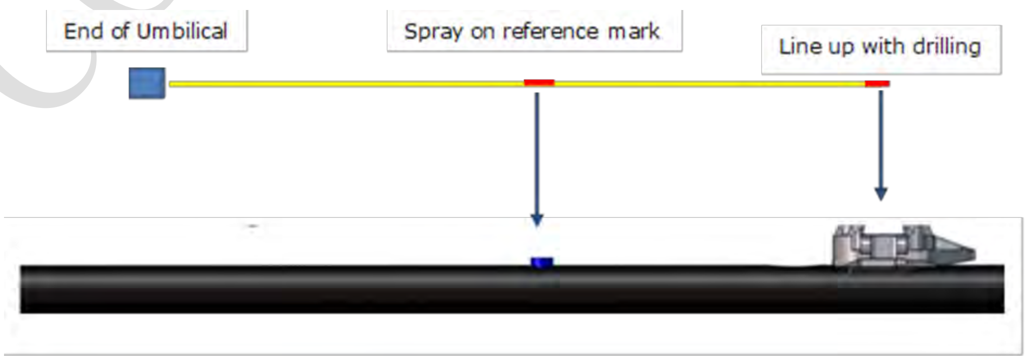
4.10 Submersion and Transient Speaker Test

1. Once in the live main, push the fibreglass cobra so that the speaker is located in the centre of the live main.

4.11 Marking out a survey

1. Currently for location a mark on the coil at the back of the Sealing Gland is the most accurate way to mark a survey. This must be done on the return journey, so the tape does not get fed through the seals causing them to leak – *need to consider the condition of the cable after interaction with wastewater. Alternative meterage solutions will be determined in the next phase as they are out of scope of the current phase.*
2. The first mark should be at the end of the survey (full driven distance) and the last mark must be when the PipeBot is back on the launch claw before it is lifted into the launch tube, this tape mark will be your reference mark for Points of Interest (POI).
3. When the survey has finished remove the umbilical from the PipeBot and launch tube. Walk out in the direction of the survey with the end of the umbilical and your reference tape mark. Once the next tape mark comes off of the coiler place this directly in line with the drilling and spray the position of your reference tape mark. Continue until you reach the end of the survey tape mark.

4. All items can be checked for distance if required using a meterage wheel. If you are unable to follow the survey with the umbilical due to location i.e. busy roads, you can lay the umbilical out in an appropriate location and use a meterage wheel working back from your reference mark to measure the items of interest distances.
5. Although it is not recommended and should be avoided for vehicles to drive over the Umbilical if it does happen there should be no damage.



4.12 Egress

1. Drive the crawler back to the launch access point, align it with the launch pole hooks and hook it.
2. Then clamp the hooks into position and pull the crawler back into the launch tube so that it is clear of the rising main access valve.
3. Close the rising main valve (1) to isolate the crawler – see Figure 9.
4. Open the end plate valve (2) to relieve pressure within the launch tube, expelling the contents through tubing connected to the vented hazardous waste container.

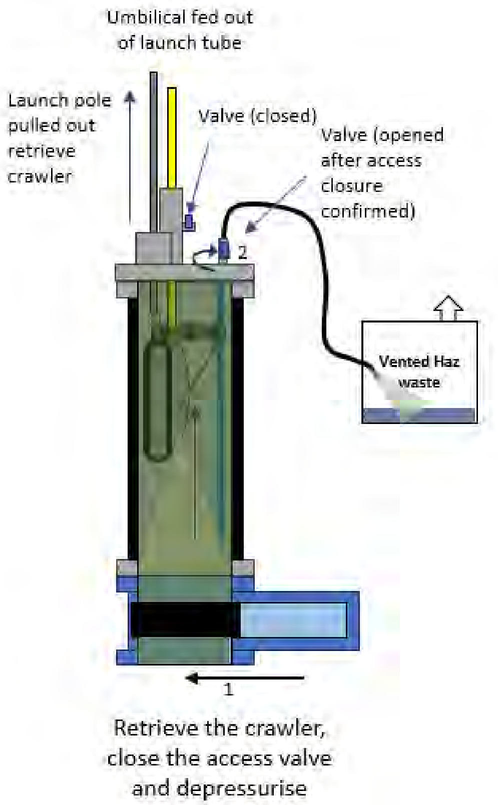


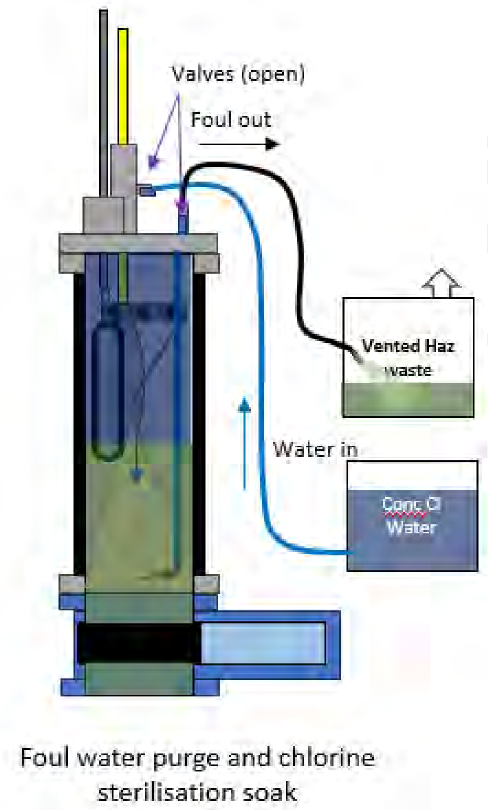
Figure 9 Crawler retrieval to launch, access valve closure and depressurisation into the vented hazardous waste container.

4.13 Cleaning / Disinfection (on-site)

1. Connect the tubing to the chlorinated water contained and pump chlorinated water into the launch tube until the fluid exiting into the waste container runs clear (essentially flushing out the majority of foul water) – see Figure 10 a). Alternatively, the foul water could be fully pumped out with a vacuum pump from the outlet, similar to those used to empty holding tanks on leisure vessels. While the figure presents a tube for the outlet, the launch tube could feature a larger bore offtake at the base to reduce the possibility of blockages.
2. Close the end plate valves and soak the system for 15-20 minutes in the chlorinated solution.

3. Pump in water to flush out chlorine for 3-5 minutes and then pump air in to push out any liquid within the launch tube – see Figure 10 b).
4. Unbolt the launch tube and separate system connections and fitting for additional cleaning.
5. Pressure wash and brush off all equipment with chlorinated water solution within a self-contained cleaning container. Drain off all wastewater into the hazardous waste container.
6. Dry off the system and pack for transport – a thorough inspection, clean and surface sterilisation will take place back at Synthotech prior to the next use.
7. Hazardous waste should be stored within containers and disposed of according to water network procedures. Wastewater could be discharged into at a local pumping station or wastewater wet well, but this will need to be confirmed in the next project phase.

a)



b)

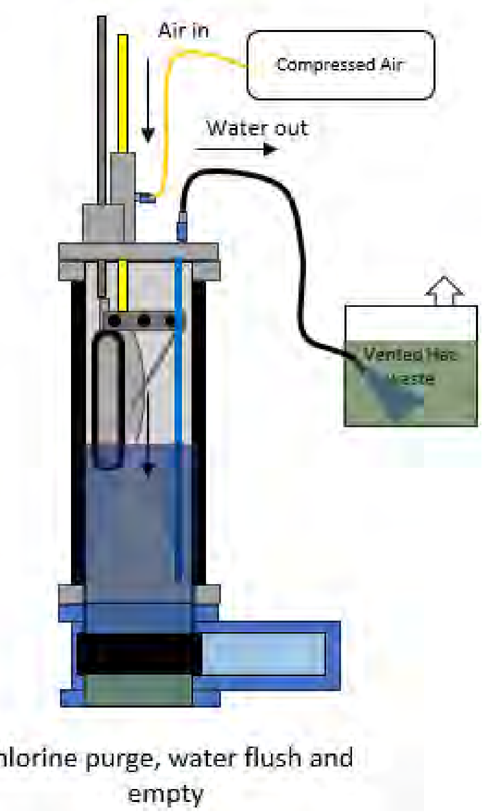


Figure 10 a) Foul water purge with concentrated chlorine solution, which is left to sterilise contents after foul water runs clear. b) after flushing the system with water, compressed air is used to remove the remaining water from the launch tube into the hazardous waste container.

4.14 Cleaning / Disinfection (workshop)

Additional measures for cleaning and sterilisation will be required to enhance the safety of personnel involved in routine maintenance, testing, and preflight checks of the system between different operations.

Any modifications to the design should prioritise ease of cleaning and sterilisation, aiming to reduce the presence of inaccessible crevices and areas prone to higher debris buildup. This would also improve the turnaround time for the system to be ready to use operationally again.

Furthermore, the selection of sterilisation techniques and the necessary equipment should be considered. Sterilisation options include chemical sterilisation (chlorination), UV sterilisation (employing UV-C at a wavelength of 254 nm), low vacuum plasma treatment, and heat sterilisation.

The next phase will thoroughly assess this process prior to field trials.

4.15 Emergency Recovery and Track Jamming

If the tracks are jamming from debris, stop the survey and skid steer left and right to see if the track can free itself of debris (Sometimes reversing also helps). If the track cannot be freed, the crawler must be manually pulled back by the umbilical.

Once the crawler is below the access hole, it must be pulled up as far as possible by the umbilical. Once within the launch tube, follow egress and on-site cleaning/disinfection procedures.

For other failure specific emergency controls and procedures, please refer to the robotic crawler platform DFMEA (Deliverable D6).

4.16 Maintenance

Track Assessment
The tracks must be inspected before and after every use to check for delamination and must be replaced if any delamination is seen.

a) b)

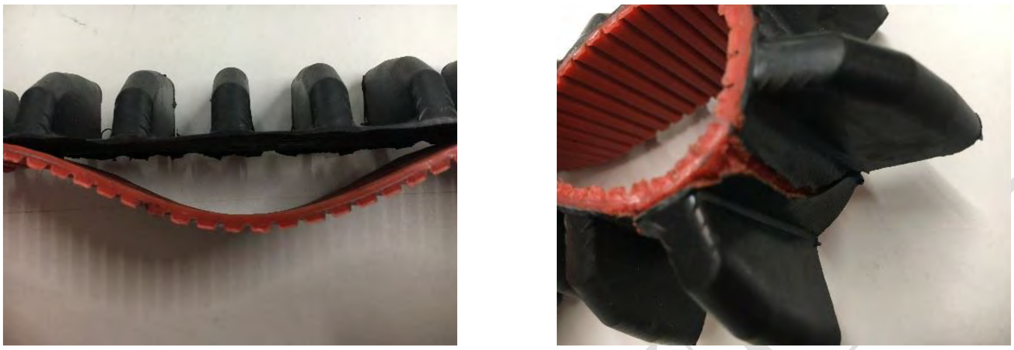


Figure 11 Track Delamination Examples

Track Cleaning and Replacement
The track must be removed for inspection and cleaning after every survey.

1. In a clean working environment place the Synthotrax™ on its side and using the provided screwdriver remove the track retain plates.

a) b)

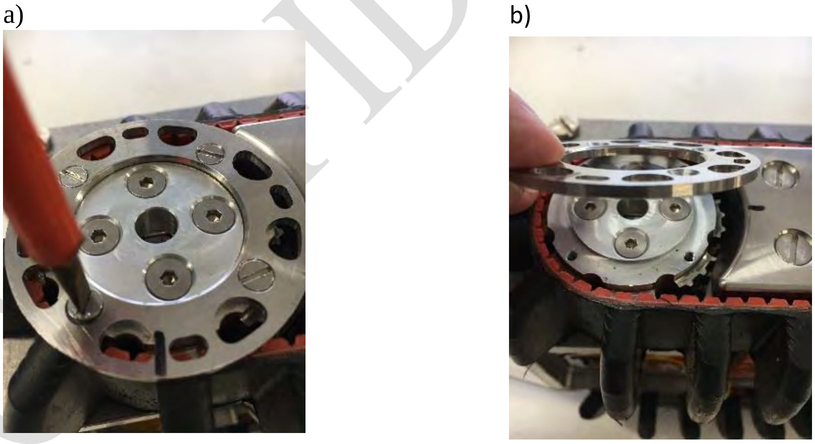


Figure 12 Remove a) retaining plate screws & b) retaining plate.

2. Rotate the track by hand and walk off the track from the drive wheels. If the track is difficult to rotate due to debris move the track backwards and forwards to release the debris.
3. Once the track has been removed check for delamination and clean.

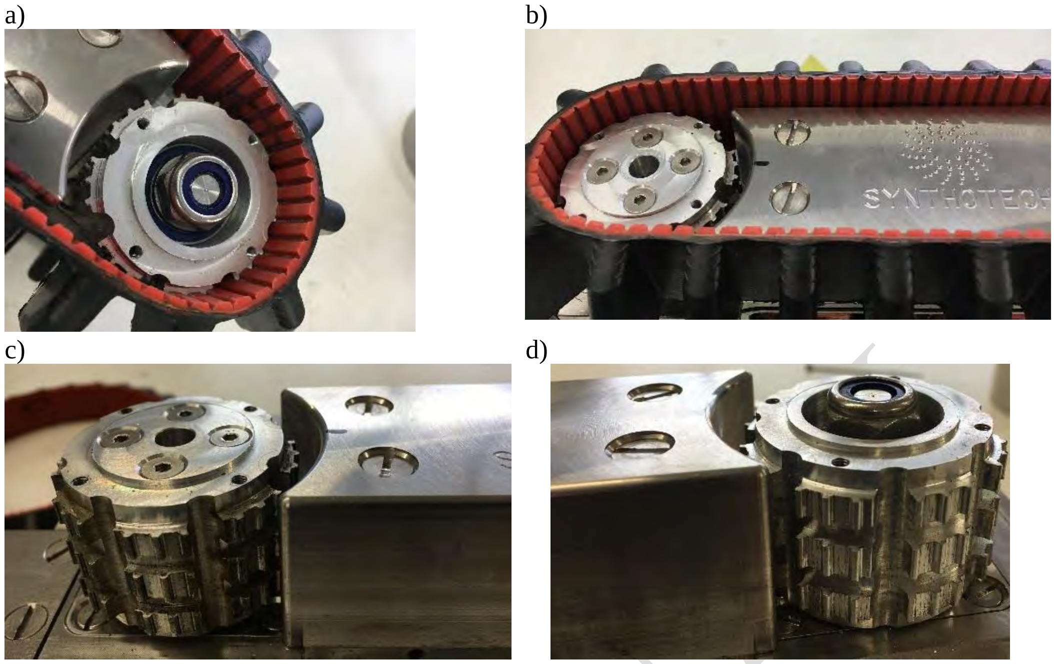


Figure 13 Remove Track (a & b), and clean drive wheels (c & d).

4. Use a brush to clean the drive wheels ensuring that all the debris has been removed.
5. Check that the drive wheels rotate with no tight spots.
6. Replace the track in the same method of removing by rotating and walking the track back into place.
7. Ensure the track is fully located on the drive wheels.
8. Replace the track retaining plate ensuring the chamfered screw hole are facing outwards

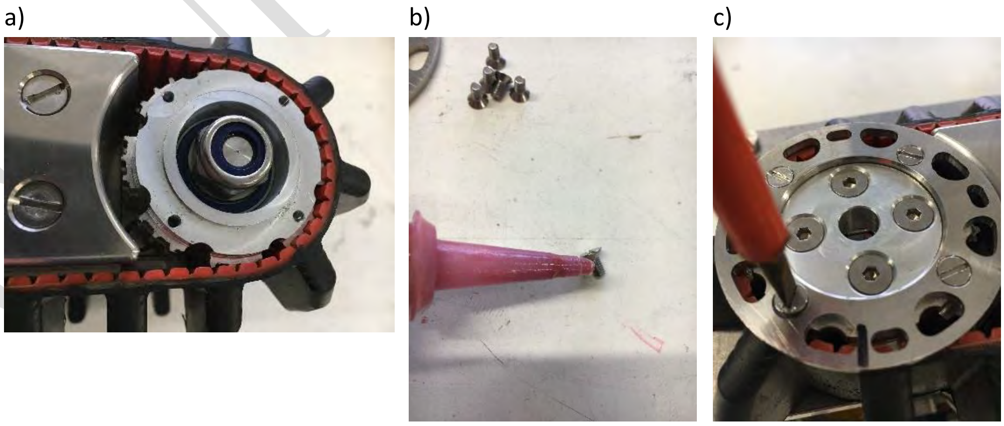


Figure 14 a) Replace track, b) Loctite screws, c) replace screws

9. Replace the screws using low strength Loctite 222 or equivalent.
10. Check the track rotates by hand.
11. Repeat steps 1 – 10 on opposite track.
12. Test the PipeBot drives under power and the on-screen power is stable.

5 Outcomes and Recommendations

The process and operation of the system works well. Once all the sub systems have been proven through extensive field trials, it is recommended that they could be integrated into a single operations system to reduce trailing leads and trip hazards, as well as making operation simpler.

Measurement systems must be automated to ensure that marking up is simpler.

A wiper cleaning system may be required (automatic sterilisation) as the umbilical is removed from the pipe for both the speaker and the crawler system.

In the next phase, there will need to be further investigation as to the quantities of chlorinated and foul water required for disinfection during the process and how this relates to the launch tube and the Halo geometry.

Design requirements to reduce the issues raised by foul water will help shape the next iteration of the assembly, insertion and robotic design including the size of tubing and vent valves as well as track lock and cleaning limitations.

Appendix 12. D6 - FMEA

SYNTHOTECH innovative engineering

Failure Mode and Effect Analysis (FMEA)

SYNOVATE

Process or Product Name:	L09 PipeBots in Riser Mains	Original DFMEA Date:	21/06/2023
Project Sponsor:		Revised DFMEA Date:	21/09/2023
Author(s):	PS, JW, AKW		

Product/ Process Description:	Robotic crawler platform with mounted sensors and camera for insertion into sewer riser mains/ test rig processes

Current State Condition (Proof of Concept)														Future State Condition - Action Plan						
Description			Description of Failure				Effect of Failure							Future State Condition - Action Plan			Actions Completed and F			
Ref No.	Component	Function	Mode of Operation	Potential Failure Mode	Potential Causes	Likelihood	Local Effect	Global Effect	Severity	Current Controls	Impact of Control (So what?)	Detection	Risk Priority Number (RPN)	Actions Recommended	Responsibility	Completion Date	Actions Taken	Likelihood	Severity	Detection
1	User Interface and control system	Powers and controls crawler, cameras, sensors Displays & records images, & sensor data	Mobilising / Setting Up	Loss of supply	Loss of generator or supply cable	6	Loss of User Interface	Unable to start operations	5	Supply cables tested, back up generator and cables. Kit checked/tested prior to leaving workshop.	Reduced likelihood of failure Reduced severity of effects Operations delay minimised	1	30							
				Loss of display	Electrical failure component/wiring failure	6	Loss of User Interface	Unable to start operations	5	Connections are wired and soldered correctly, continuity tested, and structurally secured in place. Kit checked/tested prior to leaving workshop.	Reduced likelihood of failure	1	30							
				Loss of camera feed	Electrical failure component/wiring failure	6	Loss of local environment visuals for deployment	Unable to start operations	5	Connections are wired and soldered correctly, continuity tested, and structurally secured in place. Kit checked/tested prior to leaving workshop.	Reduced likelihood of failure	1	30							
				Loss of DVR (Digital Video Recorder)	Electrical failure component/wiring failure	6	Loss of camera data capture	Unable to start operations	3	Connections are wired and soldered correctly, continuity tested, and structurally secured in place. Operations able to continue so long as cameras feed functional and sensor DaQ operational with meterage.	Reduced likelihood of failure Operations capability limited but not prevented	1	18							
				Loss of DaQ (Data Acquisition)	Electrical failure component/wiring failure	6	Sensor data not captured/saved/ quality checked	Unable to start operations	3	Connections are wired and soldered correctly, continuity tested, and structurally secured in place. Kit checked/tested prior to leaving workshop.	Reduced likelihood of failure	1	18							
				Loss of robot specific controls	Electrical failure component/wiring failure	6	Loss of User Interfaces	Unable to start operations	5	Connections are wired and soldered correctly, continuity tested, and structurally secured in place. Kit checked/tested prior to leaving workshop.	Reduced likelihood of failure	1	30							
				Reduced mobility	Unit heavy and difficult to lift Power cables reducing walkways	3	Heavy object Back injury, slips trip or fall	Minor injury to personnel	3	Proper training on lifting, HSE guidance on safe workplace management and actions. Use of mechanical advantage where required, PPE worn	Reduced likelihood of failure Reduced severity of effect	10	90							
			Deploying/Recovering Through Pipe	Loss of supply	Loss of generator or supply cable	6	Loss of User Interface	Operations halt	6	Supply cables tested, back up generator and cables.	Reduced likelihood of failure Reduced severity of effects Operations delay minimised	1	36							
				Loss of display	Electrical failure component/wiring failure	6	Loss of User Interface	Operations halt	6	Connections are wired and soldered correctly, continuity tested, and structurally secured in place.	Reduced likelihood of failure	1	36							
				Conductor short	Mechanical failure (water ingress)	4	Loss of User Interface	Operations halt	6	The control system is sealed appropriately, connections are wired and soldered correctly, continuity tests are structural secured in place.	Reduced likelihood of failure	1	24							
				Loss of camera feed	Electrical failure component/wiring failure	4	Loss of local environment visuals for deployment	Operations halt	6	Connections are wired and soldered correctly, continuity tested, and structurally secured in place.	Reduced likelihood of failure	1	24							
				Loss of robot specific controls	Electrical failure component/wiring failure	6	loss of robot movement in pipe	Operations halt	6	The robot base is tethered and can be manually recovered by a trained operator.	Reduced likelihood of failure Reduced severity of effect On-site repairs could enable recommencement of operation if solvable	1	36							
2	Umbilical Tether & Reel	Stores, deploys and recovers power supply, comms and data tether from robot platform	Mobilising / Setting Up	Conductor short on signal/data/video	Mechanical/ electrical failure from water ingress	4	Loss of input to user interface	Unable to start operations	5	Connections are wired and soldered correctly, continuity tested, and structurally secured in place.	Reduced likelihood of failure	1	20							

				Conductor short on power line	Mechanical/ electrical failure from water ingress	4	Loss of input to user interface	Unable to start operations, risk of electrocution	10	Connections are wired and soldered correctly, continuity tested, and structurally secured in place. Fuses fitted to prevent overcurrent situations.	Reduced likelihood of failure Reduced severity of effect	1	40	
				Reduced mobility	Tether on the ground, tangled around site furniture (fencing, control boxes, access points, Vans)	3	Back injury, slips trip or fall	Minor injury to personnel	3	Tether length capped at 40m, tether path visibly marked, tether positions out of main walkways and secured in place. Use of a cable reel to manage cable lengths.	Reduced likelihood of failure Reduced severity of effect	10	90	
			Deploying/Recovering Through insertion Tool	Conductor short on signal/data/video	Mechanical/ electrical failure from water ingress	4	Loss of input to user interface	Unable to start operations	5	Connections are wired and soldered correctly, continuity tested, and structurally secured in place.	Reduced likelihood of failure	1	20	
				Conductor short on power line	Mechanical/ electrical failure from water ingress	4	Loss of input to user interface	Unable to start operations, risk of electrocution	10	Connections are wired and soldered correctly, continuity tested, and structurally secured in place. Fuses fitted to prevent overcurrent situations.	Reduced likelihood of failure Reduced severity of effect	1	40	
				Failure to turn cable reel during deployment	Mechanical failure bearings seized	4	Unable to deploy	Operations halt	5	Check for signs of damage, wear and corrosion prior to mechanical checks and lubrication.	Reduced likelihood of failure	1	20	<- considerations for next phase when using a reel
				Failure to turn cable reel during recovery	Mechanical failure bearings seized	2	Operator recovers manually	Operation time increases	2	Deployment resistance is monitored by a trained operator, the system is shielded from dust/moisture in local environment. System checked over prior to use.	Reduced likelihood of failure	1	4	<- considerations for next phase when using a reel
				Reel deploys when not commanded	Mechanical failure brake failure	4	Operator re-spools and controls reel	Operation time increases	2	User by trained operator	Reduced likelihood of failure	1	8	<- considerations for next phase when using a reel
			Deploying/Recovering Through Pipe	Failure to move cable	Mechanical failure cable snagging on objects in pipe, build of of ragging	6	Reduced manoeuvrability, increased adhesion from ragged cable to pipe surfaces	Operations delayed, halted Survey incomplete Challenge to retrieve system	5	None at this stage	None	7	210	<- considerations for next phase - development of hydrophobic non stick system coating for anti-ragging/monitoring.
				Cable breaks (partial)	Mechanical failure/ component failure	2	Loss of input to user control interface	Operations halt	5	Train operator to manage cable deployment and recovery though insertion tool. Cable thoroughly inspected for signs of potential failure.	Reduced likelihood of failure Higher chance of early detection	4	40	
						2	exposed wiring in contact with pipe, loss of input to user interface	Operations halt, major injury to personnel	10	The system is powered down for manual removal. System checked over for signs of sever wear on cable sheathing prior to deployment. Cable checked for wear during recovery.	Reduced likelihood of failure Reduced severity of effect Higher chance of early detection	3	60	
						2	exposed wiring in contact with robot base, loss of input to user interface	Operations halt, major injury to personnel	10	The system is powered down for manual removal. System checked over for signs of sever wear on cable sheathing prior to deployment. Cable checked for wear during recovery.	Reduced likelihood of failure Reduced severity of effect Higher chance of early detection	3	60	
				Cable breaks (full)	Mechanical failure/ component failure	2	Loss of input to user control interface	Loss of asset (detection system) Impact on network asset flow capability/ blockage	7	Site reviewed prior to deployment to understand riser exit points and implications on flow. Trained users operate robots and judge the condition of the tether during use. The asset is recovered if any sign of damage to the tether. Tether and connections are inspected prior to and after operational use. During tests, test rig is decommissioned for asset recovery. In the	Reduced likelihood of failure Reduced severity of effect Higher chance of early detection	3	42	
				Unable to recover tether/ robot	tether/ robot snagging on large geometries	3	Unable to move robot, loss of robot	Loss of asset (detection system) Impact on network asset flow capability/ blockage	7	Review the last time the asset was cleaned/maintained prior to the deployment decision. Presurvey if possible through operational access point. Trained users operate robots and judge the risk of obstacles. Tether controlled by a trained user. If stuck and unable to free, the tether cut if under pressure, valve closed, rig depressurised, flushed and drained for asset recovery in test rig setting. In the field, asset is abandoned until recovery strategy is confirmed.	Reduced likelihood of failure Reduced severity of effect Higher chance of early detection	3	63	
3	Robot Platform	Delivers pipe condition sensors and camera to inspection location, anchors sensor platform, relays power to individual components, seal in crucial electronics.	Deploying/Recovering Through Pipe	Loss of supply	Loss of generator or supply cable	6	Loss of User Interface	Unable to start operations	5	Supply cables tested, back up generator and cables.	Reduced likelihood of failure Reduced severity of effect	1	30	

				Loss of comms	Mechanical failure from damaged tether or connections	6	Loss of input to user control interface/ control	Operations halt	5	Pre-flight checks, connections checked regularly, robot inspected for signs of damage	Reduced likelihood of failure Higher chance of early detection	1	30	
					Electrical failure component/wiring failure	6	Loss of input to user control interface/ loss of system control	Operations halt/ further damage to system	5	Connections are wired and soldered correctly, continuity tested, and structurally secured in place.	Reduced likelihood of failure	1	30	
				Breach/structural failure of seals (**clean water**)	Mechanical failure from improperly sized o rings, poor sealant used, corrosion cracks, large pressure/flow variations, pressurised clamp fittings	5	Flooding of breached zones, damage to exposed electronics, corrosion	Operations halt, potential electric shock	8	Seals, fixtures, connections and chassis are inspected regularly, O ring calculations are completed. Internally pressurised to prevent ingress. Pressure tested. Pressure monitored	Reduced likelihood of failure Higher chance of early detection	3	120	
				Breach/structural failure of seals (sewer water)	Mechanical failure from improperly sized o rings, poor sealant used, corrosion cracks, large pressure/flow variations, pressurised clamp fittings	5	Flooding of breached zones, damage to exposed electronics, corrosion, ingress of biohazardous debris	Operations halt, increased chance of user/technician interaction with contaminated components, future live surveys impacted.	9	Seals, fixtures, connections and chassis are inspected regularly. O ring calculations completed. Internally pressurised to prevent ingress. Pressure tested. Pressure monitored	Reduced likelihood of failure Higher chance of early detection	3	135	<- To consider in next phase for field trial prototype.
				Motor failure	Mechanical failure motor damage or malfunction	2	Unable to move robot	Operations halt, robot removed manually	4	Pre-flight checks on robot movement before deployment	Reduced likelihood of failure Higher chance of early detection	1	8	
					Electrical failure component/wiring failure	2	Unable to move robot	Operations halt, robot removed manually	4	Connections are wired and soldered correctly, continuity tested, and structurally secured in place.	Reduced likelihood of failure	1	8	
					Overheating from debris/friction requiring higher current to operate	3	Motor burnout and heating of local components	Operations halt, robot removed manually	4	Limit switches and fuses built into design. Speed controls to limit voltage input to motors. Regularly serviced	Reduced likelihood of failure Reduced severity of effect	2	24	
				Tracks failure	Mechanical failure from wear of track	2	loss of traction after a given distance travelled	Operational distance limited, potential manual recovery of robot.	3	Pre-flight checks on track wear, spare tracks provided with field work kit. Regular service	Reduced likelihood of failure Reduced severity of effect Higher chance of early detection	1	6	
					Incompatible pipe surface	4	loss of traction over pipe surface areas	Operational distance limited	3	H20 CCTV to assess pipe wall fouling/features prior to robot insertion. Water not to remain in test pipe for long periods. Test rig rinsed with chlorine, and rinsed with potable water before use.	Reduced likelihood of failure Reduced severity of effect (test rig) Higher chance of early detection	4	48	Do we need to test different track designs on non potable pipe wall features? (next phase)
				Reduced mobility	Unit heavy and difficult to lift	3	Heavy object Back injury, slips trip or fall	Minor injury to personnel	3	Compact system design enables single person to manually handle system with ease.	Reduced likelihood of failure Reduced severity of effect	10	90	
4	Sensor & Platform	Holds sensors, internal wiring for sensor power/data, positions sensor equidistant about the pipe's clockface,	Deploying/Recovering Through Pipe	Halo breaks	Mechanical failure - snagging/ impacting on Tee edges during deployment/ recovery, excessive pressure on mechanical connections	5	loss of sensor coms, loss of sensor data on user interface, hardware to pipe	Operations halt. Survey compromised/ abandoned	5	Test Rig built with equal Tees, Controlled deployment with tether connection, option of using a launch pole to lower robot into pipe with more control, halo body made from flexible material to allow some deflection. Spares made up. Launch pole and claw catchment system developed to assist access/egress.	Reduced likelihood of failure Reduced severity of effect	2	50	
				Halo supports break	Mechanical failure - snagging/ impacting on Tee edges during deployment/ recovery, excessive pressure on mechanical connections	5	loss of sensor coms, hardware to pipe	Operations halt. Survey compromised/ abandoned	5	Test Rig built with equal Tees, Controlled deployment with tether connection, option of using a launch pole to lower robot into pipe with more control, halo body made from flexible material to allow some deflection. Spares made up. Launch pole and claw catchment system developed to assist access/egress.	Reduced likelihood of failure Reduced severity of effect	2	50	
				Sensors come loose	Mechanical failure - sensor fitting/potting, dislodged by debris/ snagging	2	loss of sensor coms, hardware to pipe	Operations limited. Survey compromised/ abandoned	4	Connections are wired and soldered correctly, continuity tested, and structurally secured in place. Tested before leaving workshop. Checked before launch.	Reduced likelihood of failure Reduced severity of effect	2	16	
				Loss of comms	Electrical failure - component/wiring	4	loss of data on user interface	Operations halt. Incomplete survey	2	Connections are wired and soldered correctly, continuity tested, and structurally secured in place. Tested before leaving workshop. Attempt restart in-situ. Data saved intermittently.	Reduced likelihood of failure Reduced severity of effect	2	16	

				Unreliable data, poor data quality	Mechanical/ electrical - ambient noise generated from robot, sensor platform and sensor configuration lead to unreliable data open to misinterpretation, ragging	8	Loss of interpretable data	Operations halt. Survey compromised/ abandoned	2	Phase 1 testing to confirm extent of system noise on captured data. CCTV to map out expected areas of interest for data capture. Background noise subtraction algorithm implementation. Simulated testing on halo design.	Reduced likelihood of failure Reduced severity of effect	2	32
5	Internal pressurisation system	Pumps air or inert gas into robot's internal cavities to balance external water pressure	Deploying/Recovering Through Pipe	Breach/structural failure of seals (**clean water**)	Mechanical failure from improperly sized o rings, poor sealant used, corrosion cracks, large pressure/flow variations, pressurised clamp fittings	5	Flooding of breached zones, damage to exposed electronics, corrosion	Operations halt, potential electric shock, system retrieval, repair and restart Ops another day.	8	Seals, fixtures, connections and chassis are inspected regularly, O ring calculations are completed. Internally pressurised to prevent ingress. Pressure tested. Disconnect power for retrieval. Ideally, have a back-up system to swap out.	Reduced likelihood of failure Reduced severity of effect	3	120
					Mechanical failure - tether/tube	5	Flooding of breached zones, damage to exposed electronics, corrosion	Operations halt, potential electric shock, system retrieval, repair and restart Ops another day.	8	Seals, fixtures, connections and chassis are inspected regularly, O ring calculations are completed. Internally pressurised to prevent ingress. Pressure tested. Disconnect power for retrieval. Ideally, have a back-up system to swap out.	Reduced likelihood of failure Reduced severity of effect	3	120
					Mechanical failure - pump/pressurisation system	3	Internal pressure not maintained, leading to eventual water ingress	Operations halt, potential electric shock if repressurised or removed, system retrieval, repair and restart Ops another day.	7	Check valve fitted to maintain pressure, manual pump alternative on site if required, appropriate filters used on pumps, filters checked before use. Disconnect power for retrieval. Ideally, have a back-up system to swap out.	Reduced likelihood of failure Reduced severity of effect	2	42
				Unable to pressurise robot/ pressurisation lost	Mechanical failure - dust/water ingress from pump/pressurisation system, tether clogged, pump failure, system leaking	2	Internal pressure not maintained, leading to eventual water ingress	Operations halt, potential electric shock if repressurised or removed, system retrieval, repair and restart Ops another day.	7	Check valve fitted to maintain pressure, manual pump alternative on site if required, appropriate filters used on pumps, filters checked before use. Disconnect power for retrieval. Ideally, have a back-up system to swap out.	Reduced likelihood of failure Reduced severity of effect	2	28
6	PBIRM Test tig @ STARs	Simulated water/ sewer environment for sensor and sensor delivery development	Rig Commissioning	Leaks - flange joint connections/ end plate connections	Mechanical failure - bolts tightened to incorrect torque settings, gasket misaligned, gaskets damaged, debris at the interface, deformed flange surface	3	localised leaks at connections	Potential impact to data quality during tests through sound generation, air ingress or water loss to trench.	3	Bolts, flanges, pipework rated to 16 bar, PN 16 flanges used, bolts tightened to 120Nm in correct order, pressure tested to 1 Barg. Test rig buried for operator safety.	Reduced likelihood of failure Reduced severity of effect	1	9
				Leaks - 1/4" sensor ports	Mechanical failure - loosely tightened sensors, lack or gas paste/ Teflon tape, damaged threads	6	localised leaks at connections	Potential impact to data quality during tests through sound generation, air ingress or water loss to trench.	3	Fittings rated to 16 bar, Teflon tape used, tightened correctly, pressure tested to 1 Barg. Test rig buried for operator safety. Checked for corrosion at interface.	Reduced likelihood of failure Reduced severity of effect	1	18
				Leaks - 2" water inlet/outlet ports	Mechanical failure - loosely tightened sensors, lack or gas paste/ Teflon tape, damaged threads	6	localised leaks at connections	Potential impact to data quality during tests through sound generation, air ingress or water loss to trench.	3	Fittings rated to 16 bar, Teflon tape used, tightened correctly, pressure tested to 1 Barg. Test rig buried for operator safety. Checked for corrosion at interface.	Reduced likelihood of failure Reduced severity of effect	1	18
				Water stagnation	Water left in IBCs/ test rig for long periods without use, unsuccessful disinfection and cleaning process, factors that promote proliferation not minimised	5	biofilm, bacteria and other microbial growth within water	Operations halt, future operations delayed, potential for contact with biohazardous material/ contaminated surfaces	7	water containers, pipework and test rig submerged for 24 hr minimum in 20mg/l chlorinated solution and rinsed off before testing commences, IBCs wrapped in black liner to prevent sunlight penetration, IBCs, pipework and test rig drained off and emptied when not in use. regular water quality checks	Reduced likelihood of failure Reduced severity of effect	1	35
				Trapped fingers	Placement of horizontal end plates, DN300 valve, positioning pipe	6	Finger trapped	Minor injury to personnel	3	Minimum of two people for positioning of components Mechanical aids used to position and move components where necessary . i.e. hoist lifts, telehandler etc.	Reduced likelihood of failure Reduced severity of effect	10	180
			Testing	Loss of test rig sensing/ conductor short on sensing data	Electrical failure - component/wiring	4	loss of data on user interface	Operations limited	2	Connections are wired and soldered correctly, continuity tested, and structurally secured in place. Fuses fitted to prevent overcurrent situations. Operation performed in sheltered location.	Reduced likelihood of failure	1	8
				Conductor short on sensor power lines	Mechanical/ electrical failure from water ingress	4	Loss of input to user interface	Unable to start operations, risk of electric shocks	8	Connections are wired and soldered correctly, continuity tested, and structurally secured in place. Fuses fitted to prevent overcurrent situations. Operation performed in sheltered location.	Reduced likelihood of failure	1	32

			Robot Recovery/ decommissioning	Unable to empty contents of test rig	Ball valves seized, handle broken	3	water remains in rig	Rig modifications/recovery delayed	4	Valves operation checked prior to commissioning, kept covered when not in use, condition inspected before use. Riser end plates removed to enable pump access.	Reduced likelihood of failure Reduced severity of effect	1	12	
				Rapid depressurisation	Valves opened when at rig at test pressures	5	expulsion of water at force	Rig modifications/recovery delayed, trench damaged, potential harm to nearby people	8	Pressure transducers monitored when at pressure, pressure relief points installed on endplates, compressors/pumps turned off, only test personnel permitted access to rig when under pressure.	Reduced likelihood of failure Reduced severity of effect	2	80	
7	Launch apparatus & Insertion Tooling	Vessel and equipment to allow access and egress through a valve connected to live water/sewer riser	Mobilising / Setting Up/ Pre-flight checks	Fails to connect to pipe via access valve	Mechanical failure - wear, damage in transit to connecting surface, damage to connection surface on valve, corrosion	4	Unable to connect	Unable to start operations	5	Service inspection of interface surfaces and bolt fittings/ connections prior to site transit. Site inspection of valve connections. Suitability of materials reviewed. Procedure training.	Reduced likelihood of failure	2	40	
				Hand tools	Mechanical shear failure from overtorqueing bolts/valve connections	1	Unable to connect	Unable to start operations	5	Operator training, inpsection of tooling and connection fittings prior to leaving workshop.	Reduced likelihood of failure	3	15	
			System access process	Launch hook/claw	Operator error, insufficient component strength, ragging of hook/ catchment points, corrosion of mechanism	2	Unable to catch robot, robot drops	Operations halt, Damage to Robot/ pipe, Manual recovery with tether	7	Design calculations of component, appropriate materials selected, operator training, component testing	Reduced likelihood of failure	3	42	
				Launch tube fittings	Mechanical failure - weld/ O-rings/ valve connections/tube connections leaking	2	Unable to launch robot	Unable to start operations	4	Service inspection of fittings/ connections, and pressure test prior to transit to site.	Reduced likelihood of failure	3	24	
				Launch/valve seal	Mechanical failure - wear, damage in transit to sealing face, damage to/ poor condition of gaskets, bolts not tight, corrosion	4	Unable to seal, chlorinated water escapes when pressure tested (would not progress to next stage unless pressure test in situ successful)	Unable to start operations, minor chlorinated water spill, Operations delayed until seal reset.	4	Service inspection of connections, sealing surfaces and pressure tests, Suitability of materials reviewed. Site inspection of valve connections and sealing surface. Procedure training.	Reduced likelihood of failure Reduced severity of failure	3	48	
				Umbilical/gland seal (launch) & launch pole gland/pole camera cable seal	Mechanical failure - wear/ damage to foam, plastic or rubber inserts of gland stack, damage to gland stack in transit, damage gland stack valve fittings, corrosion	4	Unable to seal, chlorinated water escapes when pressure tested (would not progress to next stage unless pressure test in situ successful)	Unable to start operations, minor chlorinated water spill. Operations delayed until seal reset.	4	Service inspection of fittings/ connections, and pressure test prior to transit to site. Suitability of materials reviewed. Bring spare fittings for field replacement Procedure training.	Reduced likelihood of failure Reduced severity of failure	3	48	
				Purge valves	Operator error, mechanical failure/connection failure	2	Unable to open/close,	Unable to sta operations, unable to purge and pressure test in chloinated water.	4	Service inspection of fittings/ connections, and pressure test prior to transit to site.	Reduced likelihood of failure	3	24	
				Purge tubing blockage	Maintenace error - left uncleaned from prior operation, debris within tube bore	4	Unable to purge air efficiently, unable to fill launch vessel efficiently or at all	Unable to continue operations, unable to purge and pressure tests	4	Spare tubing part of equipment list, tubing checks and cleaned thoroughly after every use, valves checked for blockages prior to tube set up. Wider bored for outlet tubing.	Reduced likelihood of failure Reduced severity of failure	2	32	
				Access valve opened prematurely	Operator error	6	Sewer blow out into tube, potentially surrounding environment if not sealed, rapid compression of air within vessel - temperature increase	Equipment and environmental contamination, emergency shutdown of valve, operations halt.	8	Operator training, standard procedure to wait for pressure test confirmation prior to water purge opening access valve. Equipment and fitting rated appropriately specific riser main pressures.	Reduced likelihood of failure Reduced severity of failure	1	48	
				Purge tube fittings with hazardous waste container	Damaged connections, fittings, connections	4	Leaks during purge process	Chlorine water spill, Operations delayed	4	Service inspection of fittings/ connections, and pressure test prior to transit to site.	Reduced likelihood of failure	2	32	
				Hazardous waste container	Ooperator error - vent closed during operation	6	Pressure build-up in container	Potential damage to container, chlorine water spill during purge process, minor hazardous waste spill (minimal during system access)	6	Operator training, pressure relief valve as a back up to prevent container blow out.	Reduced likelihood of failure Reduced severity of failure	2	72	
			System egress process	Launch hook/claw	Operator error, insufficient component strength, ragging of hook/ catchment points, corrosion of mechanism	3	Unable to catch robot, robot drops	Operations halt, Damage to Robot/ pipe, Manual recovery with tether	8	Design calculations of component, appropriate materials selected, operator training, component testing	Reduced likelihood of failure	3	72	
				Launch pole jams	Mechanical failure - damage to pole, ragging around pole surface, corrosion, pressure transients	5	Unable to control robot retrieval	Unable to close access valve. Operation emergency shut down	9	Service inspection of fittings/ connections, glanding, surfaces and O-rings prior to launch. Move pole out of main flow, monitor visuauls on pole cam to predict levels of ragging. Occassionally test sliding of launch pole during operation to minimise large scale build up.	Reduced likelihood of failure	5	225	Again, need to think about additional surface mopdifcations to ensure non-stick/anti-ragging coating appiled in next phase.

				Launch tube fittings	Mechanical failure - weld/ O-rings/ valve connections/tube connections leaking	4	Localised foul water contamination	Operatives exposed to hazardous waste	9	Service inspection of fittings/ connections, and pressure test prior to transit to site. Self-amalgamating on hand for unexpected minor leaks. Appropriate PPE worn on site and access to washing facilities provided.	Reduced likelihood of failure Reduced severity of failure	3	108	
				Umbilical/gland seal (launch) & launch pole gland/pole camera cable seal	Mechanical failure - wear/ damage to foam, plastic or rubber inserts of gland stack, damage to gland stack in transit, damage gland stack valve fittings, corrosion, debris blockages and related wear.	4	Localised foul water contamination	Operatives exposed to hazardous waste	9	Service inspection of fittings/ connections, and pressure test prior to transit to site. Suitability of materials reviewed. Bring spare fittings for field replacement Procedure training. Appropriate PPE worn on site and access to washing facilities provided.	Reduced likelihood of failure Reduced severity of failure	3	108	
				Purge valves	Operator error, mechanical failure/connection failure	3	Unable to open/close, wrong valve opened - localised foul water contamination	Unable to sta operations, unable to purge foul water/ Operative exposed to hazardous waste	9	Service inspection of fittings/ connections, and pressure test prior to transit to site. Operative training. Appropriate PPE is worn on site and access to washing facilities provided.	Reduced likelihood of failure Reduced severity of failure	3	81	
				Purge tubing blockage	Mechanical failure - foul water debris blocks purge tubing.	4	Unable to purge foul water from tube in a contained manner	Operations delayed, potential for operatives to be exposed to hazardous waste.	9	Wider bore tubing is used for the launch tube outlet, and pipe cleaning tools are an option to intermittently unblock purge tubing. An alternative approach is to remove top end cap and pump out from there. Appropriate PPE is worn on site and access to washing facilities provided.	Reduced likelihood of failure	3	108	
				Access valve	Mechanical failure - debris/ragging preventing valve closure, robot blocking valve.	5	Unable to close valve	Unable to close operations, operation emergency shutdown	9	Assess valve interface with crawler and launch pole CCTV, attempt to clear debris with launch pole claws (impact robot retrieval). Appropriate PPE is worn on site and access to washing facilities provided.		3	135	<- Could be a possible issue to define within next phase. Commented on in concerns log.
			Cleaning, Sterilisation and waste disposal	Pump/compressor failure	Mechanical failure - blockage within waste mangement system, debris in pump	5	Unable to clean/ rinse off equipment effectively before removal from access point	Operatives exposed to hazardous waste	9	Spec out the pump appropriately, and monitor purge tubing and fittings during cleaning operations.		4	180	<- Will need to define within next phase.
				Cleaning efficiency	Mechanical failure - flushing not effective method of removing debris	6	Hazardous remains on equipment	Operatives exposed to hazardous waste	9	Manual cleaning outside of the launch tube to remove remaining debris. Potential to develop a contained jet/brush system to enter launch tube for contained cleaning operations. Appropriate PPE is worn on site and access to washing facilities provided.	Reduce severity of failure	4	216	<- Will need to define within next phase.
				Sterilisation efficiency	Chemical treatement failure - chlorine solution isnt enough to sterilise equipment fully	5	Hazardous remains on equipment	Operatives exposed to hazardous waste	9	Alternative means of equipment sterilisation to scope out - low vac UV Plasma cleaning? Appropriate PPE is worn on site and access to washing facilities provided.	Reduce severity of failure	4	180	<- Will need to define within next phase.
8	Sound Generator	Generates monotonous hum which sensors detect within the pipe. Specifically relating to the speaker, wiring, amplification, signal generator and submerisble speaker housing.	Deploying/Recovering Through Pipe	Conductor short on power line	Mechanical/ electrical failure from water ingress	4	Loss of input to user interface	Unable to start operations, risk of electrocution	10	Connections are wired and soldered correctly, continuity tested, and structurally secured in place. Fuses fitted to prevent overcurrent situations.	Reduced likelihood of failure Reduced severity of effect	1	40	
				Reduced mobility	Tether on the ground, tangled around site furniture (fencing, control boxes, access points, Vans)	3	Back injury, slips trip or fall	Minor injury to personnel	3	Tether length capped at 40m, tether path visibly marked, tether positions out of main walkways and secured in place. Use of a cable reel to manage cable lengths.	Reduced likelihood of failure Reduced severity of effect	10	90	
				Loss of Sound	Water ingress, damage to speaker diaphragm/cone, overcurrent	4	No pressure waves generated in water	Unable to inspect pipe condition	5	Seals, fixtures, connections and housing are inspected regularly, O ring calculations are completed. Speaker tested above ground prior to submersion. Spare components part of standard site kit.	Reduced likelihood of failure Reduced severity of effect	4	80	