Project closure report

Acoustic Communication in Gas Mains

Phase 1 & 2

NIA_SGN0040

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A consolidated summary report by Caroline Geddes
on behalf of Angus McIntosh, Innovation & New Technology Manager

Key contributors:	N S Ferguson	University of Southampton
	P F Joseph	University of Southampton
	C Paruchuri	University of Southampton
	Martin Chorley	SGN, Innovation Project Manager

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Document control

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Reviewers

Name	Job Title	Email Address
Max Paladini	Innovation Graduate	Max.paladini@sgn.co.uk
Angus McIntosh	Innovation & New Technology Manager	angus.mcintosh@sgn.co.uk

Management approval

Name	Job Title	Signature
Angus McIntosh	Innovation & New Technology Manager	

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1 Introduction

The Acoustic Communication in Gas Pipes project is concerned with developing an alternative communication method to interconnect pressure monitoring and control equipment.

This project aimed to potentially replace the rented telephone landlines and mobile communication links presently used, and also provide improved network pressure control to minimise gas leakage.

Currently many of the low pressure gas networks employ data logger and electronic control equipment to monitor pressures and profile control governors. These collect operational data for management and planning purposes and minimise network pressures to reduce gas leakage.

The technique to be investigated is the use of acoustic communications within low pressure gas networks. The acoustic technique, through laboratory simulation and field trials was anticipated to provide gain an understanding of typical pipe network acoustic characteristics under operational gas conditions to ascertain a suitable transmission signature signal for data transfer and to discover the potential restrictions of the technique.

Having discussed potential new solutions with existing suppliers, it was deemed more valuable to send invitations to partner to Universities that have relevant experience in this area of work. Various Universities were contacted throughout Great Britain (GB), from which SGN received one positive response from the University of Southampton’s Institute of Sound and Vibration Research. Their extensive experience in the analysis of sound and vibration propagation in pipe work systems demonstrated their pertinence in working on this project. Additionally, the University of Southampton extensive specialist research facilities for laboratory testing provided reliable and available testing conditions. SGN would provide access to typical low pressure networks to gather acoustic data for analysis and information to allow network models to be built and assessed for acoustic propagation.

To achieve the project aims, the University of Southampton proposed to develop suitable measurement, testing and recoding techniques capable of gathering acoustic data based on their understanding of SGN’s pipe networks’ acoustic characteristics. Laboratory simulation to test this new method would then be carried out, followed by an acoustic study on a typical gas main network. The equipment and techniques used to receive suitable acoustic signals would also be assessed. The received signal transmission would then be analysed to establish the characteristics of a potential suitable signature acoustic signal for transmission.

Following the testing of the electroacoustic instrumentation on metallic and plastic pipes, the equipment demonstrated that sound can be transmitted and measured along distances of up to 750 metres. A suitable sound signal level was also established to be typically below 1800 Hz in a 100mm plastic pipe diameter. Acoustic communication is possible using the electroacoustic instrumentation. However, sound reflected along metallic pipes and against certain pipe layouts, makes it difficult to communicate information accurately. Therefore, since pipes cannot be adjusted for acoustic communication purposes, the next steps would be to develop more suitable frequency modulated signals.

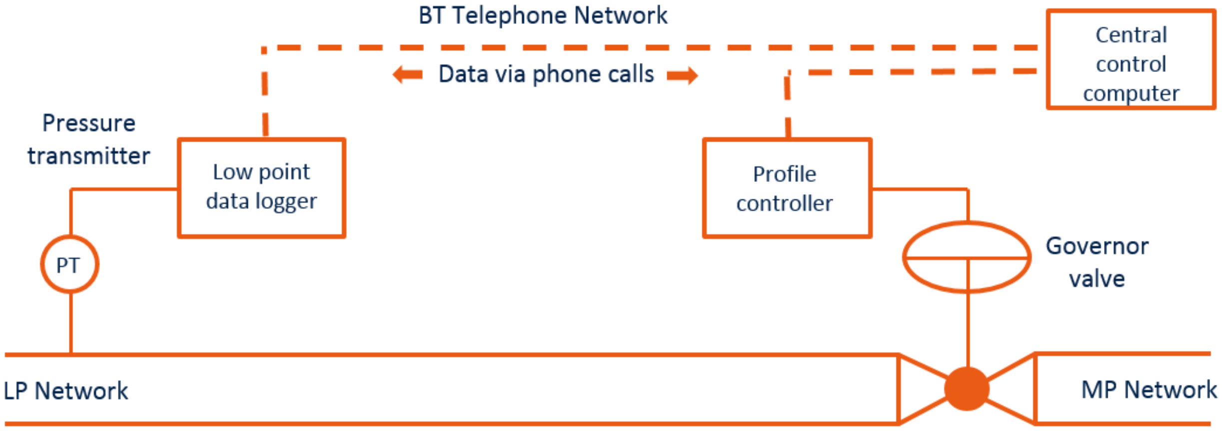
1.1 Project background

Currently many of the low pressure gas networks employ data logger and electronic control equipment. These technologies monitor pressures and profile control governors to collect operational data for management and planning purposes and to minimise network pressures to reduce gas leakage.

Approximately 6000 SGN locations on the gas networks, where monitoring or control facilities are required, communication is provided by telephone land lines and mobile GSM (Global System for Mobile) communication rented facilities. The installed equipment communicates with depot based modems and computer systems to transmit and receive network parameter data and control commands and settings. These rented facilities, whilst providing a reasonably reliable service, suffer from the following disadvantages:

- High installation costs for landlines
- High line rental and call charges
- Fault rectification by service provider outside the control of SGN resulting in additional delays in returning to normal profile control and associated elevated pressures
- GSM signal coverage is limited and unreliable in some geographical areas

A simplified block diagram of an existing profile control system using landline communication is shown below:



A typical acoustic system may consist of transmission and collection sensors mounted on a pipeline designed to convey operational data using pulses of low to medium high frequency sound through the gas media.

SGN have a large number of leased telephone lines which are used to communicate with remote electronic equipment to monitor and control low pressure networks, across both our Scotland and Southern license areas. These systems allow network pressures to be constrained at the safest minimum low pressure to ensure security of gas supply to the customer, whilst minimising gas leakage.

Leased lines suffer from system disconnections and line faults, which often results in the loss over extended periods of monitoring and control facilities with the consequence of higher network pressures and increased leakage. These faults are generally difficult to resolve and require multiple site visits between SGN and service providers, which are problematic to coordinate. Associated remedial work is generally outside the direct control of SGN relying on the cooperation of service providers.

1.2 Network Innovation funding

Innovation is a key element of the new RIIO (Revenue = Incentives + Innovation + Outputs) model for price controls. One of the key innovation proposals was the introduction of both the Network Innovation Allowance (NIA) and the Network Innovation Competition (NIC) for all Network Licensees funded under the RIIO framework.

The purpose of these funding mechanisms is to provide a consistent level of funding to Network Licensees to allow them to carry out research, development and demonstration projects which, when at an early stage, yield uncertain commercial returns. In addition, where benefits are linked to the decarbonisation of the network, it may be difficult to commercialise the respective carbon and/or environmental benefits and shareholders may be unwilling to speculatively fund such projects.

The Acoustic Communication in Gas Mains project forms part of SGN's NIA. The NIA funds smaller innovation projects that will deliver benefits to Customers as part of a RIIO-Network Licensee's price control settlement. The SGN Investment Committee were asked to approve the total operating expenditure of £42,760 in 2013/14 and 2014/15 for a project to investigate the feasibility of acoustic communications in gas mains, to provide an alternative means of data communication between data logger and profile equipment used to monitor and control the low pressure networks.

1.3 Acoustic Communication in Gas Mains

The University of Southampton's Institute of Sound and Vibration Research has developed innovative acoustics research over the last 50 years. Their researchers work collaboratively with major industrial stakeholders and other leading research institutions. Key research areas include engineering noise control, transport noise, vibroacoustics, underwater sound, audio engineering and sound perception. Subsequently, in collaboration with SGN, the University of Southampton have identified a means to measure sound transmission along complex pipe systems as an alternative to wireless communications using electromagnetic transducers. This equipment was tested to determine the distance that sound can travel and provide information about gas pressure for gas control and regulation purposes.

The electroacoustic instrumentation is used to produce sound using a compact loudspeaker driven by a computer generated Bluetooth signal. The instrumentation wirelessly communicates sound to vented microphones connected to an amplifier, which collect the acoustic measurements. For the transmitted sounds to be picked up by the microphones, it must be 3 decibels louder than background noise to avoid any interference. The sounds transmitted were a combination of broadband frequency content random signals, or "white noise" and impulsive signals and "chirp" sounds for example. The microphones (shown below) were located at different locations along the pipe and acoustic pressure measurements were gathered at each microphone location.

1.4 Project objectives

The objectives of this study were to:

- Develop proof of concept of an acoustic communication solution capable of replacing telephone lines for pressure data logger and control equipment
- Evaluate the performance of the acoustic technique to establish the potential transmission distance
- Provide relevant information to other Network Licensees.

2 Investment options

Following SGN's open invitation to tender, the University of Southampton provided a positive response to implement a three-phase project.

Phase 1:

Planning, familiarity with the gas pipe network, review relevant research, develop suitable test methodology and complete laboratory simulation.

Phase 2:

Acoustical study on a typical gas main network with data recordings, analysis and signature identification for transmission requirements.

With the successful delivery of the above phases, the University of Southampton now propose to continue with the third phase.

Phase 3

Investigate hardware requirements, signal characteristics and processing for technology transfer, providing the Final Report for the feasibility study.

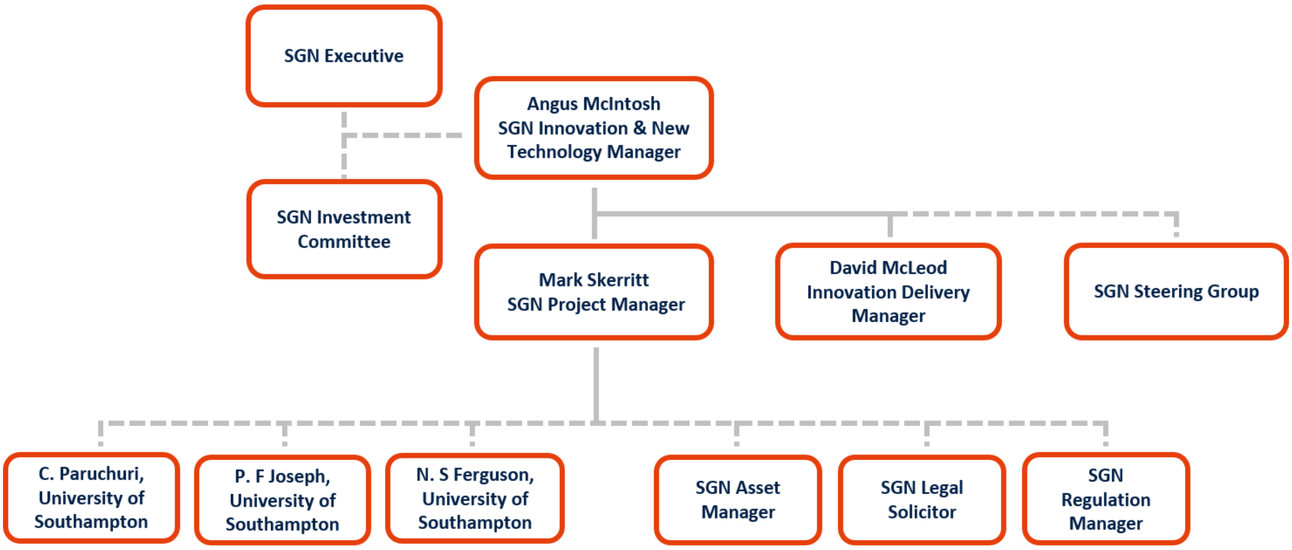
3 Project delivery

This project experienced delays due to ongoing negotiations regarding the legal agreements between SGN and project partners, the University of Southampton. A change in personnel at the University of Southampton also resulted in further negotiations, specifically around the Intellectual Property Rights (IPR) and Warranties sections of the legal schedules.

The issues around these sections were resolved with an extension of one year added to the project duration to ensure the success criteria in the original project registration were met. This change had no impact on the original project benefits, outcomes or project budget.

4 Project team structure

To ensure the project was delivered efficiently with adequate internal support from within SGN, the project team shown was developed.



5 Site preparation works

With the availability of SGN's redundant pipe network site in Northam, results from testing an existing pipe network could be collected. It enabled testing of sound signals to be carried out across a variety of conditions; bends, junctions and pipe diameter. The data collected from the testing at this site provided a set of comparable results to the tests carried out at the pipe system training site in Poole. This plastic pipe network of 100mm diameter pipes was set up for training purposes and was representative of an actual gas network pipeline. This readily available site provided an opportunity to carry out testing without needing to insert into a live gas mains, which avoids associated disruptions and safety concerns.

6 Results of testing

Following the testing of the electroacoustic instrumentation at two redundant gas pipe sites, one metallic and one plastic, the equipment demonstrated that sound can be transmitted and measured successfully along distances of up to 750 metres in plastic pipes. A suitable sound signal level was also established to be typically below 1800 Hz in a 100mm plastic pipe diameter.

However, the metallic pipes in particular demonstrated that the length and layout of the pipe reflected sound. This enabled sound to travel further, however the sound reflections made it difficult to communicate information accurately. Sound reduction also occurs at valves and junctions, which are areas of greater decay and occur regularly in metallic pipes. Sound reduction occurs mostly at junctions due to the pipe layout as it causes an acoustic obstruction and reflections. On 90° bends though, some sound is able to continue along the pipe route by sound reflections with less interference.

An alternative to transmitting sound in a reflective environment would be to use plastic pipes. This is where it was found that due to fewer reflections, acoustic communication was more efficient and sound can be transmitted up to 750m. However again, the presence of bends and junctions etc. reduce the transmission range of sound.

These results show that acoustic communication is possible using the electroacoustic instrumentation, however the reliability of results vary between pipe material and layout. Therefore, the next steps would be to develop more suitable frequency modulated signals for more accurate acoustic communication.

7 Conclusion

Following SGN’s invitation to partner to develop an alternative communication method to connect pressure monitoring and control equipment, the University of Southampton proposed to test sound transmission using commercially available electroacoustic instrumentation. This equipment produced a variety of sounds across different gas pipe surfaces and pathways.

The testing was carried out at two gas pipe sites, which were representative of actual live gas mains. One site was built up of redundant metallic gas pipes and the other presented an opportunity to test in plastic pipes. It was found that the highly reflective surface of the metallic pipes prevented sound from being transmitted efficiently at all frequencies through long distances, which limited the accuracy of the information being communicated.

The transmission of sound along plastic pipes was slightly higher attenuated or reduced in level with distance travelled than in metallic pipes. In all pipe diameters there is a frequency above which sound travels both along and across the pipe cross-section, rather than travelling as a plane wave along the length and so above these frequencies sound will not travel in a clear manner and be applicable for communication purposes. Likewise, the presence of valves, junctions, area changes and bends partially reflected the sound and decreased the transmission range.

8 Recommendations

As a result of the sound transmission interference caused by pipe material and pathway reflections, the University of Southampton recommend a next phase to develop more suitable types of signals that would be transmitted and measured using advanced signal processing method for data recovery. Following this stage, this potentially improved process would then be tested on live gas mains.

9 University of Southampton Executive Summary

9.1 Phase 1: Planning, familiarity with the gas pipe network, review relevant research, develop suitable test methodology and complete laboratory simulation

1. Finalise the scope of work for the project with SGN.

Clarify the requirements; identify any information on the gas pipework including pipe geometries, pressure, flow rates, etc., which is required and possible limitations for gas main tests.

Over a number of meetings with the SGN representatives, the layout of typical gas services were examined with a suggestion of identification of a live part of the network, pipe dimensions, etc. This also incorporated a visit to a repair of a live section in London, where a tethered robot was being trialled to inspect and seal leaks in cast iron pipe. The on board microphone of the robot was considered as a possible means for use during subsequent acoustic tests, but the signal to noise level was poor and its main purpose and function deemed insufficient for this project in addition to the signal connections being integral within the connecting cabling and control unit.

2. Understand typical pipe networks and their acoustic characteristics.

A number of dimensions and distances were considered and, as will be shown later, the frequency for which plane acoustic wave behaviour estimated. A site visit to the SGN depot at Northam, Southampton, familiarised the team with the potential inherent noise sources due to supplies, regulators, etc. Over two later visits the team undertook measurements on a number of geometries and lengths to quantify on the available geometries the effect of bends, changes in pipe diameter, restrictions and attenuation (reduction in sound level) with distance. These results are presented in later sections 13-14 of this main report and were presented at the Project Review B stage.

3. Complete a review and evaluation of relevant published research to support project.

Much of the published work is in the area of leak detection or pipe inspection, with acoustic related techniques applicable for either gas or fluids (oil, water, etc.) flowing within the pipes. Typically acoustic methods for leak detection (Hunaidi, Osama, and Wing T. Chu. "Acoustical characteristics of leak signals in plastic water distribution pipes"). Applied Acoustics 58.3 (1999): 235-254.) include monitoring the sound that occurs due to a leak, with noise sources covering a wide frequency range (1 kHz to 1 MHz) and propagating further in the pipe wall than the fluid or gas itself. For plastic pipe, with higher mechanical dissipation losses, then using the pipe as the conduit for propagating a vibration signal in these instances for communication in the gas network will be limited in distance rather using sound propagation in the acoustic volume itself.

An alternative leak detection method, known as Acoustic Reflectometry (Sharp, D. B.; Campbell, D. M., Acta Acustica united with Acustica, Volume 83, Number 3, May/June 1997, pp. 560-566(7)) deliberately introduces sound into the pipe to get reflections from the presence of blockages, leaks or changes to the pipe geometry and separates out the incident and reflected sound waves in the measured signal that is downstream of the acoustic source. It had been suggested that such methods could be used for up to hundreds of metres from a source and reflecting leak, blockage, etc., for gas filled pipes.

For a pipe filled with a heavy fluid, the propagation can be over much greater distances of up to 5 km (Papadopoulou, K. A., et al. "An evaluation of acoustic reflectometry for leakage and blockage detection." Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science 222.6 (2008): 959-966), but this is due to the low attenuation of the vibration in the pipe wall although there is still a need to remove the effect of reflections of the signal at bends, etc., to recover the information which is due to the presence of the leak.

One important difference between air and fluid in pipes is the amount of coupling between the sound inside the pipe and the vibration of the pipe walls. For air, gas, etc., the acoustic and wall material properties (impedance) are very different and essentially little coupling and energy transfer occurs into mechanical vibration of the pipe from the internal sound. In contrast, for fluids in pipes the acoustic to mechanical coupling is strong. The only special case is for high pressure gases in pipes, where a resulting leak can cause structural excitation of the pipe walls and vibration in the form of propagating wave disturbances which could propagate over large differences (5 km or more have been quoted), but in this case the excitation mechanism is not sound in the internal gases themselves. For many references on leak detection, use is made of the measured pipe wall vibration.

The simplest concept of voice pipes or speaking-tubes dates back to the late nineteenth century, typically used for propagation over distances of tens of feet up to a hundred feet. The main principle being that sound when contained within typically cylindrical pipes travels more efficiently with less sound level reduction compared to radiation in free space with additional spherical spreading. Early observations showed that the levels decreased as the pipe diameter increases and also when the surface of the pipe was rougher. This first early comment has now been reversed when consideration of the losses in sound energy due to the wall area has been considered, typically the loss (or reduction in level) in decibels (dB) is inversely proportional to the cross-sectional area of the pipe and so theoretically a 5 cm straight pipe, without flow, etc., should have a reduction of 30 dB per 100 m. This will be tested and reported later in phase 2 of this study.

In terms of methods for communicating information in pipes for applications to the gas industry, fewer articles were found. The most relevant article by Sakuma et al considered communication in a six storey building in order to transmit information for automatic reading of gas meters. A pulse acoustic signal was introduced and the subsequent transmitted and reflected signals acquired. The details of the method are complex but essentially involve using a particular type of signal to transmit the information (Two-way communication over gas pipe-line using multicarrier modulated sound waves with cyclic frequency shifting, Acoustic Science and Technology, Vol. 27, pp 225-232, 2006)

The main innovation in this work is the development of a signal that is amplitude modulated in addition to having multiple carrier frequencies contained in the initial introduced signal that reduces the effect of echoes due to multiple reflections and the multiple paths. This type of signal in this environment allows the 'hidden' signal to be recovered and separated out from the numerous echoes. The signal processing is reasonably well developed. It uses a process whereby the original signal is used to vary the amplitudes of a number of single frequency carrier signals and then the received signal is demodulated in order to retrieve the original signal information. Such methods have been well developed for underwater acoustic applications, were reflections can occur off the sea bed etc., and look promising for adoption to this application in future studies. Likewise they are used for amplitude modulation of radio transmissions.

4. Develop suitable measurement, test and recording techniques to gather network pipe acoustic data.

From the measurements made, the project identified the appropriate frequency range (below 1800 Hz in plastic pipes of 100 mm, for example) for which sound will propagate with lower attenuation. The use of standard commercially available electroacoustic instrumentation, comprising a compact source loudspeaker with a reasonably flat frequency response from 20-5000 kHz and not necessarily expensive could be used to produce the sound, wirelessly driven, with sound measured using vented microphones to allow acoustic pressure measurements in pipe system at high ambient pressure. The microphones do not need to be instrumentation class, as used in the project, but should be able to measure sound over the same frequency range as the adopted loudspeaker and preferably have a flat frequency response. Whilst the source needs to be compact, so that it will fit inside the pipes or an attachment to the pipes via a connected volume such as a side branch, its sound power output might be limited by its compact size, particularly at low frequencies.

The signals need to be received at levels at least 3 dB (decibels) above the background noise of sound in the pipe. Multiple reflections seen in the measurements indicated that it is preferable to develop a combined acoustic signal with a single or multiple carrier frequency rather than solely use a method based on using the level of the received signal at a remote point or its frequency content, the latter might be affected by resonances within pipe sections.

5. **Complete a laboratory simulation to prove test method. Subsequent to the outcomes of Stage 1, the tests might be on scaled pipework, with or without flow or raised pressure.**

The availability of the redundant cast iron pipe networks and long lengths of pipe at SGN in Northam allowed for these phases to be substituted for tests on available existing pipe network. There were a number of pipe lengths, junctions, bends as well as pipe diameters. A summary of the results are given later. The tests used a loudspeaker source, driven by signals sounds of different frequency content, in a number of small lengths (up to 10 m) comprising many straight and 90 degree bends. A number of microphone locations were cut into the pipe wall before and after the changes of direction of the sound. The sound propagation measurements made over the longer distances were conducted using the longer pipe lengths connecting a redundant gas holder to the ends of the disconnected pipe lines which were located close to the gas regulators. This provided measurement distances of up to 200 m between the loudspeaker and the furthest microphone measurement positions.

9.2 Phase 2: Acoustical study on a typical gas main network with data recordings, analysis and signature identification for transmission requirements

6. **Complete an acoustic study on a typical gas main network.**

The availability of the network at SGN Northam provided a useful and important dataset for subset tests at the Corporate Safety Management (CSM) training centre in Poole. The set-up provided at CMS was a small network comprising 100 mm diameter plastic pipes, multiple long pipe lengths and multiple bends and outlets in addition to an air supply with flow. This avoided requiring equipment to be inserted into a live gas network and the complications associated with intrinsically safe instrumentation, etc.

7. **Analyse acoustic data and pipe networks characteristics to investigate the feasibility of signal transmission.**

Examination of the later tests at Poole show clearly the cut-off frequency, where sound no longer travels as plane waves down the pipe length. Above this frequency there exists a variation in acoustic pressure over the pipe cross section and is more strongly coupled to the pipe wall and is therefore more strongly attenuated. This is important as it identifies a useful frequency limit above which the sound will not propagate efficiently and will potentially propagate a shorter distance. Typically the separation between installations or regulators and low pressure locations might be in the range of 400 m to 2 km depending on the network geometry.

8. Establish the characteristics of a potentially suitable signature acoustic signal for transmission.

From the highly reverberant measurements on the larger diameter pipe network (Northam) the measured response signal due to a short-duration acoustic signal contained multiple high-amplitude reflections. So if using pulses to send data in a 'Morse code set of pulses' it would be impossible to recover the original signature due to multiple pulse reflections adding to and changing the received pulse train signal.

It is a more preferable approach is to use a signal which is not dependent upon the separation of individual pulses, but is something which uses frequency separation techniques recover the required information. Such a requirement leads to the idea of taking either a single or a multiple number of single frequency tones whose amplitude can be modulated or specified using the required information. When this is received at a remote distance from the original sound source location, then the combined signals can be demodulated to recover the underlying signal which modulated the carrier tones. Alternatively, one could use a signal where the single frequency signal can have its frequency generally increased or decreased, known as a chirp or swept sine signal, and use the required signal as being the measure of the change in frequency whose sweep rate can be retrieved. This sweep rate could contain the important data such as the pressure in the gas, for example.

9.3 Phase 3: Investigate hardware requirements, signal characteristics and processing for technology transfer, providing a Final Report for the feasibility study

9. Investigate equipment and techniques to transmit and receive suitable signature acoustic signals.

The tests at Northam examined the frequency content and its influence on the range of propagation due to attenuation caused by losses in the pipe wall and the rough surface of the pipe etc. The tests considered both a broadband frequency content random signal (known as white noise), in addition to a chirp or swept sine signal and an impulsive signal. The signals were generated with the commercial analyser software and system (Data Physics Quattro system), but could have been created as audio files which were sent via Bluetooth to the loudspeaker inserted into the pipe network. Over the large range of distances tested at Northam the reflected pulses were in the background noise of the microphone (PCB Piezotronics ½" microphone) measurements, but were seen on the shorter lengths where there were multiple bends and junctions, so allowing for strong reflections arriving soon after the initial signal was transmitted.

10. Produce a feasibility study report incorporating project data, acoustic trial results and recommendations for future follow on studies for implementation of the outcomes of the project.

The report containing the project data from the two test sites has been produced and assists in identifying the feasibility and expected propagation distance and source level requirements from the data using an empirical fit to the sound levels below the cut-off frequency where only plane wave sound can propagate within the pipe. The report summarises the main outcomes, highlight points of interest and suggest recommendations for future activities and improvements or limitations of using acoustic measurements.

8.0 Outputs

1. Final oral presentation to an SGN representative (Project Manager M. Chorley in December 2015)
2. Final written report with the main findings, likelihood of technology transfer and identification of any further refinements or additional developments necessary for implementation, incorporating hardware and software requirements.

10 Introduction

SGN, as is typical with all mains gas networks, ideally needs to know the pressure at different parts in the low pressure gas network. This would then in principle allow any changes at the regulators to be made as demand or gas supply varies within the system. The use of pressure measurements requires this information to be communicated back to the control rooms. Presently, costly land lines are generally used as locations are possibly remote and would not be accessible to wireless or mobile signal communication. This project responded to an invitation to partner SGN in exploring the feasibility of using sound within the gas pipes as the conduit or path for the gas pressure information to be communicated. Typically the distances between installations could be in the range of 400 m to 2 km apart, so for such distances one question to consider is whether the sound could travel in a sufficient manner to act as a possible alternative to the fixed telephone lines. The issues conceived as potential limitations includes the possibility of any background noise, the effect of variations in the gas pressure, flow rates etc., and the expected distance for reliable acoustic communication.

The nature of sound propagation in pipes is reasonably well understood theoretically, but the introduction of sound within gas pipes of various material constructions (cast iron or plastic) is less well known as are the effect of pipe joints, outlets or bends, which are less amenable to simple analyses or quantification other than by experimental means in the first instance.

Hence this final report covers the experimental studies and the analysis of the data in order to assist SGN and other gas network operators in determining distances over which it might be feasible to transmit sound as the communication path for transducers in the pipe network. These would be used for monitoring aspects of the pipe such as the gas pressure at potential low gas pressure points etc., which can then be used for subsequent gas control and regulation.

11 Scope of document

The scope of this document is to report and interpret the data obtained from the experimental tests undertaken at two test sites as well as analysis of the data, derive conclusions and summarise the findings of the project. The report covers:

- The test procedures and instrumentation, including the use of different acoustic signals (broad band, single frequency or swept-sine (chirp) frequency).
- The frequency range over which sound propagates with the least attenuation and the reason for attenuation at higher frequencies and the effects of absorption of sound by the pipe walls and the reflection of sound due to bends.
- An empirical relationship for the sound attenuation or reduction in level with distance travelled
- A summary and conclusions for the whole project

12 Project objectives

12.1 General

The principal objectives of the work presented in this report is the acoustical characterisation of typical gas pipe distribution networks for the purpose of assessing the distance over which information can be transmitted acoustically along the network. Presently, information related to pressure and flow rate is transmitted using a costly fixed line telephone system as illustrated in the project background. This report includes the findings of tests that use sound to transmit information along the pipe system as an alternative to wireless communications.

The objectives of this investigation may be summarised as:

- To establish a test procedure for the measurement of sound propagation along complex pipe systems typical of gas distribution networks, which include valves, bends and other junctions.
- To identify / procure transducers and acquisition systems that facilitate the measurement of sound propagation along complex pipe systems.
- To quantify the transmission loss (reduction in acoustic pressure in decibels) per unit distance (per metre) as a function of frequency for a straight section of metallic and plastic pipes used in gas distribution networks.
- To quantify the transmission loss (reduction in acoustic pressure in decibels) across a bend or junction as a function of frequency for a straight section of metallic and plastic pipes used in gas distribution networks.
- To arrive at a formula to determine the distance (as a function of frequency) along the pipe system over which sound can be transmitted that is at least 3dB above background noise levels. This assumes that source levels and background noise levels are known. The latter will vary strongly according to location in the network and time of day.
- To arrive at a formula to determine the source strength (as a function of frequency) required to transmit sound a particular distance along a pipe system with a given number of bends and junctions.

12.2 Benefits

Whilst not directly focussing on the implementation or costs of such a replacement to the fixed telephone line systems, there is still benefit in knowing the gas pressures at known low pressure locations and, ideally, do this in real time rather than using present methodologies. The existing 24 hour gas profiles allow monitoring and the safe operating levels to be maintained from existing profile control, historical data, etc., but do not offer the potential of direct closed loop control in real time. If an acoustic system, once set up and suitably powered, is available and if necessary having repeater stations, then other than the small delay for the sound to propagate over the required distances the data can effectively enable real time control at an affordable cost.

12.3 Challenges

Two of the main challenges for any implementation are the knowledge of the distance over which sound will travel within a typical gas pipe network and how any hardware for such a system could be inserted or connected to the gas main how it would be powered whilst operating inside it. This project is not concerned with the latter requirement in any sense, but concentrates on the sound propagation issues, limitations and requirements in terms of frequency content, sound attenuation and the effects of pipe geometry.

12.4 Project scope

The scope was primarily limited to an experimental investigation, considering applicable instrumentation, sound sources and signatures which might be suitable for recommending for future investigations, development and technology transfer to a live gas main network.

12.5 Success criteria

The main success of these tests will be in quantifying a suitable frequency bandwidth to use to propagate sound with the least attenuation, and to identify over what distances a potential acoustic communication system could be envisaged as being possible. The suitability of different acoustic signals will be compared, but not specifically taken forward at this stage for more advanced signal processing and noise removal techniques.

13 Summary of test conducted

The tests were undertaken in two phases. The first was undertaken on a metallic pipe network and the second on a plastic pipe network. Sound was introduced at one end of a network and subsequently measured at a number of distances and analysed for its frequency content and the effect of the distance and path over which the sound has propagated.

13.1 Phase 1. Measurements on the metallic pipe network at SGN Northam Depot, Southampton

The first test was undertaken to characterise sound propagation in a redundant cast iron gas pipeline made between 19/02/2015 & 25/03/2015 at a decommissioned site in Northam, Southampton.

Figure 1. The test site in Northam, Southampton

The site comprises a complex series of metallic pipe sections of large diameter. We shall show in section 5.1 that attenuation along this pipe system is very small. However, the complication in this type of pipe system for transmitting information along the pipe acoustically is the presence of strong reflections at the terminations. The diameter of the network pipe is 18 inch.

Another set of experiments were carried on long straight pipe between the original gas holders, to establish the attenuation of sound in long larger diameter (48 inch) pipes. The maximum length of the straight section is around 200 metres and 48 inch in diameter.

13.2 Phase 2. Measurements on the plastic pipe network at Bourne Valley Road, Poole

The second phase of test campaign was undertaken between 26/10/2015 and 27/10/2015 on a pipe system based in Poole, Dorset. A photograph of part of the pipe network is shown below in figure 2.

This site consists of the gas network with realistic mean flow. The gas network is representative of a realistic live gas network. The gas network have a straight section and also two 135^o bends as described in section 5.2.

To understand the sound attenuation in long pipe and 90^o bend plastic pipe, measurements are performed on them. Here the measurements are performed in a non-live state.

Figure 2. The test site in Poole, Dorset

14 Results

14.1 Phase 1

A schematic of the section of pipe system investigated in this part of the project is shown below in figure 3. One end the pipe was capped. A rectangular section was cut into the pipe at this end in order to introduce a loudspeaker 112mm from the capped end.

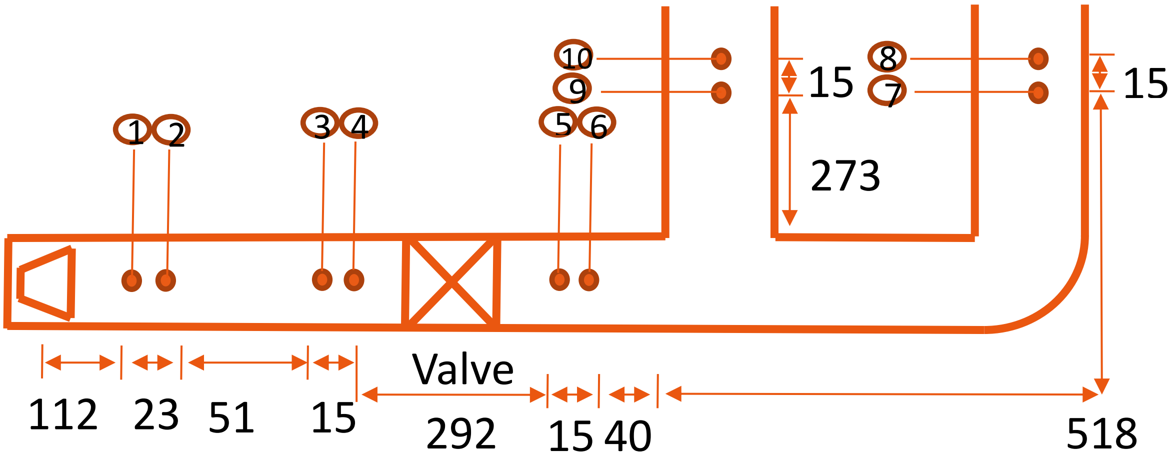


Figure 3. A schematic of short pipe-line at SGN in Northam (dimensions in mm)

A total of 10 holes were drilled into the pipe, (figure 2) in order to measure the acoustic pressure at various strategic locations along the pipe. A photograph of holes 1 and 2 with one microphone inserted (B&K 4472 microphone), is shown in figure 4 below.

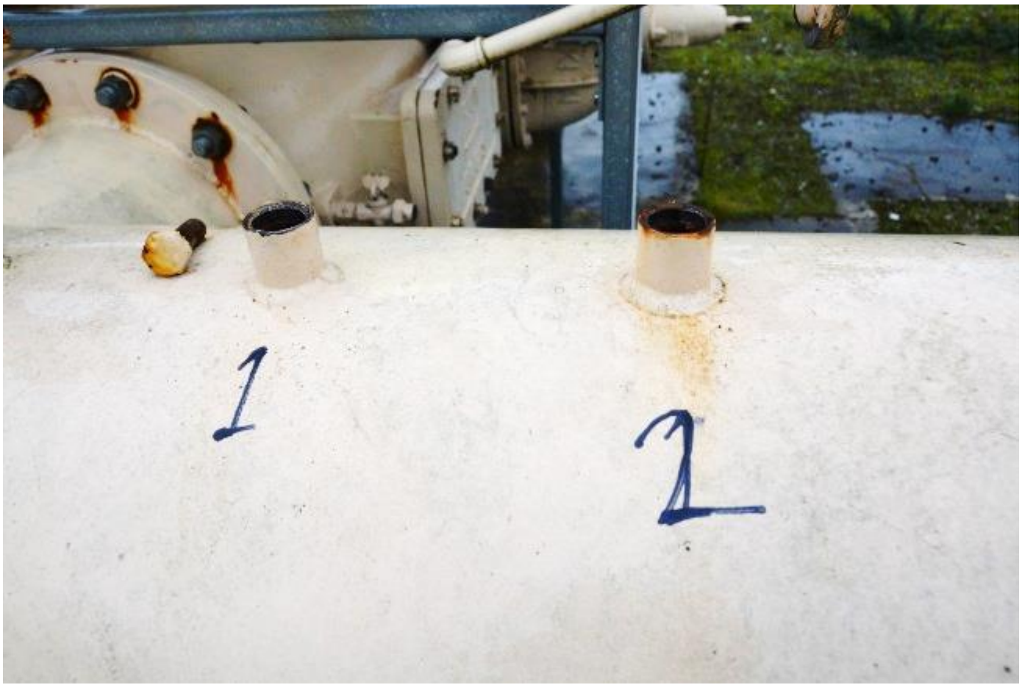


Figure 4. Microphones holders used to measure the sound pressure in a duct at test site in Northam

Six of the holes were located along the straight section (holes 1, 2, 3, 4, 5 and 6), two located along a side branch (holes 9 and 10) and two across a 90° bend (holes 7 and 8). Holes 3, 4 and 5, 6 are located either side of a valve.

Instrumentation:
The loudspeaker was driven by a signal generator, which generates a broadband (wide frequency) random white noise signal. Acoustic measurements were made by a two 1/2” condenser microphones (B&K Model no: 4189-L-001) which are connected to a Nexus amplifier. A four channel data physics analyser was used to acquire the signals at sampling rate of 25600 Hz. (samples acquired per second).

Results:

Sound pressure measurements on the short pipe

The sound pressure level spectrum in very narrow frequency bands at microphone location 1, close to the loudspeaker, between 50Hz and 200Hz is plotted in figure 5 to show the existence of resonance frequencies in the pipe response.

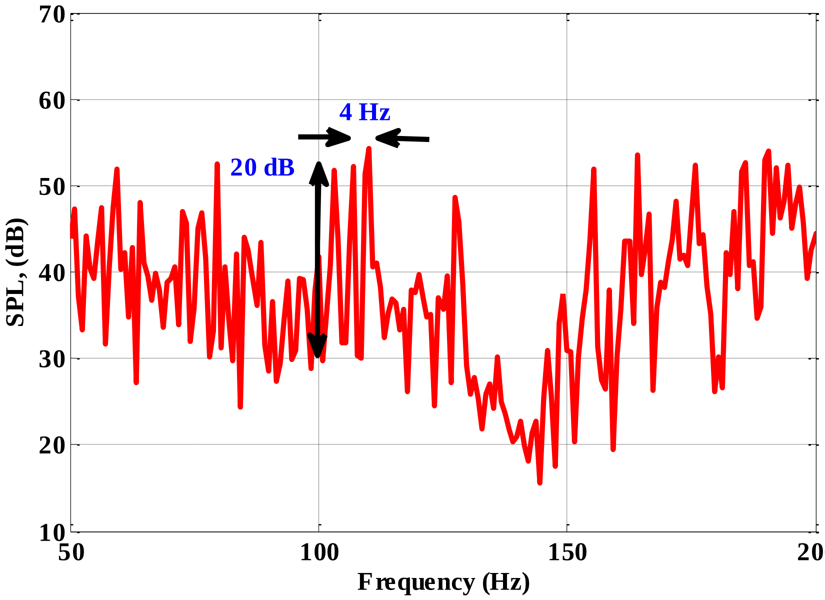


Figure 5. Sound Pressure Level (in decibels) narrow band spectra (versus frequency in narrow frequency bands) at microphone location 1.

The main characteristic of the noise spectrum is the presence of numerous peaks that are 20dB above the background spectral level, separated by multiples of 4 Hz. These peaks are due to axial resonances of sound along the pipe length. Modes of the cross section, and hence resonances, would not exist in this low frequency range. These peaks have high amplitude (20dB) and narrow bandwidth, which suggests low damping (sound absorption) in the metallic pipe.

Further evidence for very low levels of sound absorption in the pipe system is shown in figure 6 where the Sound Pressure Level spectrum (frequency content) at locations 1, 3, 5, 7 and 9 are plotted. The frequency bandwidth is much higher to show the general trend in the spectrum rather than the details, as shown in figure 6.

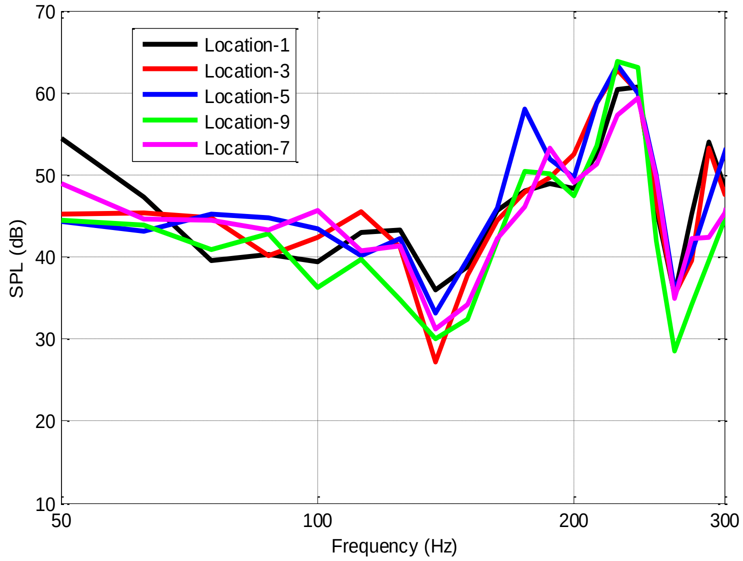


Figure 6. Sound Pressure level spectral variation at different microphone locations

Even though some of the microphone pairs (1 and 2, 3 and 4 etc.) are located more than 5m apart the difference in sound pressure level is less than a few dB, even at the highest frequency of interest. The dip in the spectrum at about 140Hz is identical at all microphone locations suggesting that it is an effect of the source rather than propagation in the pipe. This dip can be attributed to destructive interference between the direct sound from the loudspeaker and the sound due to reflections from the terminated end. Interference is the phenomenon whereby two waves simply add together, sometimes cancelling each other. The resultant wave may therefore be less than the original disturbance depending on the phase relationship between the two waves. In live networks, with the source away from finite ends and reflections then this dip in level with frequency would not be present.

Figure 7 shows the variation of the Overall Pressure Level (summed across all frequencies) for all ten positions plotted against their distance from the source.

In the band of frequencies between 50Hz and 300Hz, the overall pressure level rises slowly and peaks at about 10m from the source. Beyond this distance the overall level begins to fall. The sharpest drop of nearly 3dB occurs between the distances of 13m and 15m, which are positions either side of the 90 degree bend. This variation in overall level can be related directly to interference between the incident and reflected sound waves from the terminated end and from valves, bends and other junctions. This noise variation therefore does not arise from sound absorption by the duct walls. This finding is important as it demonstrates that in a complex pipe distribution network comprising multiple valves, bends and other junctions, sound can be strongly reflected at these positions, which may limit the transmission of sound over large distance at some frequencies.

The variation in the acoustic pressure spectrum and the variation in overall level with distance, in the higher frequency band between 300Hz and 500Hz, are shown in figures 8 and 9 respectively.

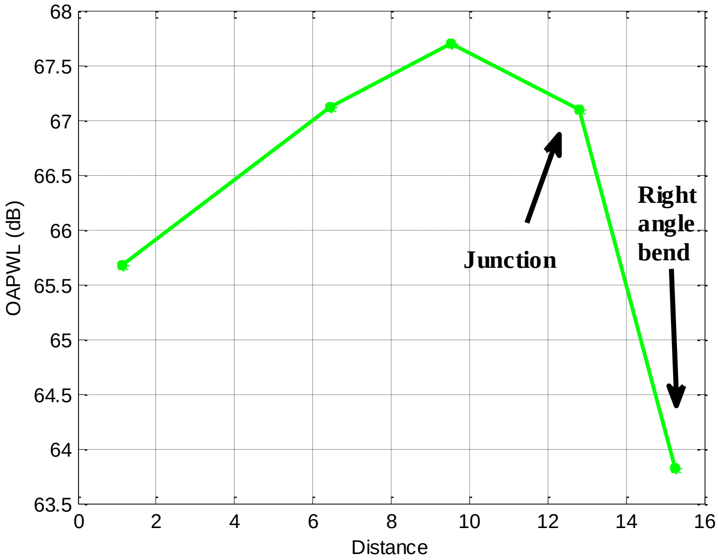


Figure 7. Overall Sound Pressure level spectral (50-300Hz) variation at different microphone locations.

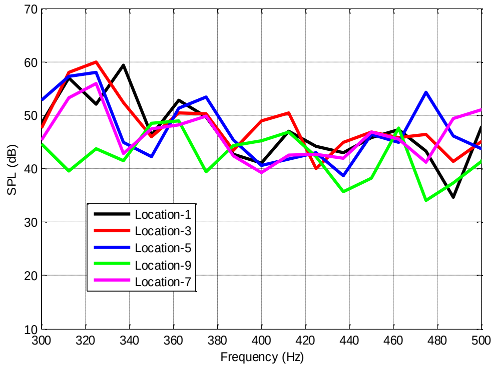


Figure 8. Sound Pressure level spectral variation at different microphone locations

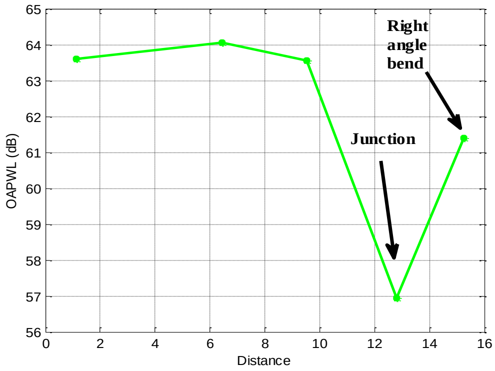
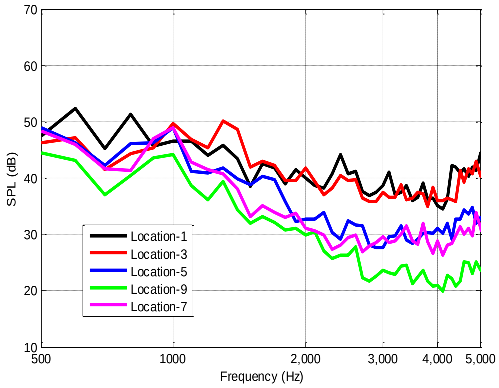


Figure 9. Overall Sound Pressure level spectral (300-500Hz) variation at different microphone locations and distance

Figure 8 shows that at any particular measurement position, the level of the frequency spectrum is highly oscillatory, with variations in sound pressure level of up to 10dB. This again is highly suggestive of interference between incident sound (from the loudspeaker) and reflected sound from the junctions. Figure 8 showing the variation in overall level with distance from the source again shows a sharp drop of about 5dB at a distance of about 13m, corresponding to the microphone position 9 across the junction. This again is further evidence of strong reflections at the junction across the frequency band.

At much higher frequencies, between 500Hz and 5000Hz, the variation in Sound Pressure level spectrum over the different microphone locations and variation in overall level versus distance is shown in figures 10 and 11 respectively. A much greater sensitivity to measurement distance is observed in this higher frequency range. This can now be directly attributed to sound absorption by the pipe walls since the pressure reduced progressively as distance is increased. Moreover, at these high frequencies a significant difference is now observed between the side branch and right-angle bends.



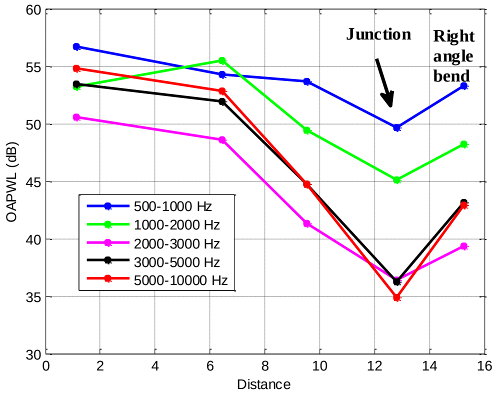
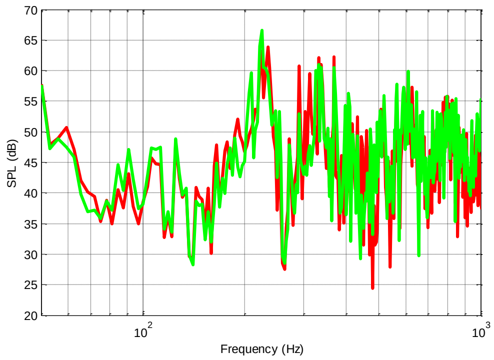


Figure 10. Sound Pressure level spectral variation at different microphone locations.

Figure 11. Overall Sound Pressure level spectral variation at different microphone locations for different frequency bands.

Coherence and reflection coefficient in the duct:

The narrow band Sound Pressure level spectrum at the microphone positions 1 and 2 separated by 0.23m are compared in Figures 12 and 13 in the low (500Hz to 1kHz) and high (1kHz to 10kHz) frequency bands, respectively. The spectra closely match, as expected, but oscillate considerably due to the presence of axial (along the length) resonances and the presence of high order modes whose pressure varies across the cross section of the pipe. These latter modes are the result of repeated reflections between the pipe walls.



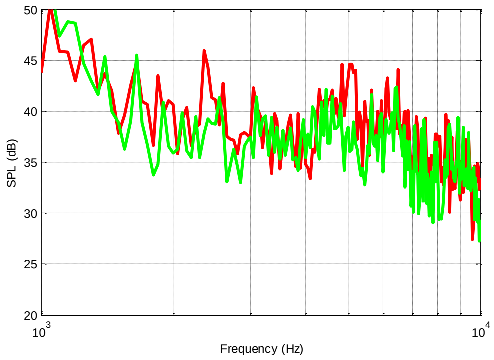


Figure 12. Sound Pressure level spectral comparison (500-1k) between microphones location 1 &2

Figure 13. Sound Pressure level spectral comparison (1k-10k) between microphones location 1 &2

However, even though the spectra are similar at these two closely spaced positions, the time delay between them is complicated, as demonstrated by measurements of the coherence function between the signals. The coherence function (which varies between 0 and 1) is a useful measure of the degree of correlation (agreement) between two microphone signals as a function of frequency. The coherence function between two microphones locations 1 & 2 (separated by 0.23m) is plotted in Figure 14.

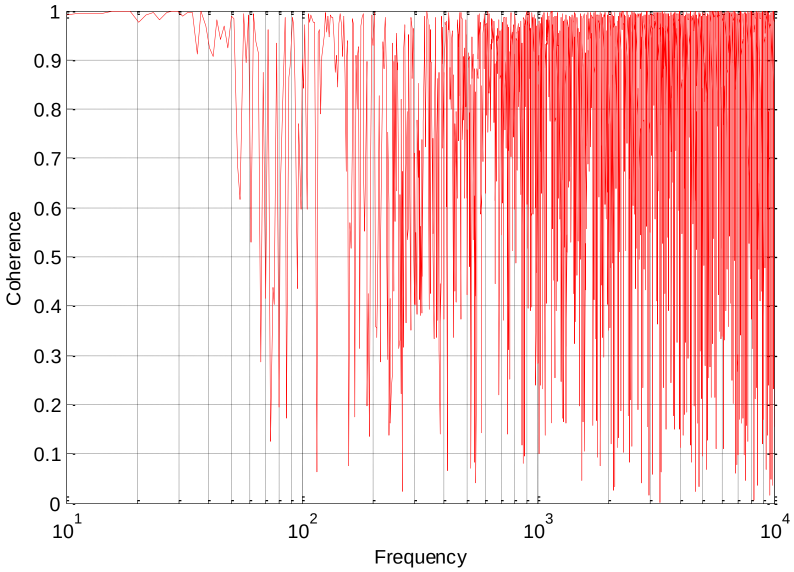


Figure 14. Coherence function between two microphones locations 1 & 2

The coherence function in figure 14 is observed to be highly fluctuating, which can be directly attributed to duct resonances and not the presence of background noise. This provides further evidence for the highly reverberant characteristics of the sound inside large metallic gas distribution pipes.

As the network contains numerous reflections and other unwanted propagation characteristics, as discussed in the previous section, it is worth quantifying the loss per metre based on straight pipe and 90^o bend pipes. This would help quantify the propagation and the frequency range where the losses are minimal.

Sound pressure measurements on a long large diameter (48 inch) pipe section:

The measurements presented above are useful for characterising the sound field in very large metallic pipes in the vicinity of valves, bends and junctions. In this section we investigate the sound field along a long length of pipe, well away from junctions in order to determine the rate of sound attenuation due solely to losses in the duct wall. The schematic of the long pipe is described in figure 15.

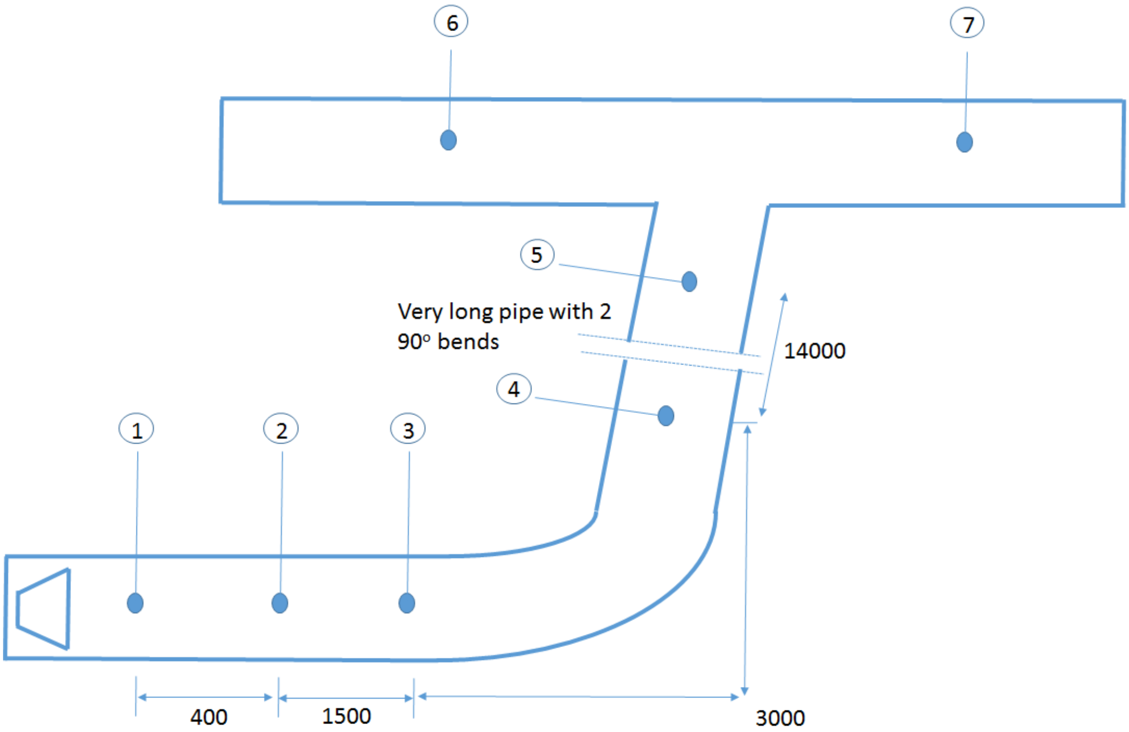


Figure 15: Schematic of the long pipe section at SGN Northam (Dimensions are in cm) (not to scale)

Figure 16 & 17 shows the long duct used to study the propagation effects of sound in the very long, straight pipe section.

Fig 16. Photograph of the long pipe which is used to measure the sound transmission

Figure 17. Loudspeaker is used as a source at the one end of the long duct.

One end of the pipe was excited using a loudspeaker, as shown in figure 17, which shows a rectangular section cut out of the pipe in order to introduce the loudspeaker. Sound pressure levels were measured at the 5 different locations 2, 6.2, 22.6, 53.6 and 208 metres from the source. The initial measurement of the narrow band spectrum contains numerous peaks at multiple of 50 Hz. This was due to contamination of the signals by the electrical mains supply from the petrol generator used to power the amplifier and loudspeaker. The data at these frequencies was therefore disregarded.

To overcome contamination by the electrical mains supply, the source was battery powered and the measurements repeated. Figure 18 shows the sound pressure level spectral variation at the different microphone positions along the long pipe. Also shown (cyan and yellow) is the background noise level spectra measured at two different ends. The loudspeaker signal can be observed to be significantly greater than the background noise levels only above 100Hz. This is important as it indicates that, even though sound transmission is most effective at low frequencies, source levels are usually lowest at low frequencies where the background noise is greatest.

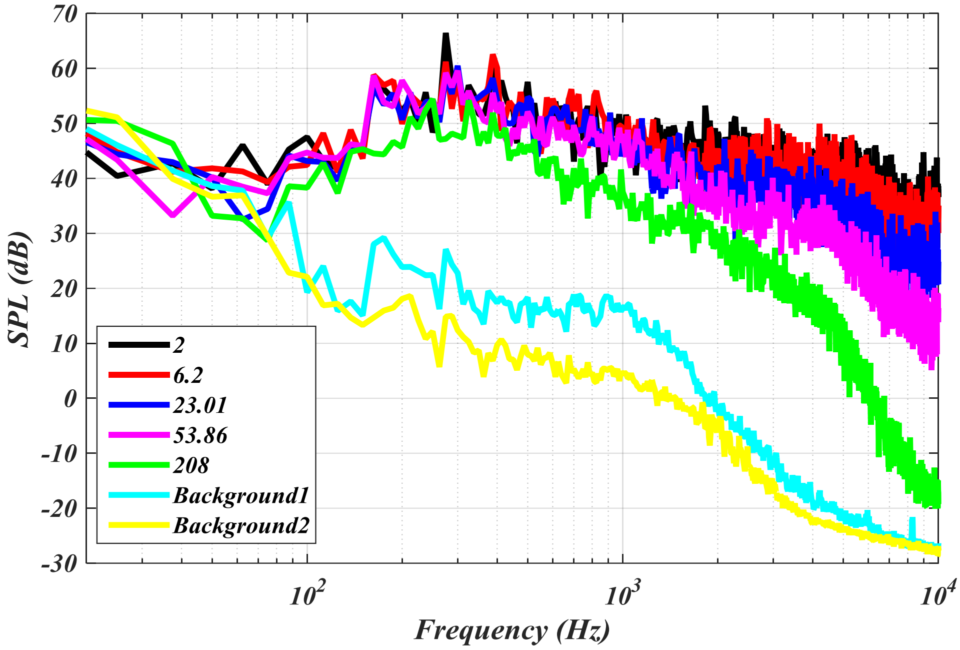


Figure 18. Sound Pressure level spectral variation at different microphone locations in long pipe (Distances are shown in metres)

As shown in figure 15 the maximum length of the pipe is roughly 200 metres. The results in figure 18 were used to calculate the attenuation in decibels per metre. Attenuation per metre is calculated between two points over the straight section between 1-3 and 1-5. The attenuation rate in decibels per metre as a function of frequency is shown in figure 19.

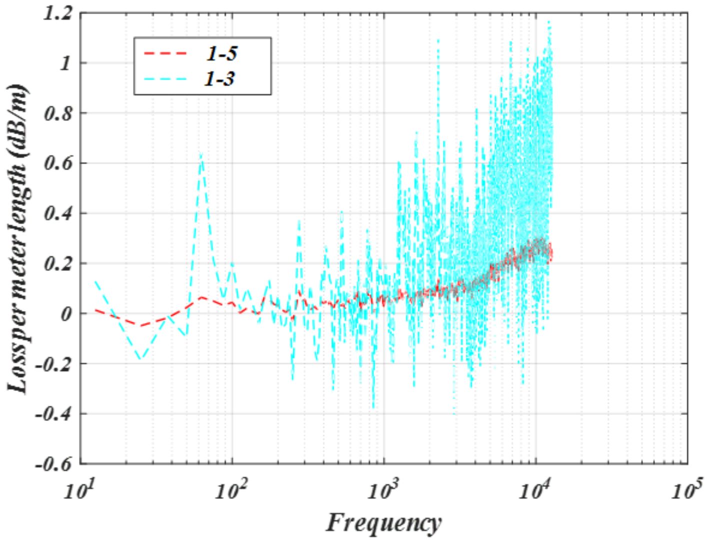


Figure 19. Attenuation per metre (dB/m) as a function of frequency calculated between 1-3 (Straight) & 1-5 (Overall)

The attenuation rate obtained between positions 1 and 3 exhibit high levels of oscillations in the spectra due to strong reflections from bends in the pipe, leading to high levels of reverberation in the pipe. However, the attenuation rate spectra obtained between positions 1 and 5 is much smoother since there is a much higher level difference between these two positions compared to 1 and 3. The sound pressure level variation in octave bands versus distance from the source is plotted in figure 20, obtained by summing the sound pressure in a fixed octave frequency bands.

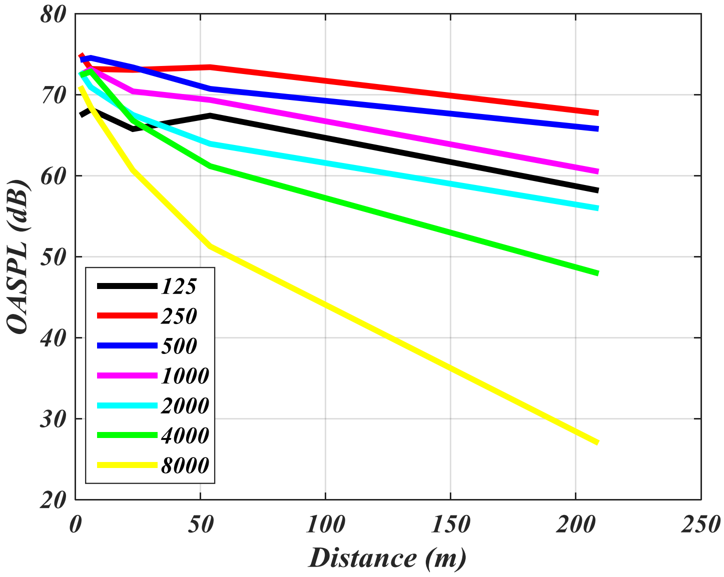


Figure 20. Overall sound pressure levels variation with distance at fixed range of octave frequencies.

For the sake of clarity the noise attenuation per unit metre is plotted again in octave bands in figure 21. Also shown (red curve) is the attenuation rate obtained between positions 3 and 4, which, as shown in figure 15, are located on either sides of a gradual bend of roughly 45 degrees. Finally, the attenuation rate is plotted between positions 4 and 5, which are separated by 140m and two 90 degree bends.

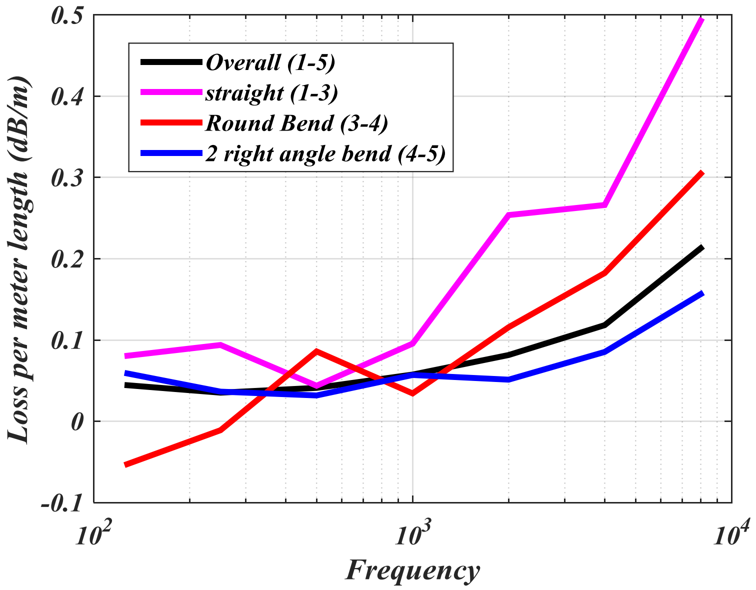


Figure 21. Loss per metre calculated in octave bands calculated based on two given locations.

The results shown in figures 20 and 21 may be summarised as follows:

- The rate of attenuation below about 1kHz is generally very small, typically less than 0.05dB per metre.
- The attenuation rate is roughly independent of frequency below about 1kHz.
- Above 1kHz the rate of attenuation increases with increasing frequency.

- The attenuation rate obtained between sections 1 and 3 is least reliable since it is obtained over the shortest distance and is therefore most affected by reverberation (reflections), as discussed above.

- The rate of attenuation obtained from the other positions is roughly similar. Any variation can be attributed to the effects of reverberation from bends and other junctions.

- Small variations in the attenuation rate with frequency can also be attributed to the effects of reverberation.

14.2 Reverberation characteristics

To quantify the reverberation (echo) properties of the pipe section, the side of the pipe was hit with a hammer roughly every 2 seconds and the acoustic response of the pipe recorded. Figure 22 shows the acoustic response to these impacts, where sound pressure decays. Figure 23 shows the same data plotted in decibels from which the time taken to decay by 60dB can be computed. This is a well-known acoustic measurement which quantifies the level of damping in the pipe. The reverberation time is calculated as 5.67 seconds. This high reverberation time is due to very strong axial reflections from the ends of the pipe and from bends. The spectra at 2m and 22.6m from the source are in very close agreement. All the data obtained in this straight pipe section therefore indicate very low levels of acoustic loss in the metallic pipe, consistent with the data in figures 20 and 21.

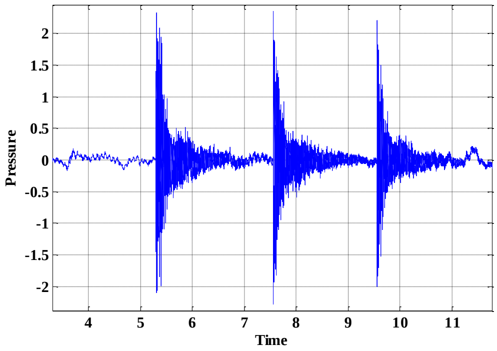


Figure 22. Time series pressure data during impact test

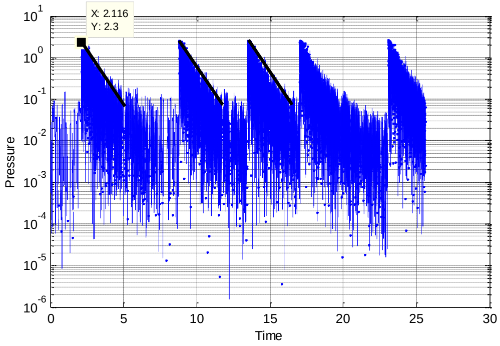


Figure 23. Time series pressure data during impact test in dB scale

14.3 Phase 2. Acoustic transmission measurements on the plastic pipe network at CMS Poole

This section describes the measurements made at Bourne Valley Road in Poole on 25/10/2015 aimed at quantifying the sound transmission characteristics along a plastic pipe gas distribution network comprising numerous bends and side branches. Acoustic measurements were in the pipe without flow as the static pressures and flow speeds in a typical gas distribution system are not sufficiently high to affect acoustic measurements in the pipe. The internal diameters of the pipes were 100mm. First, measurements were made to quantify the attenuation along a straight section of pipe.

a. Straight pipe

This section of the report focuses on the sound attenuation measured along the straight pipe section. Schematic picture of the straight pipe is represented in figure 24. A photograph of the tail end of the pipe is shown in the figure 25.

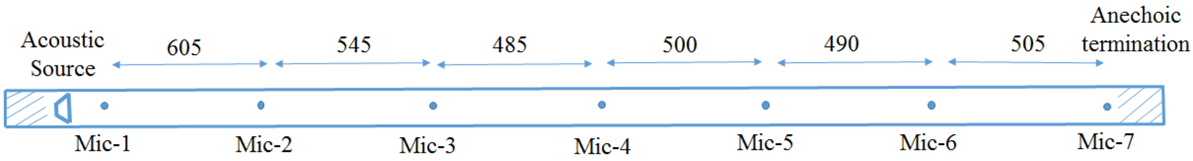


Figure 24. Schematic diagram of straight pipe section (all dimensions are in cm)

Figure 25. Photograph of anechoic termination in straight duct.

A total of 7 flush-mounted microphones were located at different locations along the pipe as shown in figure 24. A loudspeaker was located at one end of the pipe and the other end is terminated with foam to minimise reflections from the closed end. The loudspeaker was driven by a random signal generated from a laptop computer. Acoustic pressure measurements were made sequentially at every microphone location. The sound pressure level spectra at the different microphone locations are plotted in figure 26.

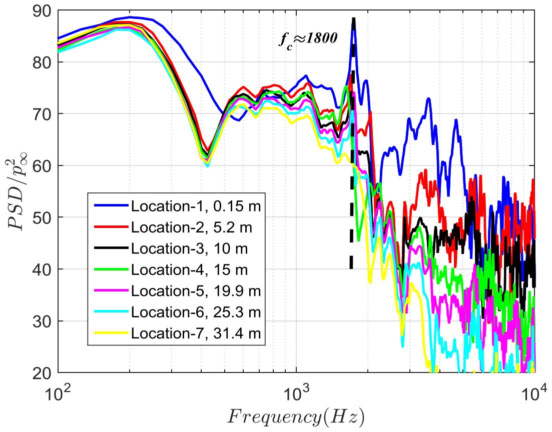


Figure 26. Sound pressure level comparison at different microphone locations in straight pipe with semi-anechoic end termination

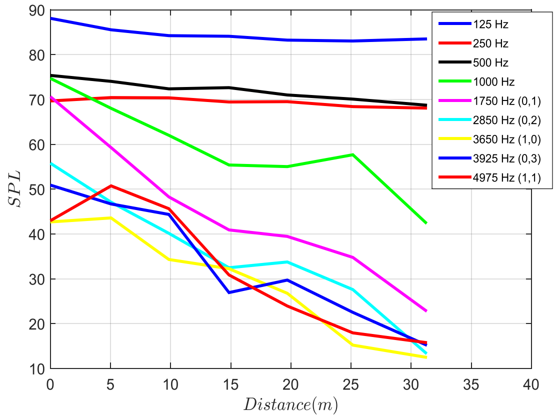


Figure 27. Attenuation in straight long pipe at different frequencies (including few cut-on frequencies)

The spectra shown in figure 26 shows two frequency regions of behaviour; below 1800Hz and above it. The frequency of 1800Hz is referred to as the cut-off frequency. Below this frequency sound travels along the pipe as plane waves where the acoustic pressure is uniform across the duct cross section. Above this frequency there are strong variations in acoustic pressure. The cut-off f_c frequency depends on the diameter of the pipe *d* and is given by,

$$f_c = \frac{1.84c}{\pi d}$$

where *c* is the speed of sound approximately equal to 340m/s and *d* is the pipe diameter in metres.

Below the cut-off frequency of 1800Hz, the sound pressure levels are very similar at all microphone locations except the location close to the loudspeaker. This measurement is not useful since it is dominated by the radiation radiated directly to the microphone. This is referred to as a near field effect of the loudspeaker.

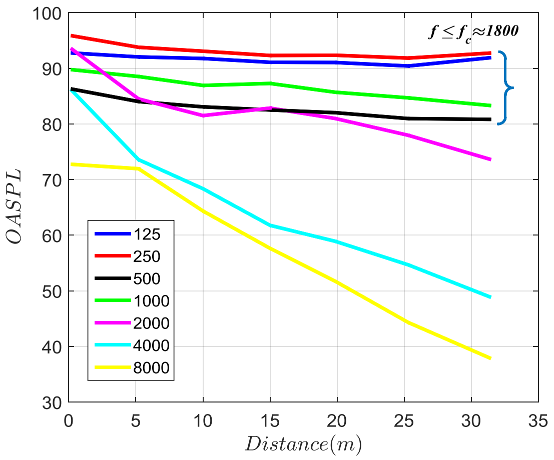


Figure 28. Overall sound pressure levels at different microphone locations for various octave band frequencies

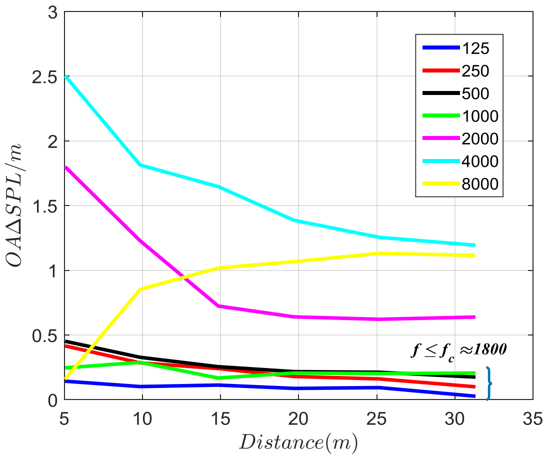


Figure 29. Overall sound attenuation levels with varying distance at different octave band frequencies

The sound pressure attenuation at different fixed frequencies is plotted in figure 27. Higher order cut-on frequencies are plotted and this explains that at these frequencies the attenuation is very high compared to the low frequencies. The sound pressure level variation with distance from the source calculated in octave band frequencies are plotted in figure 28. The corresponding reductions per metre obtained from the data in figure 28 are plotted in figure 29.

Finally, the average attenuation per metre in 1/3 octave bands is plotted in figure 30 where the coloured dots indicate the distance over which the data was measured.

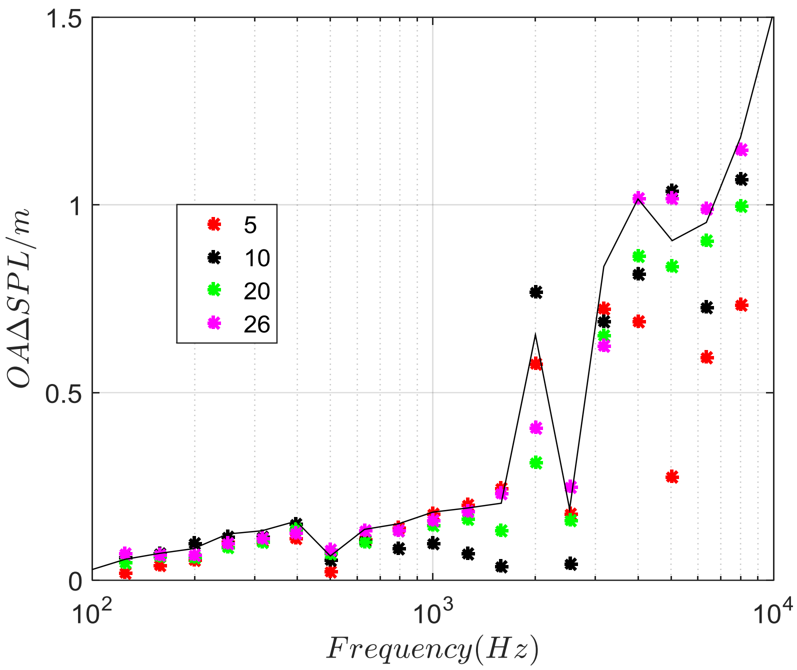


Figure 30. Overall sound attenuation per unit distance (dB/m) calculated at different 1/3rd octave band frequencies is compared against mean attenuation constant for straight long section (solid line)

The acoustic measured data presented in figures 27 – 30 obtained for the straight pipe section may be summarised as follows:

- The lowest attenuation rate is observed at frequencies below the cut-off frequency of 1800 Hz.
- The rate of attenuation increases sharply at frequencies above the cut-off frequency.
- The dip in attenuation at about 500Hz is due to a drop in response caused by interference between the sound transmitted directly to the microphone and the reflection from the closed end.

An average value for the attenuation rate is tabulated in section 7.

b. 90° bend pipe:

A separate measurement study was undertaken to measure the transmission loss across a 90° bend. A schematic diagram of pipe bend and the location of the microphones is shown in figure 31.

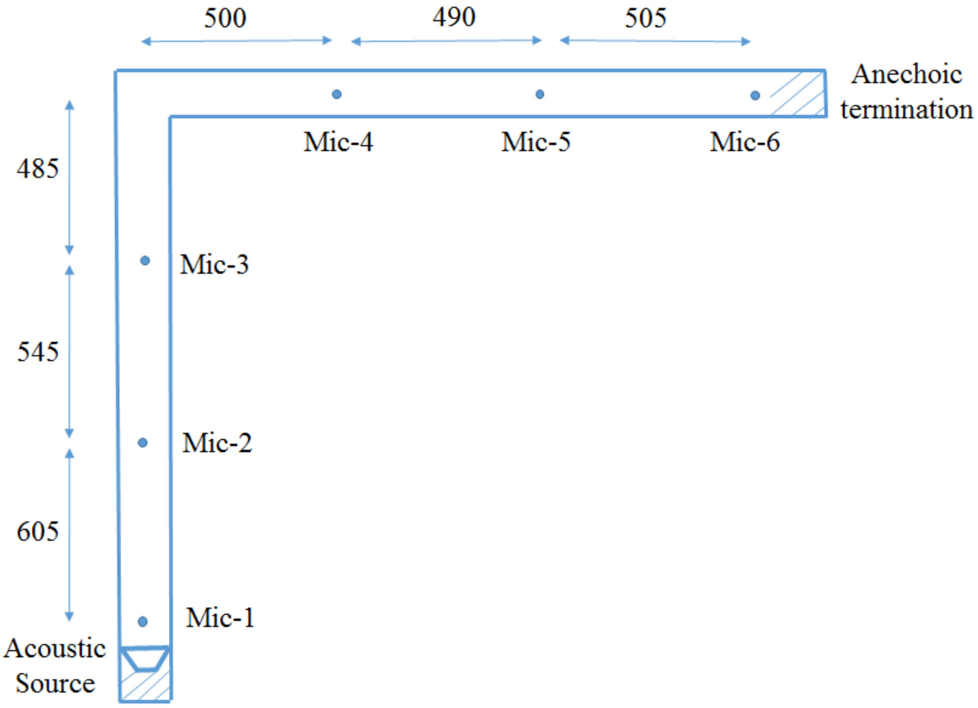


Figure 31. 90° duct schematic diagram

Sound pressure levels at the different microphone locations are plotted in figure 32. Results are similar to the straight pipe section where greatest attenuation is observed above the cut-off frequency.

Overall sound pressure levels are calculated in octave bands and plotted against distance in figure 33. Note that this loss is the sum of losses due to the absorption by the pipe wall and reflection at the pipe bend. The loss (in dB) per metre is calculated in octave bands and plotted in figure 34. The average attenuation per metre for the 90° bend is tabulated in section 6.

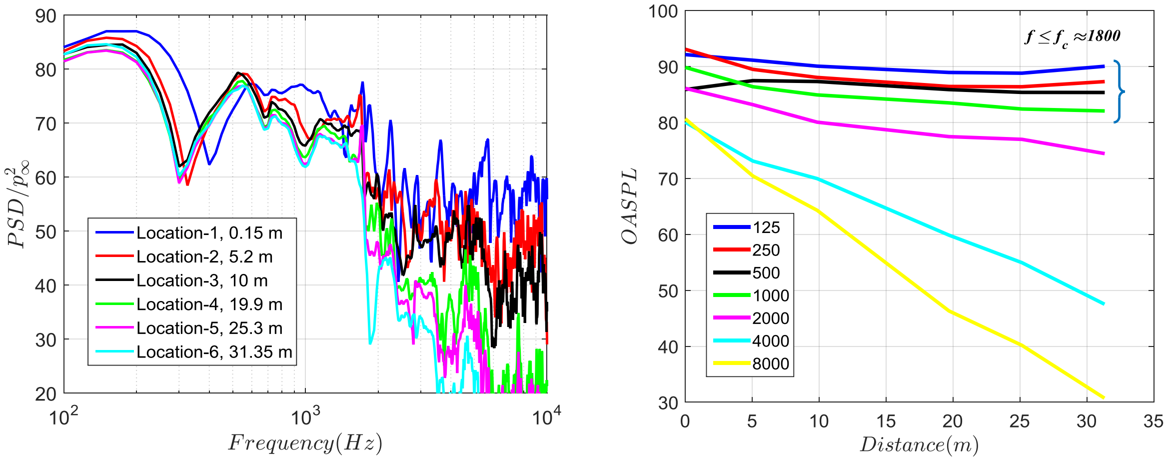


Figure 32. Sound pressure level comparison at different microphone locations in a 90° bend duct with semi-anechoic end termination

Figure 33. Overall sound pressure levels at different microphone locations for various octave band frequencies for 90° bend duct

The rate of attenuation in dB/m as a function of frequency in 1/3 octave bands is plotted in figure 34.

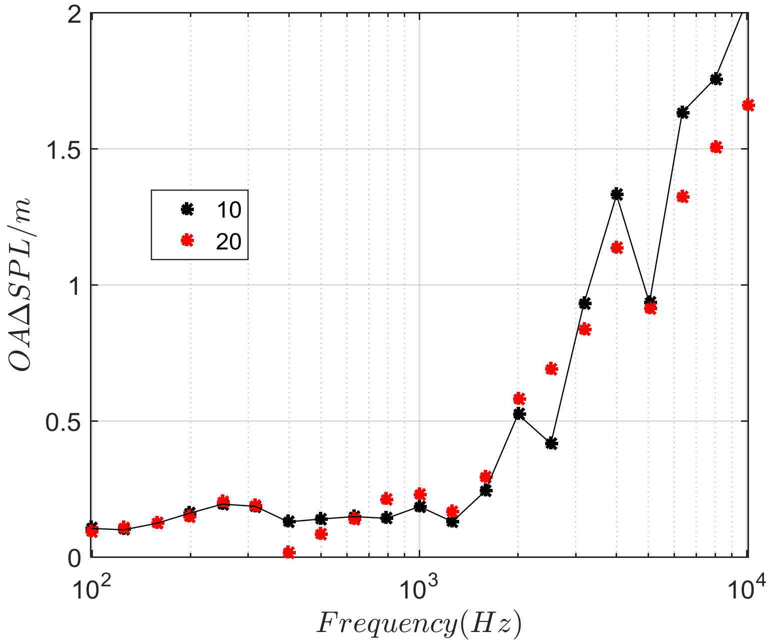


Figure 34. Overall sound attenuation per unit distance calculated at different 1/3rd octave band frequencies is compared against mean attenuation constant for 90° bend duct (solid line)

It well known from the literature that the attenuation in the frequency range below than cut-on frequency f_c is minimum, as shown in figure 35. The transmission coefficient in frequency range $f/f_c<0.5$, i.e. frequencies less than half the cut-off frequency for plane waves, is almost 1. Hence, the acoustic plane wave at the low frequencies, in terms of its propagation, doesn't see the presence of a 90^o bend.

Comparison of this result with the attenuation rate measured for the straight pipe section is shown in figure 36. Similar levels of agreement are observed below the cut-off frequency of 1800Hz, but greater attenuation at frequencies above this, suggesting that the losses and reflection at the 90° bends are insignificant at low frequencies. This finding is supported by theoretical work due described by Dequand in ref [1] who computed an expression for the reflection coefficient due to a 90° bend. The result is reproduced below in figure 35 and confirms our experimental result where near perfect sound transmission is observed at frequencies below the cut-off frequency.

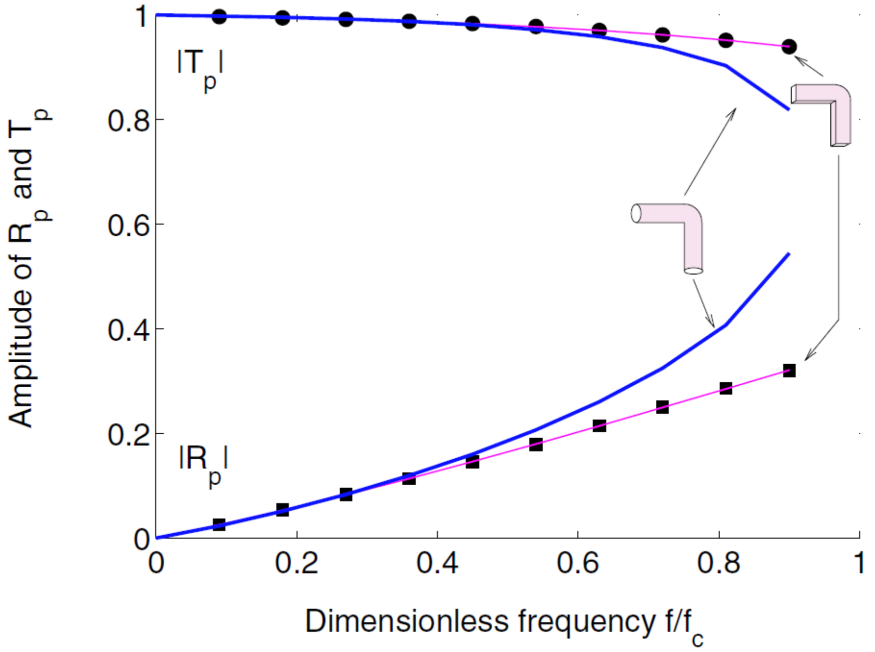


Figure 35. Bend with a rounded outer corner. Amplitude and phase of the pressure wave reflection Rp and transmission coefficients Tp and in terms of the dimensionless frequency f/fc. ([1])

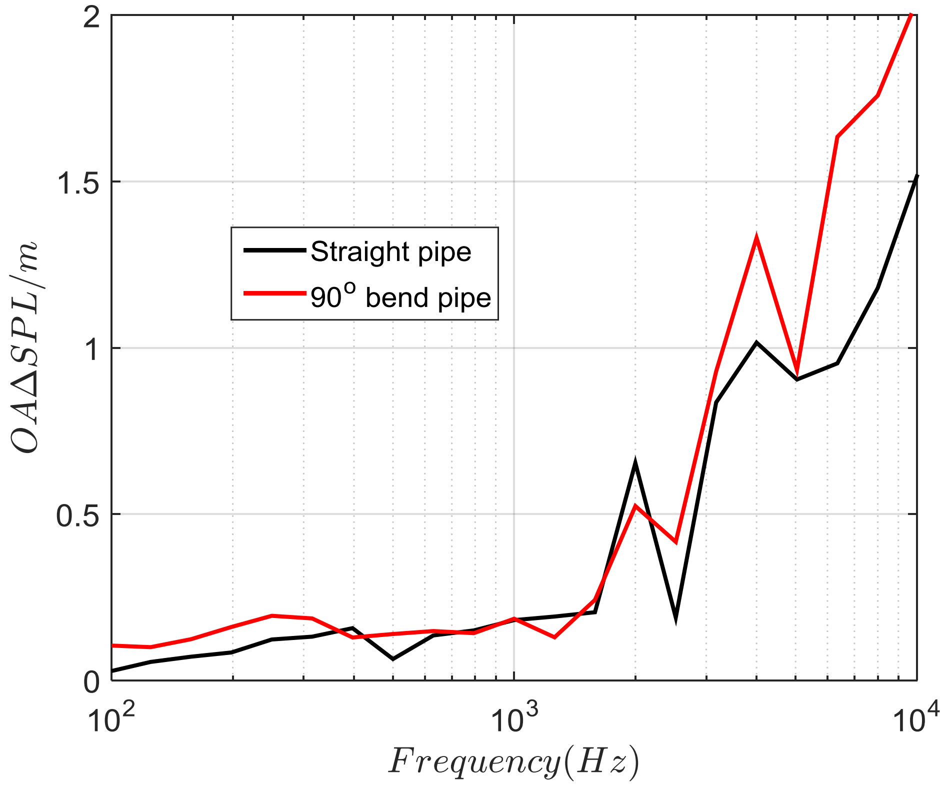


Figure 36. Comparison of attenuation per metre for straight and 90° bend pipe.

14.4 Network

Finally, a measurement study was undertaken to quantify the transmission of sound around a complex pipe network comprising numerous bends and junctions.

c. Experimental setup

A photograph of part of the test network is shown in figure 2 previously (section 4.2). A simple schematic of the pipe network, showing dimensions of the various pipe sections and distances between microphone positions is shown in figure 37.

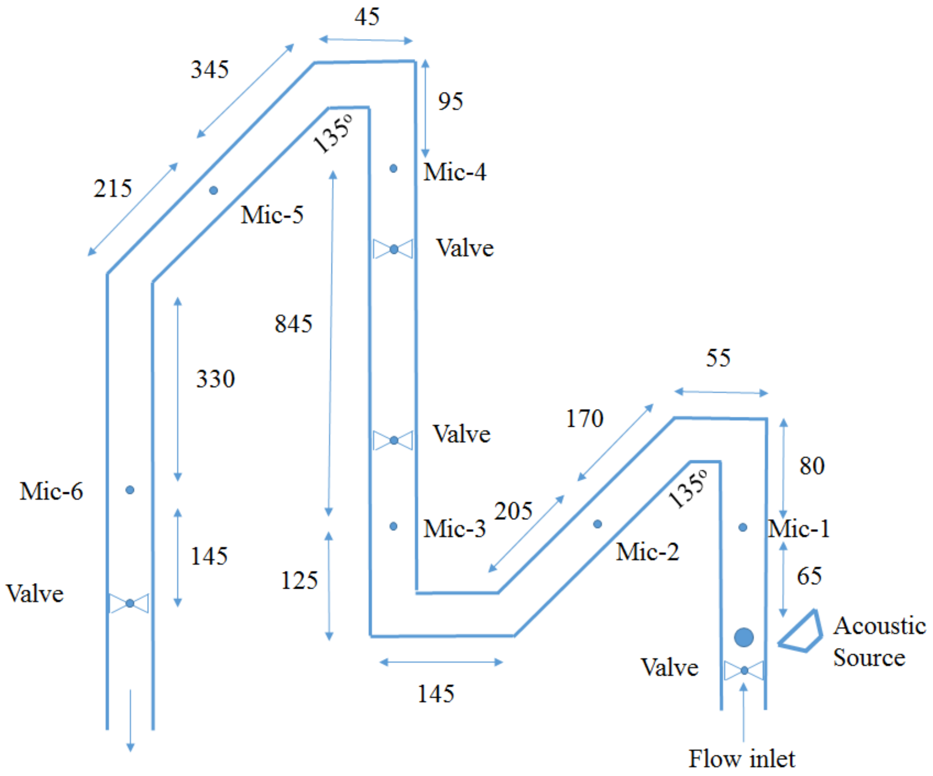


Figure 37. Network schematic diagram (distances in cm)

A T-joint was constructed and inserted 65cm before location 1, as shown in figure 38, to allow a small powerful loudspeaker with built-in amplifier to be introduced. The loudspeaker was excited by a random signal generated a laptop computer via a Bluetooth device. Figure 38 shows a photograph of the loudspeaker connected to the side of the pipe. The sound pressure was measured using a B&K 4472 microphone at the different locations indicated on figure 37.

Figure 38. Photograph of loudspeaker

The Sound Pressure Level spectra at the 6 locations shown in figure 37 is plotted in figure 39 and the variation in Sound Pressure Level with distance from the source in 1/3 octave bands shown in figure 40.

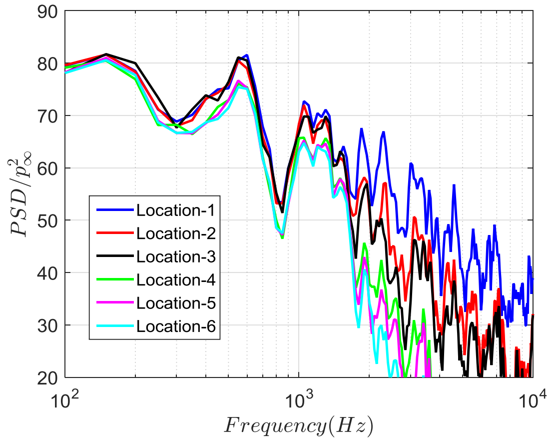


Figure 39. Sound pressure level comparison at different microphone locations of network shown in figure.

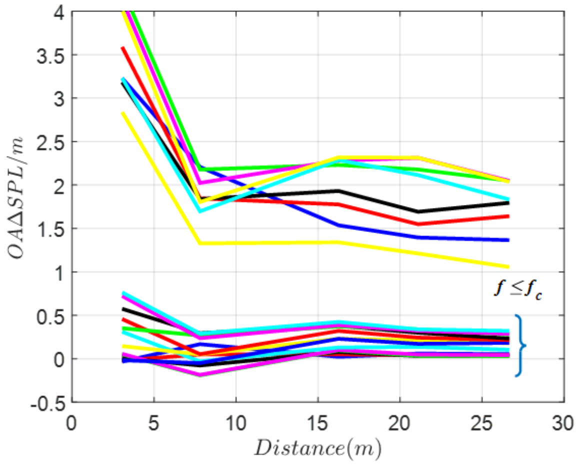


Figure 40. Overall sound pressure level attenuation at different microphone locations of network shown in figure at various 1/3rd octave band frequencies.

Figure 40 is shown again in figure 41 but restricted to four frequency bands.

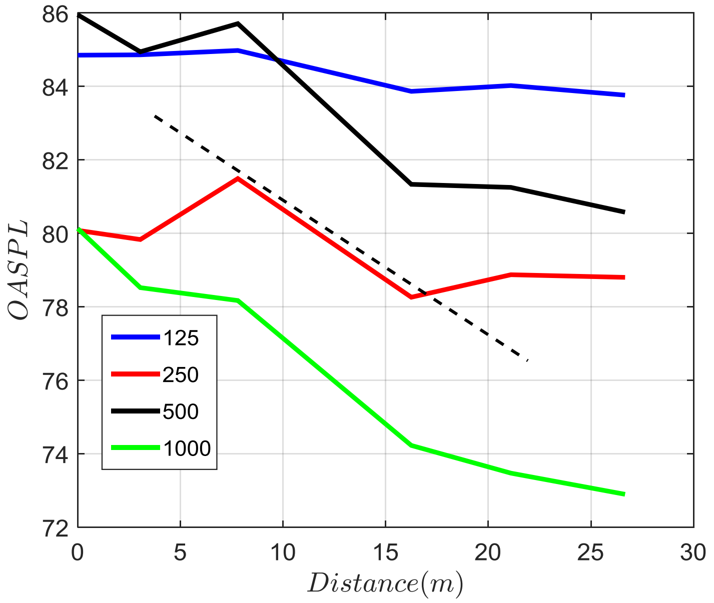


Figure 41. Sound pressure level comparison at different microphone locations of network shown in figure 37 for different octave band levels

The rate of decay between microphones at distances of 7m and 16m show anomalously high levels of decay. This may be attributed to the presence of valves, a contraction and an expansion of the pipe diameter in between microphone locations 3 and 4 (figure 37).

The attenuation rate in dB/m across the bends of various angles (shown in the legend) is shown in figure 42. In general, the greatest levels of loss below the cut-off frequency of 1800Hz are observed for the 'straight pipe section (between 3 and 4) which includes two valves and one contraction and expansion. This suggests that the presence of valves and other discontinuities may have an even greater effect on noise transmission than losses at the pipe wall.

Figure 43 shows the variation in average attenuation rate in dB/m with frequency between the source and the end of the network at microphone 6 (blue dots). Also shown in the predicted averaged decay rate (black curve) is the averaged decay rate measured for the straight pipe section. The difference in values at any one frequency is therefore due to the presence of bends, valves and pipe contractions.

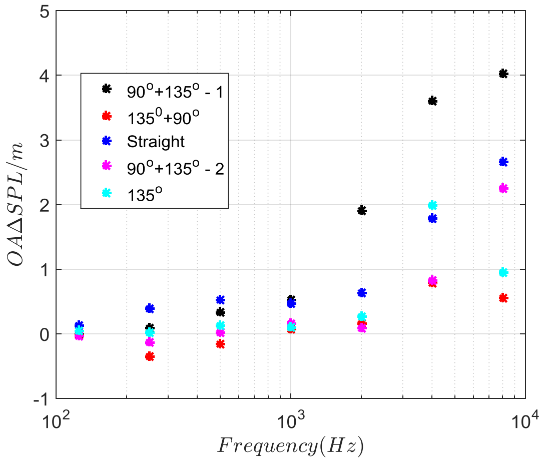


Figure 42. Overall sound pressure level attenuations per unit length due to different segments of network

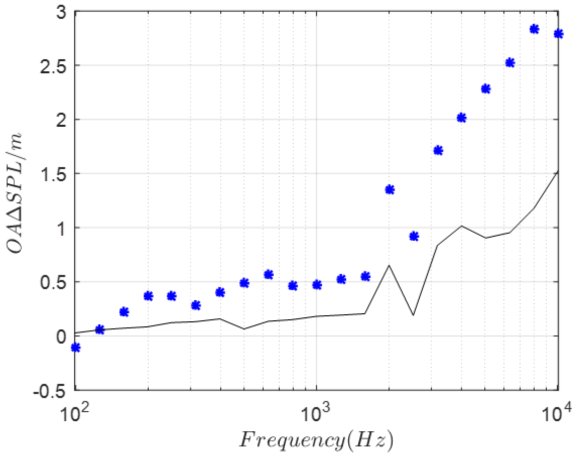


Figure 43. Attenuation constant comparison between measurements, blue dots (network), and estimated solid line(from long straight pipe)

Comparison between the two curves reveals a significant difference in values again highlighting the importance of bends, valves and contractions to the ability to transmit sound along the pipe network.

d. Loss per bend

Finally, the measurements presented above are now used to compute the average loss per bend. Note that it was not possible to compute the loss for each bend individually since the noise reduction was generally too small to measure accurately. However, by measuring the loss across all bends and dividing by the number of bends an average value can be computed.

Figure 44 shows the attenuation rate in dB/m measured for the straight pipe section and the entire network. The loss in dB across the entire network was subtracted from the loss obtained for the straight section but extrapolated to the entire network. Taking the difference in these assessments provides an estimate for the attenuation due to all bends. Dividing by the number of bends provides an estimate for the average noise reduction per bend. This evaluation is shown in figure 45.

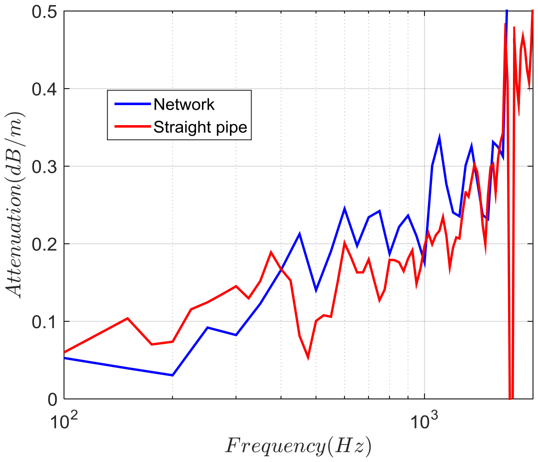


Figure 44. Attenuation constant comparison between network and straight pipe

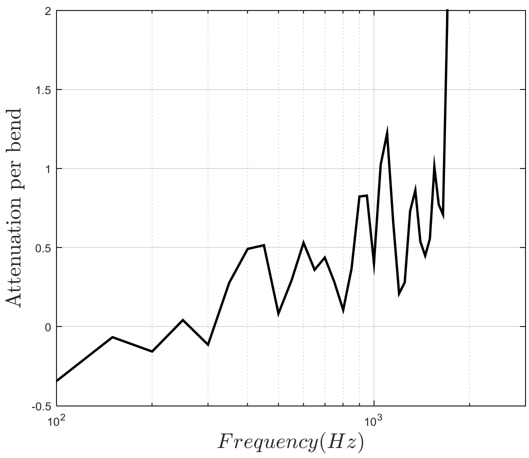


Figure 45. Attenuation constant or sound reduction per bend

The loss per bend can be seen to be fairly significant even at low frequencies below the cut-off frequencies. The presence of bends can therefore be the limiting factor in determining transmission loss in short sections of pipe.

15 Prediction model of sound transmission

Equation 1 provides a simple empirical expression for the source strength *S (f)* in dB as a function of frequency (i.e., pressure level just outside the near field of the source) necessary to transmit sound over a distance *d* in which there are *N* bends, that is at least 3dB above the background noise level *BG (f)* in decibels.

The relationship is

$$S(f) = \Delta_t(f) + BG(f) + 3 \tag{1}$$

where $\Delta_t(f)$ is the total attenuation in the level (dB) produced by the propagation over distance and around N bends, $BG(f)$ is the background level. The total attenuation for a distance *d* and *N* bends is given by

$$\Delta_t(f) = \mathrm{d}_s(f)d + N\Delta_{bend}(f) \tag{2}$$

where $\Delta_{bend}(f)$ is the attenuation per bend plotted in figure 45 and $\mathrm{d}_s(f)$ is the attenuation rate or loss per metre (dB/m) for metal and plastic pipes plotted in figures 21 and 30 respectively.

Similarly, Eq. 3 can be used to estimate the range *d(f)* over which sound can be transmitted along the pipe system with a given source strength *S(f)* that is at least 3dB above background noise. The 3 dB signal to noise ratio is deemed sufficient to recover the signal information required to be communicated for monitoring the state of the gas at low pressure points in the network.

$$d = \frac{S(f) - N\Delta_{bend}(f) - BG(f) - 3}{\mathrm{d}_s(f)} \tag{3}$$

16 Conclusions

16.1 Overview of Phase-1 – Metal pipes

- Acoustic tests undertaken on a short pipe system with bends and junctions and tests on a much straighter section suggest that acoustic propagation within the pipe is highly reverberant (reflective). This is due to the steel construction of the pipe and an absence of sound absorbing elements.

- The absence of acoustic damping in the pipe leads to a large number of very strong axial (along its length) resonances within the pipe.

- The absence of acoustic damping within the pipe suggests that sound will propagate to large distances along the pipe. However, owing to strong reflections makes it difficult to communicate information accurately along the pipe.

- At positions well away from valves and junctions the rate of decay is low, typically a few dB per metre. This decay rate generally increases with increasing frequency.

- The greatest noise reduction is observed to occur across a junction (side branch) due to sudden acoustic impedance change at this junction.

- Lower levels of noise reduction are observed around a 90° bend, where some sound is reflected along the pipe and some is transmitted. Again, a change in acoustic impedance due to this bend is the cause.

- Noise measurements made in the straight section of pipe using a loudspeaker, was found to be contaminated by interference from the 50Hz mains supply from the petrol generator. These measurements could therefore not be used to infer acoustic properties in this straight section.

- Recent measurements on very long pipe have also shown strong reverberation fields and the loss per unit metre has been evaluated.

- The noise due to an impact on the side of the pipe was measured accurately as this did not require the use of a power supply to operate the signal generator. The measurements revealed the slow decay of the sound field, again confirming the very low acoustic damping or absorption of the energy in the pipe.

- In summary, the highly reflective environment within the steel pipes means that transmitted information to large distance will be difficult, similar to attempting to hold a conversation within a hard-walled room with a high level or reverberant sound.

- An alternative to transmitting signals to communicate information is to transmit sound at a frequency which is not altered by the highly reflective environment within the pipe.

16.2 Overview of Phase-2 – Plastic pipes

- The transmission characteristic of sound along the plastic pipes typically used in gas distribution networks is generally significantly higher than in metallic pipes.

- The reduction in sound per metre along plastic pipes is typically 0.5dB per metre below the cut-off frequency, the reduction or attenuation rate is typically a factor of 10 times greater than the attenuation rate for steel pipes. For an 11cm diameter pipe this limiting cut-off frequency below which sound can propagate best is about 1800Hz. For example, with no bends, for a source level that is 40dB above background noise, below the cut-off frequency sound can be transmitted up to a distance of approximately 750m. However, the presence of valves, junctions, area changes and bends has been shown to attenuate the source further by reflecting the sound back upstream leading to a smaller transmission range.

- Above the cut-off frequency, sound attenuates much more rapidly within the pipe than at lower frequencies.
- The effects of gas flow on the acoustic measurement will be negligible owing to the generally low static pressure and flow speeds common in gas distribution networks.
- Vented microphones should generally be used to equalise the static pressure on both sides of the microphone diaphragm for future tests on live gas networks.

17 Recommendations

Sound can be transmitted and measured effectively over distances that are typically several hundreds of metres using commonly available off-the-shelf electromagnetic transducers (compact and efficient loudspeakers and microphones). The project has confirmed that the sound signal should preferably be below the cut-off frequency for plane wave propagation (typically 1800 Hz for 100 mm internal diameter plastic pipes).

Due to the potential for multiple reflections and reverberation, it is suggested that the next phase should consider developing suitable frequency modulated signals or signals with multiple carrier frequencies that can be transmitted and interrogated using advanced signal processing methods for data recovery, such as a transmitted value for the pressure at a location. Once the signal production and processing has been identified and implemented, the use in a live gas main then needs to be conducted.

The communication to the loudspeaker could potentially be wireless, but the speaker with an active amplifier will still require a source of electrical power, preferably generated or produced within the live gas pipe rather than need physical external to internal power supply connections.

18 References

[1] Dequand, S.; Hulshoff, S. J.; Aurégan, Y.; Huijnen, J.; Riet, R. Ter; van Lier, L. J.; Hirschberg, A., Acoustics of 90 degree sharp bends. Part I: Low-frequency acoustical response, ‘’Acta Acustica united with Acustica’’, Vol. 89 (2003) 1025 – 1037.