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To cite this article: M Salimi *et al* 2019 *J. Phys.: Conf. Ser.* **1264** 012059

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Design and laboratory testing of pneumatic devices for the acoustic excitation of water filled plastic pipes

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Abstract. Tracing of buried plastic pipes by the means of acoustic methods has become a subject undergoing intense study, thanks to the encouraging results in comparison to other commercial techniques. The current acoustic technique for tracing underground plastic pipes involves the excitation of the pipe wall or the contained fluid at a fixed location. As wave attenuations are generally large for plastic water pipes, signals cannot be sensed at large distances away from the exciter's location, or at high frequencies. Although in-pipe sources allow tracking of the pipe at larger ranges, current acoustic exciters are not always appropriate, being cumbersome and too large to fit into smaller pipes. In this work, two types of pneumatic device were evaluated, with the aim of generating high amplitude signals at low frequencies and with the ability of accessing pipes with a wide range of diameters, down to 1 cm. The devices are experimentally characterised by a series of laboratory tests in a water-filled plastic pipe section. A comparison of the acoustic power transmission to a fluid filled pipe between a standard electro-acoustic device, an electromagnetic shaker, and the pneumatic ones is made.

1. Introduction

The use of plastic pipes made from PVDF (polyvinyl chloride) and MDPE (medium density polyethylene) became popular in the marketplace due to their lower cost, sustainability and easy handling. It is important to assess their condition to mitigate the risk of disastrous failure resulting from their deterioration. Determining the condition of such buried utilities followed by repairing or installing new services, requires the knowledge of their route. Traditional techniques to locate plastic water pipes can be problematic, as it is often necessary to occupy public road space for excavation purposes at multiple locations, many turning out to be unnecessary [1]. Furthermore it might cause damage to the pipes, which results in numerous practical problems, costs and dangers for the contractors and road users [2]. Localising the buried pipes without excavation therefore will reduce the number of holes that need to be cut in roads and mitigate the risk of pipe damage.

Vibroacoustic techniques to determine the location of buried water pipes have been studied at the University of Southampton's Institute of Sound and Vibration Research (ISVR) over the past 10 years [3]. One technique involves acoustical excitation of water pipes at available access points (e.g. hydrants) and the measurement of surface vibration for locating the pipes. In this case, the excitation source's ability to acoustically drive the contained fluid at low frequencies, ranging from 10 Hz to approximately 100 Hz, affects the distance at which buried water pipes can be located through the technique. Below 10 Hz the environment noise is dominant and beyond 100 Hz, attenuation due to material damping of the pipe wall as well as the spreading of the acoustic wave from the pipe wall to the surrounding medium is too strong. Fuller and Fahy [4] investigated the characteristics of the wave propagation and energy distribution within empty and fluid-filled thin walled cylindrical shells. They have shown that there is a good coupling between the axisymmetric fluid and shell borne waves. Therefore applying either



acoustical or structural excitation leads to there being energy within both wave types. The distance at which a buried pipe can be detected with this technique depends upon the pipe excitation, configuration and material as well as its geometrical properties, type of surrounding medium, environmental noise and the sensor that are selected to record the surface vibration [3, 5].

Due to a recent change in the legislation, inside access to the buried pipes for determining the pipes location and assessing their condition is allowed to the water pipe locator companies [6]. This then allows for the use of moveable acoustic devices to generate acoustic waves within the pipe at any required location, leading to overcome the problem of attenuation. Locating the water pipes by means of acoustical exciters is a new area of research because, as yet no acoustic source has been manufactured for this matter. However, there is a number of sources that can be adopted to directly drive the contained fluid and based on their operation mechanisms, they can be divided into four main source types: (1) Electroacoustic Transduction (2) Detonative (3) Electric sparks and (4) Marine seismic sources.

The excitation sources based on electroacoustic transduction mechanisms can be divided into six categories: piezoelectric, electrostrictive, magnetostrictive, electrostatic, variable reluctance and moving coil transducers. Advantages and drawbacks of each transducer as a underwater source are explained in detail in [7]. The use of electroacoustic transduction sources for pipe detection is deemed satisfying due to their repeatability and their providing a convenient reference signal. To have a better understanding about the performance of current electroacoustic devices a standard moving coil device and an electromagnetic shaker have been investigated. However, their moderate power at low frequency (<100 Hz) has led to some motivation to look into other sources of excitation. Using a detonative source in a water filled pipe is dangerous, might cause unwanted heat transfer to the fluid, and it requires a licence [8]. There are two main problems associated with the electric sparks as source of excitation: 1- they are naturally dangerous, as high voltages and electrical charges are necessary to generate discharge. 2- The discharge will emit powerful radio-frequency interference which has the potential to damage test equipment [9]. Instead, marine seismic sources can produce a broadband signal in the fluid and are well known in the petroleum industry as well as they are used for seismic surveys into the ocean [10–12]. For the purpose of pipe detection, the bubbles generate into the fluid by airguns could reduce the wave re-radiation from the pipes and hinder the pipe tracing. Although the generated pressure wave from the water guns to the fluid is normally lower in amplitude than from air guns (in the frequency bandwidth of interest, 10-100 Hz), it is worth re-engineering water-gun technology as an in-pipe acoustic source.

In the present study, a novel pneumatic device, the balloon gun, is developed with the aim of generating high amplitude acoustic waves in the low frequency region, 10-100 Hz. The balloon-gun is benchmarked against a re-engineered water gun in Section 3, here called pipe water-gun. For the sake of assessing the performance of these two pneumatic devices, the pressure transmitted to the fluid from these devices are also compared with two selected electroacoustic devices, an underwater loud speaker and an electromagnetic shaker.

2. Experimental measurement using the selected electroacoustic devices

All the measurements were conducted on a 2.1 metre long MDPE pipe with outer diameter of 18 cm and the thickness of 1.1 cm, shown in Figure 1. The pipe was filled with water up to two metres and was hung vertically from a jack. To investigate the pressure transmission to the fluid, a hydrophone was placed at 1.3 distance from the water surface. The two electroacoustic transduction based sources that were selected for further study are an underwater loud speaker and an electromagnetic shaker. Although there is a wide range of underwater loudspeakers available in the market, the size of selected device should be small enough to fit into a typical water pipe. Here a Coomber 1932 underwater loudspeaker, rated at 20W (8ohms), is chosen for driving the fluid [13]. The speaker looks like a cylinder with a radius and a height of 7 cm and 14 cm respectively, and with a square rubber flange externally attached to the circumference of the speaker. A picture of the loudspeaker and the test rig is shown in Figure 2.

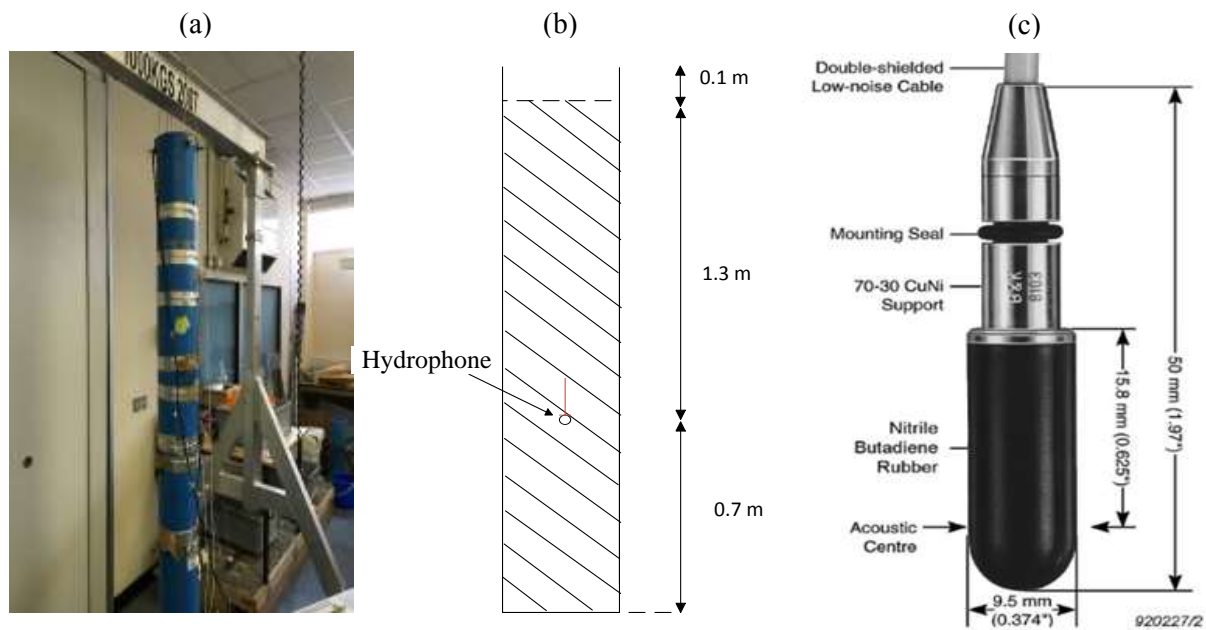


Figure 1. The pipe rig and the sensor position for measuring pressure transmission the contained fluid. (a) The pipe is hung vertically from a jack. (b) Position of hydrophone and the level at which the pipe is filled with the water. (c) A picture of the Bruel & Kjaer hydrophone 8103 used to measure the fluid pressure [14].

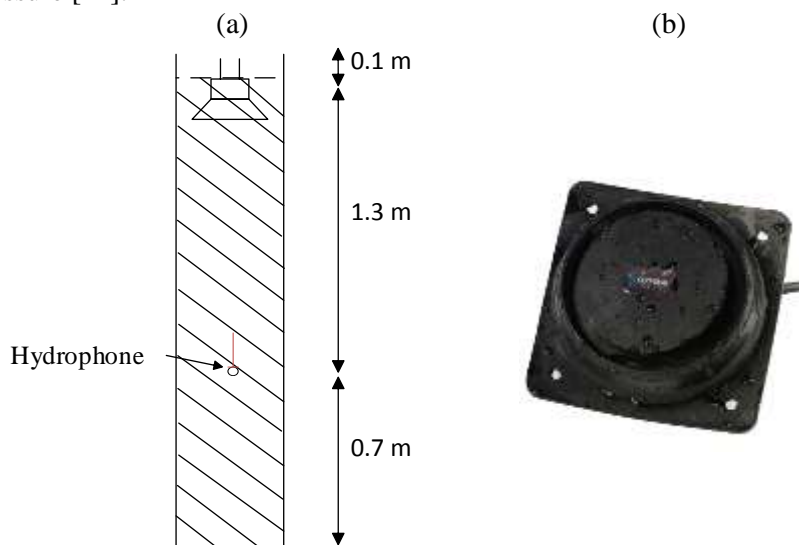


Figure 2. The location of the underwater loudspeaker (a) and its picture (b).

The use of structural excitation to generate acoustic wave into the pipe is also considered in this investigation, as it is widely used in the market for detection of buried plastic pipes. Three different configurations were tested using an electromagnetic inertial shaker. In the first configuration, illustrated in Figure 3 (a), the pipe shell was subjected to an axial structural excitation by mounting the shaker onto an end plate and the end plate was attached to the top end of the pipe. In the second configuration, shown in Figure 3 (b), structural excitation was applied radially at the top end of the pipe. This type of excitation can resemble the situation where a buried pipe is subjected to an axial structural excitation from a hydrant. In this case, normally the pipe has a 'L' or an inverse 'T' shape configuration and applying axial excitations to the hydrant can be deemed as a radial excitation for the buried pipe. Finally, in the third configuration, the fluid was excited by attaching a light and rigid piston (made of a composite honeycomb sandwich panel) to the shaker. To ensure that the water column is excited, the honeycomb piston was slightly submerged in the water.

For all tests, including the experiments with the loudspeaker, the device was driven with 16 linear chirps ranging from 10 Hz to 1000 Hz, each lasting 2 seconds. Signals were measured with a sampling frequency of 2.5 kHz and a low pass filter was set into the Prosig 8000 Data Acquisition System to avoid aliasing. Although the frequency range of interest for detection is between 10 Hz and 100 Hz, a larger frequency range was acquired for the sake of comparison of the different devices.

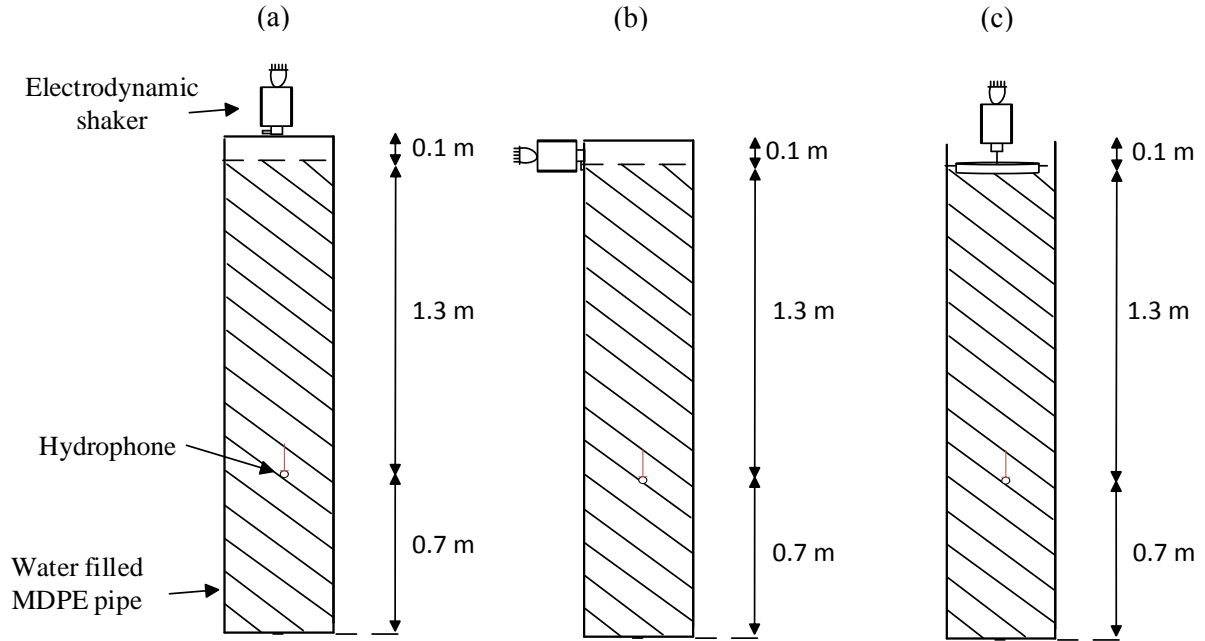


Figure 3. Pipe excitation arrangement using electromagnetic shaker. To increase energy transmission from the shaker to the pipe, the base of the shaker was clamped to a rigid support. (a) Axial excitation to the shell. (b) Radial excitation to the shell. (c) Direct fluid excitation.

2.1. Electrical power

To estimate the efficiency of each excitation source or configuration, the results of the pressure transmitted to the fluid borne wave from the utilised electroacoustic devices was normalised with respect to the input electrical power of the exciter. The time averaged electrical power input to a system can be calculated by multiplying the instantaneous voltage by the current and integrating over a specific time period as shown below:

$$\langle \hat{W}_{EI} \rangle = \frac{1}{T} \int V(t)I(t)dt, \quad (1)$$

where $V(t)$ and $I(t)$ are the input voltage and current which are supplied to the excitation source. Normally, it is more revealing to express the behaviour of time varying oscillation systems in the frequency domain. Here, use of the Cross Spectral Density (CSD) allows modelling the input electrical power in the frequency domain:

$$\langle \hat{W}_{EI}/Hz \rangle = \text{Re}\{G_{VI}(\omega)\}, \quad (2)$$

where G_{VI} is the one sided cross spectral density between the voltage and current. It can be seen from equation (2) that estimation of the electrical power can be achieved by recording the current and the applied voltage to an exciter. Since the impedance of the drivers change with the frequency, a resistor was placed between the amplifier and the exciter and the supplied current has been estimated by recording the voltage across a resistor, V_2 as illustrated in Figure 4. The input voltage to the driver, V_3 , was recorded directly.

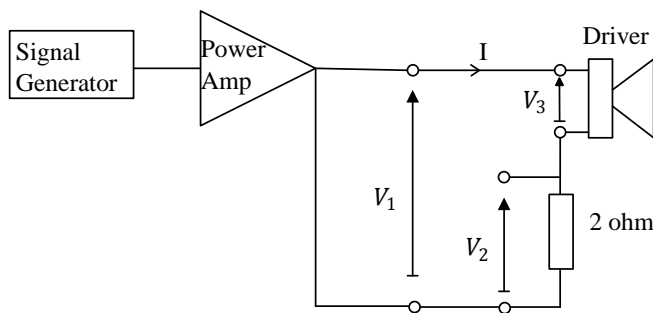


Figure 4. Circuit diagram for measuring electrical power.

2.2. Experimental results from selected electroacoustic transduction mechanism based devices

The PSD of the pressure wave transmitted to the fluid for the configurations illustrated in Figure 1 and Figure 2 is plotted in Figure 5 (a). The illustrated PSDs in Figure 5 (a) were normalised with respect to the input electrical power of the exciter and are plotted in Figure 5 (b). As the measured quantities are PSDs rather than input acoustical powers, it is clear that the ratio of the two could be higher than one. In another study, an attempt was made to measure the input acoustic power, however, for brevity those data are not presented in this paper.

As illustrated in Figure 5 (a) and Figure 5 (b), when the pipe is subjected to shaker radial and direct fluid excitation, a better performance is obtained at frequencies below 50 Hz, in comparison to the loudspeaker. Applying axial shell excitation to the pipe fluxes the energy to the structural borne wave and lower pressure is recorded in the fluid. As illustrated in Figure 5 (b), direct fluid excitation drives the fluid more efficiently compared to the loudspeaker at frequencies below 600 Hz, while beyond that the efficiency of the loudspeaker become comparable. As shown in Figure 5 (b), except from the frequency range between 60 Hz and 129 Hz, the shaker radial excitation drives the contained fluid as efficiently as the loudspeaker. Of the arrangements tested, the shaker direct fluid excitation drives the intended wavetype, at the frequency range of interested, most efficiently.

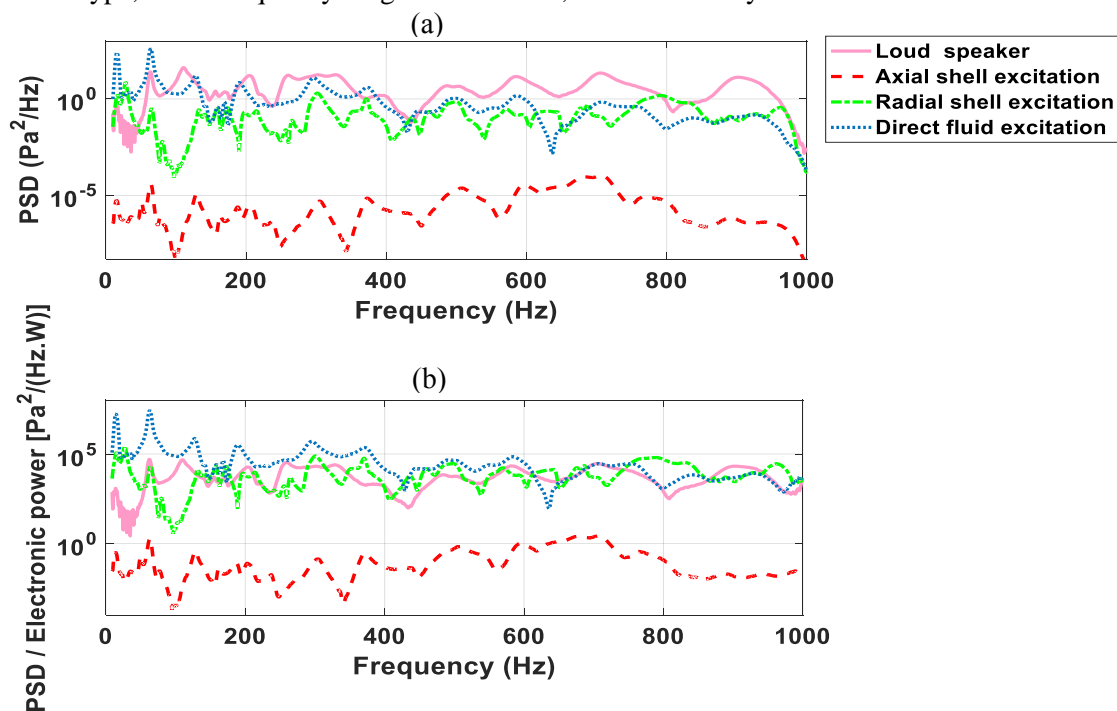


Figure 5. (a) PSD of the recorded pressures when the pipe is subjected to fluid excitation by the loudspeaker (—), shaker axial shell excitation (---), shaker radial fluid excitation (---) and direct shaker fluid excitation via the honeycomb piston (• • •). (b) Ratio between the PSDs of the recorded acoustic wave and the input electrical power to the driver.

3. Design of the pneumatic devices

The design structure of the balloon gun and of the pipe water gun is explained in this section. Creating such devices mainly requires a mechanism able to release time and pressure adjustable and controllable compressed air. How the compressed air is then drained of the device from an outlet is also of outmost importance.

3.1. Working principle

A pressure regulator has been attached to an air compressor device to control the pressure of the compressed air releasing. To control the release time of the compressed air from the pressure regulator a three port solenoid valve is connected to the pressure regulator and controlled with an Arduino. The Arduino acts as a time controller and specifies the time at which the valve opens and closes. Despite this it was found that the opening time of the valve could vary up to 0.05 ms due to the mechanical variation in the opening and closing mechanisms of the valve. Because of this, a reference signal can be established by wrapping a polyvinylidene fluoride (PVDF) films around the hosepipe near to the output port of the solenoid valve. However this signal is not been used in the results reported here. A schematic of each pneumatic device is illustrated in Figure 6.

The utilised valve is normally closed (see Figure 6 (a)) and it operates within the required pressure range. A reinforced pressure hosepipe was connected to the output port of the solenoid valve to transfer compressed air from the valve to the inside of the pipe. In the case of a pipe water gun the end of the hosepipe ends possesses a metal orifice with a calibrated hole, as shown in Figure 7. In the case of a balloon gun a rubber balloon is wrapped around the orifice. A party balloon, made of rubber with a nominal diameter of 30 cm was used. When the balloon is not inflated its thickness is about 0.5 mm. As the balloon capacity is much higher compared to the volume of the transferred compressed air, it is very unlikely to have a burst.

In the case of the balloon gun, when the valve is opened the compressed air goes into the balloon and expands it. When the valve is closed the third port of the valve acts as an output port and it drains the trapped air in the balloon.

In the case of the pipe water gun the hosepipe is submerged and the water fills it. When the valve is opened the compressed air pushes the penetrated water out of the orifice and generate the required pulsation into the water filled pipe. Since most of the buried water pipes are buried at a depth of 1 to 1.25 m, this type of excitation source has a potential to be used and create the required pressure wave into the fluid.

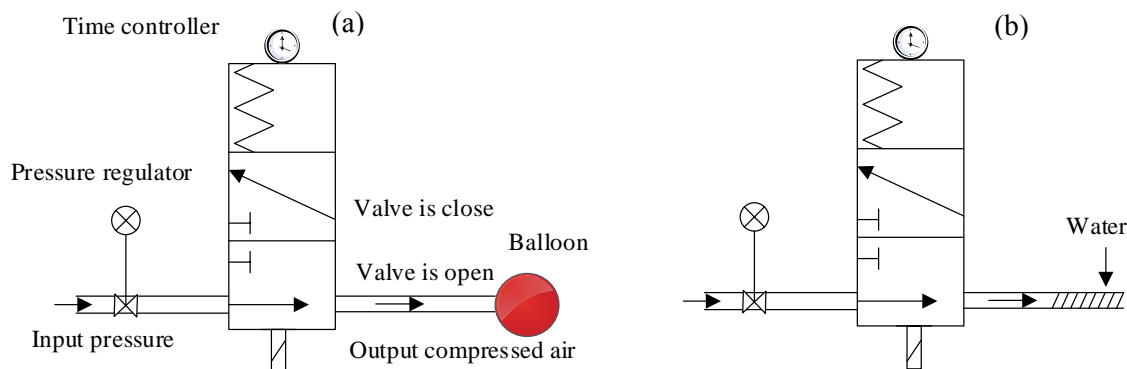


Figure 6. The diagrams of the developed pneumatic devices: balloon gun (a) and pipe water gun (b) configurations.

3.2. Parametric study

In this section experimental studies were undertaken on the rig shown in Figure 1, in order to characterise the performance of the developed devices. The fluid pressure was measured via the hydrophone at 1.3m from the water surface. For the both devices, an initial measurement was carried out by adjusting the pressure regulator to release a pressure of 3 bar, and the valve was set to open for 20 ms and close for 4.98 seconds. The signals were acquired for a time duration of 80 seconds, using 16 firings from the valve, at a sampling rate of 2.5 kHz. A low pass filter with a cut-off frequency at 1 kHz was used to

avoid aliasing. To fill the reinforced exhaust with the water, the last 20 cm of it was placed like a coil and submerged to the water at the top of the pipe. Coiling of the reinforce exhaust was made so to avoid its contact with the pipe wall. Following this, further experimental work has been performed to investigate the effect of changes on the generated acoustic wave into the water filled pipe to some parameter such as increasing the compressed air pressure and release time as well as the size of outlet orifice. A diagrams of the orifices attached to the end of reinforce exhaust is illustrated in Figure 7.

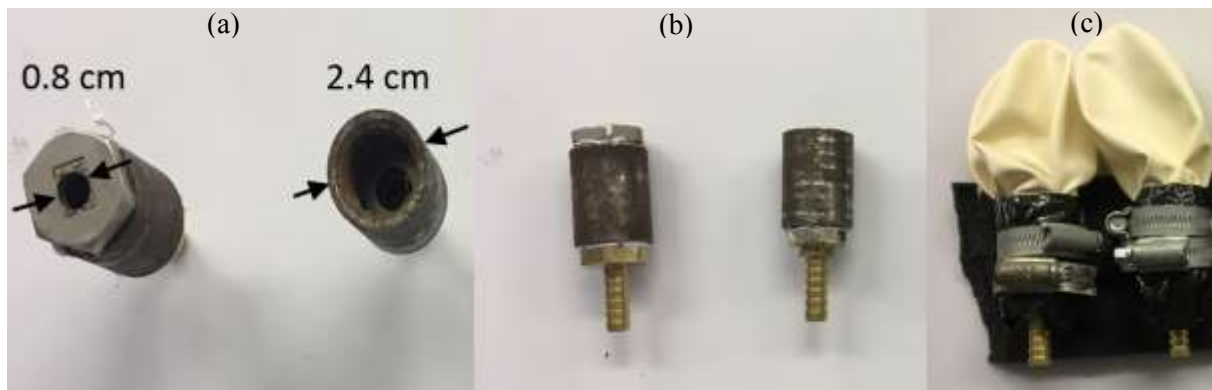


Figure 7. A picture of the end connections attached to the reinforce exhaust outlet. (a) The two different tips used for parametric study, showing the difference between their orifice diameters. (b) A plan view of the tips used for the pipe water gun. (c) The tips with the attached balloon.

The PSDs of the transmitted pressure obtained by the balloon gun from changing the aforementioned parameters are plotted in Figure 8. Due to high changes to the value of the PSD at low and high frequencies it is difficult to discuss on the result by looking at Figure 8 (a). Since the low frequency region is of the interest, it was decided to plot the data between 10 -100 Hz in figure 8 (b). As illustrated from Figure 8 (b), by doubling the pressure of the compressed air, the PSD of the recorded signal increases approximately 6 dB. Increasing the release time and the diameter of the orifice seems to have minor effects on the generated signal compared to its initial setup.

A similar procedure was followed for the pipe water gun and the results are plotted in Figure 9. Similar to the obtained data from the balloon, a rapid change to the value of the PSDs from low to high frequencies makes it difficult to discuss on the result by looking at Figure 9 (a), and the results are replotted in the frequency range of interest in Figure 9 (b). As shown in Figure 9 (b), a considerable change to the value of the PSD was observed by increasing the size of the orifice. In this case, the PSD amplitude increased between 20-40 dB compared to the other data. Changes to the time duration seems to have no considerable effect on the obtained data while doubling the pressure of compressed air caused 6 dB increase to the value of the PSD.

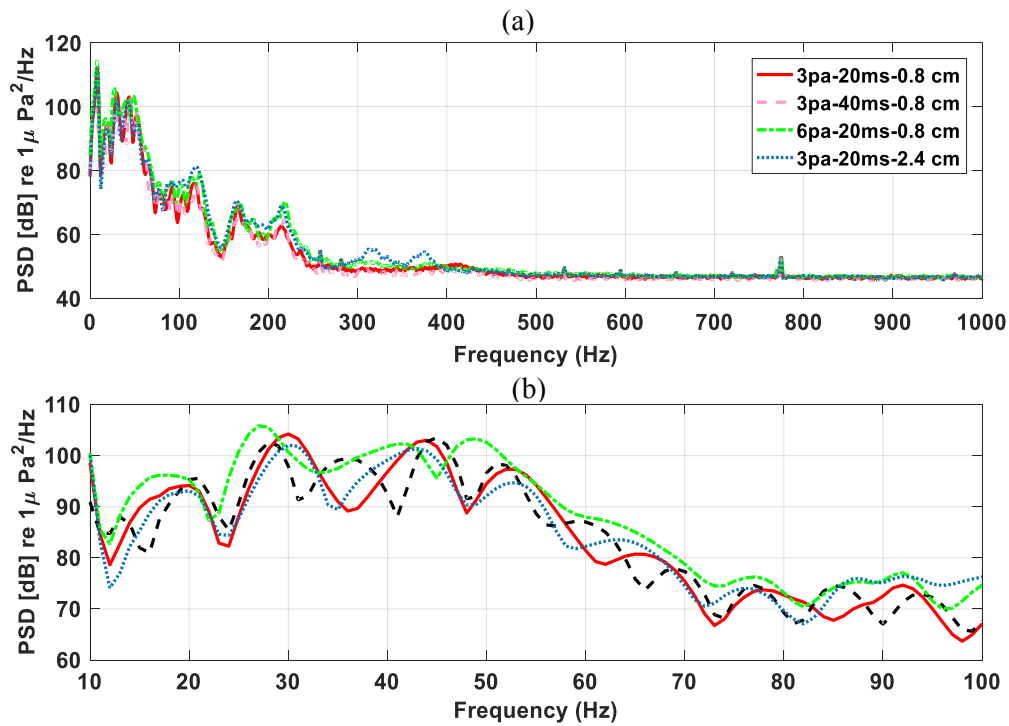


Figure 8. PSDs of the water pressure generated by the balloon gun. —: Compressed air supplied at 3 Pa for 20 ms duration with a 0.8 cm diameter orifice. ---: Time of the release increased to 40 ms. ---: Pressure increased to 6 Pa. · · · : orifice diameter increased to 2.4 cm.

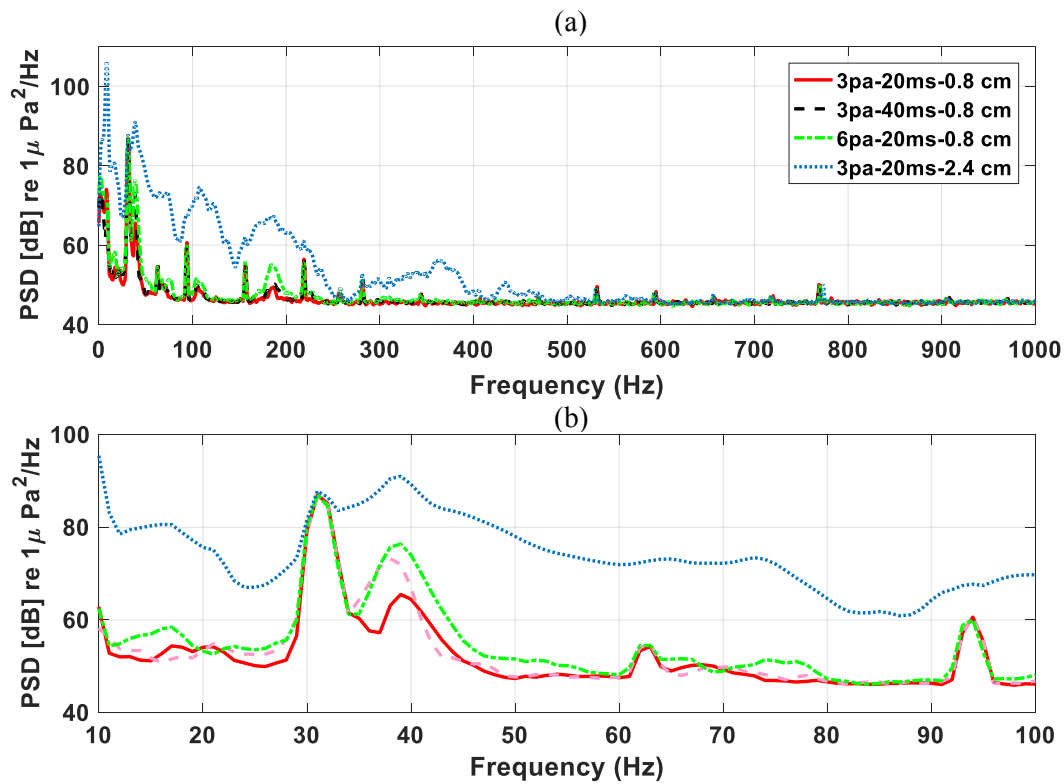


Figure 9. PSDs of the water pressure generated by the pipe water gun. —: Compressed air supplied at 3 Pa for 20 ms duration with a 0.8 cm diameter orifice. ---: Time of the release increased to 40 ms. ---: Pressure increased to 6 Pa. · · · : orifice diameter increased to 2.4 cm.

4. Comparison of the developed pneumatic device and the loudspeaker

In this section a comparison between the obtained data from the two pneumatic devices and the results from the loudspeaker is made. As shakers cannot be inserted into the buried water pipes and generate an in-pipe excitation along the pipe, its data excluded in this section. The PSDs of the measured pressure from the two pneumatic devices with a pressure of 3 Pa, release time of 20 ms and orifice diameter of 0.8 cm, plotted in Figures 8 and 9, are compared to the results from the loudspeaker, illustrated in Figure 5 (a), and replotted for convenience in Figure 10.

As illustrated in Figure 10, using the balloon gun as the excitation source will drive the fluid more strongly, approximately 100 in PSD amplitude, compared to the pipe water gun. Since the number of chirp signal used for the loudspeaker was equal to the number of pulsations made from the pneumatic devices, it might be fair to compare their results to one another. Although lower value of the signal was obtained from the loudspeaker at frequencies below 200 Hz, it can drive the fluid with higher amplitude afterward. One might claim that amplifying the signal through the power amplifier will cause to generate a higher pressure wave from the loudspeaker into the fluid. It should be noted that the maximum power at which the loudspeaker can operate is 20 watt. In the loudspeaker measurement, the maximum current that passed through the resistor box was 0.4 ohms. Assuming that the resistance of the loudspeaker is constant and is 8 ohm, the loudspeaker can approximately perform 24 dB at the best. This still drive the fluid with a lower amplitude compared to the results from the balloon, at < 80 Hz. It is worth to note that the developed device has potential to be used within smaller pipes down to 1 cm and are the most cost-effective devices that can be utilised for the pipe detection.

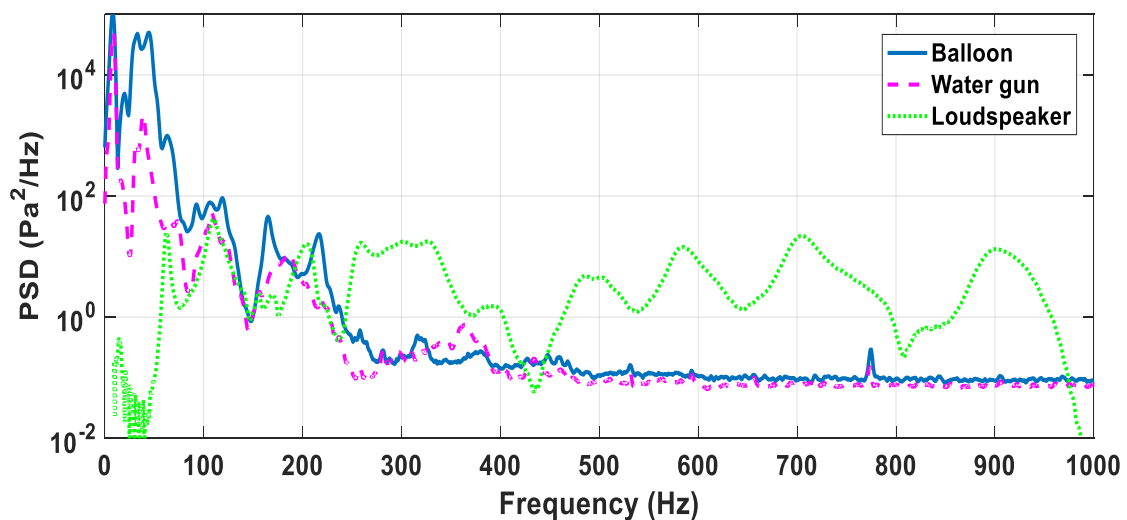


Figure 10. PSDs of the water pressure in logarithmic scale, generated by the balloon gun (—) and by the pipe water gun (---) with a pressure of 3 Pa, release time of 20 ms and orifice diameter of 0.8 cm; and PSD of the water pressure obtained from the loudspeaker (· · ·).

5. Conclusion

This study was carried out with the aim of developing vibroacoustic techniques to determine the location of buried water pipes using an excitation source inside the pipes that can be moved along the pipe length. Due to promising results from the previous vibroacoustic technique at low frequencies (< 100 Hz), a novel pneumatic device, the balloon gun, has been designed with the aim of generating high amplitude low frequency pressure wave into buried water pipes with wide range of diameter. Another pneumatic device called pipe water gun has been re-engineered for the same purposes. Although the obtained pressure wave from the pipe water gun is slightly lower in amplitude compared to the developed device, it can produce a higher amplitude signal, at the frequency range of interest, into the fluid compared to current underwater loudspeakers that can fit into a typical buried water pipe.

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