

The influences of soil and nearby structures on dispersion characteristics of wave propagating along buried plastic pipes

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Abstract. Water loss in distribution systems is a global problem for the water industry and governments. According to the international water supply association (IWSA), as a result of leaks from distribution pipes, 20% to 30% of water is lost while in transit from treatment plants to consumers. Although governments have tried to push the water industry to reduce the water leaks, a lot of experts have pointed out that a wide use of plastic pipes instead of metal pipes in recent years has caused difficulties in the detection of leaks using current acoustic technology. Leaks from plastic pipes are much quieter than traditional metal pipes and comparing to metal pipes the plastic pipes have very different coupling characteristics with soil, water and surrounding structures, such as other pipes, road surface and building foundations. The dispersion characteristics of wave propagating along buried plastic pipes are investigated in this paper using finite element and boundary element based models. Both empty and water-filled pipes were considered. Influences from nearby pipes and building foundations were carefully studied. The results showed that soil condition and nearby structures have significant influences on the dispersion characteristics of wave propagating along buried plastic pipes.

1. Introduction

The supply of sufficient water has a great impact on the future of the UK economy. However due to the leaks in the distribution system, there is about 19% of treated water (3.28 billion liters) lost each day in the UK. This water loss would meet the daily need of about 21 million people. The UK government and environment agency have been aware of this and since the 1990s have advised the water industry to reduce water loss. According to the UK water industry watch dog (OFWAT), £85 billion has been invested in fixing leaks since 1989, and £7.5 billion has been spent on changing infrastructure during the past 10 years.

A lot of research [1-17] has been carried out to investigate the characteristics of leaks and their propagations along pipelines, in order to improve the efficiency of detection and localization of different types of leaks. For example, Mpesha investigated the leak size and location using the frequency response method, though only circular opening pipes were considered [1]. Brunone used the Transient Test-based Technique to assess the condition of pipe systems and proved the method is effective [2, 3]. Kim investigated the impedance method which is based on inverse transient analysis for branched pipeline systems [4]. Taghvaei took advantage of the pressure fluctuation introduced by water hammer and used the reflected signal and cepstrum to detect leak in pipes [5]. Gong detected the leak of the pipe with the first three order resonant responses [6]. He also investigated the frequency response diagram for leaks in pipelines [7, 8]. Ghazali investigated the characteristics of instantaneous phase and frequency for detecting leaks in pipeline systems. The Hilbert-Huang transform was used in his method to obtain the instant phase and frequency information [9].



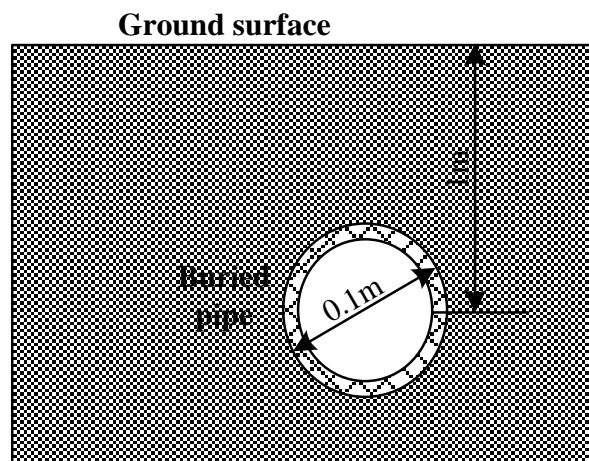
Although a lot of attention has been put into this field, experts have pointed out that a wide use of plastic pipes instead of metal pipes in recent years has caused additional difficulties in the detection of leaks using current acoustic technology (which was developed for metal pipes and relies on detecting and comparing the signals generated by the leak noise source [17]). Feedback from industrial users shows that leaks from plastic pipes are much quieter than traditional metal pipes and have a very poor detection and localization accuracy. That is due to the fact that the plastic pipe has a very different coupling effect with surrounding mediums compared to a metal pipe, and its attenuation rate is 5 times larger.

To further develop current technology to effectively detect leaks in plastic pipes, firstly, the acoustic characteristics need to be better understood. A fair amount of research has been conducted on this subject and found that most of the sound energy emitted from leaks in plastic pipes is concentrated in the low frequency band ($< 1000\text{Hz}$) [17]. However, more parametric studies need to be carried out on pipes with different sizes and different leaks. Secondly, the propagation of sound along plastic pipes needs to be carefully studied, due to the coupling effect with surrounding medium/structure and high attenuation rate. This paper will mainly focus on the coupling effect between pipes and surrounding medium/structures and try to highlight their influences on the dispersion characteristics of wave propagating along the plastic pipes.

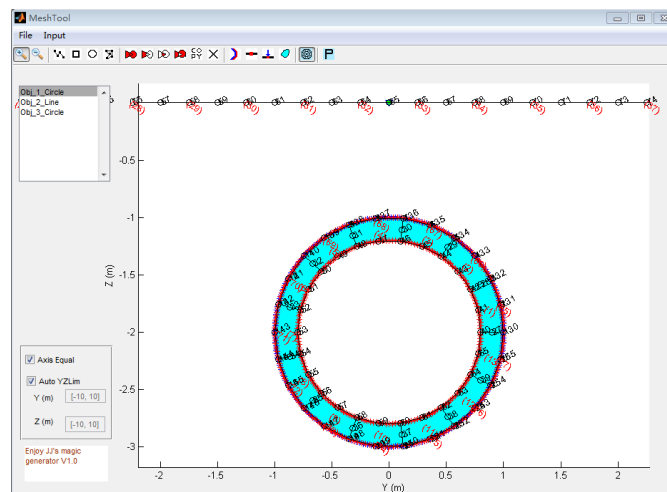
In Sec.2, the methodology used in the investigation is introduced. In Sec.3, numerical studies are carried out and results are discussed. Conclusions are given in Sec.4.

2. Methodology

A 2.5D finite element (FE) and boundary element (BE) based model, WANDS [19], was used in this study. The 2.5D approach requires that the system investigated has invariant geometry in one direction which is satisfied for underground pipeline structures. By using a Fourier transform with respect to the longitudinal coordinate, the three-dimensional (3D) response of the structure and the radiated wave field can be determined using a two-dimensional (2D) FE-BE mesh in the frequency domain. The mesh can be generated by using a Matlab based program called Meshtool, which was originally developed during EU FP7 Railway Induced Vibration Abatement Solutions (RIVAS) project. The program allows users to generate mesh and WANDS input files from given geometry. User interface and atypical example of the structure considered in this study are shown in Fig.1. In Fig.1a, the sketch of a buried pipe is presented; in Fig.1b, the pipe was meshed using 8-node rectangular (quadrilateral) finite elements. The ground was meshed using 3-node boundary elements with appropriate element size ensuring that there were at least 6 nodes per wavelength. Result obtained in frequency and wavenumber domain for each node can be plotted out as a color map. Dispersion curves (for each propagation mode) can then be identified in the $f-k$ map, as they will be highlighted by the spots with much higher amplitude than surroundings.



(a) Sketch of the buried pipe



(b) The buried pipe model with meshtool

Figure 1.Interface of Meshtool and the mesh of a pipe buried underground.

3. Numerical study

3.1. Empty pipe in vacuum

A simple case of an empty pipe in a vacuum was studied first to test the methodology. Two different methods were used to get the dispersion curve. One was using WANDS's output in frequency-wavenumber domain and the other was based on the eigenvalue method provided by WANDS[19]. For the WANDS model, a force was placed on top outer boundary of the pipe. Frequencies considered were from 5 Hz to 500 Hz with a 1 Hz increment, and 1024 wavenumbers were considered in the model from -8 to 8 rad/m. Response in frequency and wavenumber domain was calculated. For the eigenvalue method the same frequency range was considered. Results (dispersion curves in frequency and wavenumber domain) were obtained by analyzing the eigenvalues of assembled system matrix. The pipe considered is made of typical PMMA. Geometry and material properties of the PMMA pipe are listed in Table 1.

Table 1.Geometry and material properties of the PMMA pipe.

Parameters	Value
length	infinite
Outer diameter	100 mm
Inner diameter	90 mm
Young's model	$2.1 \times 10^9 \text{ Pa}$
Poisson's ratio	0.4
Density	$1.15 \times 10^3 \text{ kg/m}^3$
Loss factor	0.02

The results are shown in Fig. 2. The color map was produced from WANDS's output and the black circles show the results from eigenvalue method. The WANDS's output can easily highlight the predominantly excited mode, though eigenvalue method highlighted other weaker modes too. This can be due to the difference between the settings in these two methods.

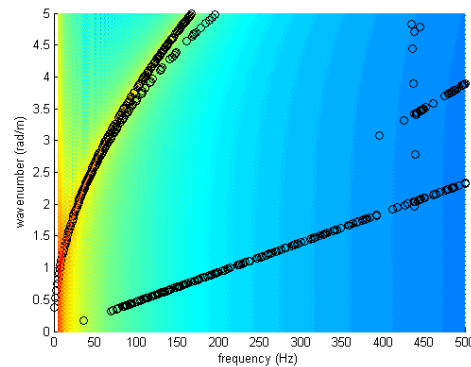


Figure 2.Dispersion curve in frequency-wavenumber domain for empty pipe in vacuum. The color map was produced from WANDS's output. The black circles are obtained from eigenvalue method.

The WANDS results are based on the setting that a force is placed on the top outer boundary at Z (vertical) direction, which is a simplification of a leak causing pressure variation on the top of the pipe. However the eigenvalue method considers all the possible propagation modes. Despite the modes that cannot be excited by the force setting in WANDS, results from the two methods match well. This gives us the confidence of using WANDS to investigate the pipe's propagation mode in more complicated scenarios which cannot be easily handled by eigenvalue method.

3.2. Buried empty pipe

If the pipe is buried underground, the pipe should couple with the surrounding soil and hence the dispersion curve will change. Here a pipe with same geometry and material properties shown in Table 1 is buried 1m under the ground surface. The soil is half space homogeneous. Soil properties are shown in Table 2. The f - k map obtained from WANDS is shown in Fig3. Comparing Fig.3 to Fig.2, due to the coupling with soil, the dispersion characteristics of the strongest mode (which starts from 0.5 rad/m about 5 Hz and reaches 8 rad/m at about 180 Hz) have changed. It looks more linear in Fig. 3 than in Fig.2. There are also other weaker modes can be recognized in the figure.

Table 2.Geometry and material properties of the PMMA pipe.

Parameters	Value
Young's model	$1.197 \times 10^8 \text{ Pa}$
Poisson's ratio	0.333
density	$2 \times 10^3 \text{ kg/m}^3$
Loss factor	0.03

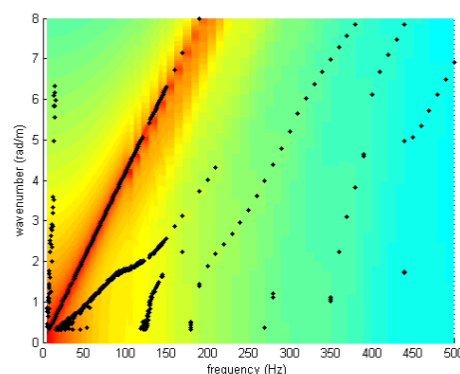


Figure 3.The f - k map for buried empty pipe.

3.3. Buried water filled pipe

If water is also included, the situation becomes more complicated. Here the same buried pipe used in Sec.3.2 was filled with water in the model. The water region was meshed using Fluid Boundary Element provided in WANDS. Result is shown in Fig. 4. Although the main mode from Fig.3 can still be recognized, due to the coupling with water, more energy has been distributed to other potential modes. The purpose of this paper is only to highlight the influences of surrounding medium and nearby structures on buried plastic pipes. The situation becoming more complicated when water is involved and the Fluid modal in WANDS hasn't been carefully validated. Therefore, in the following studies, only empty pipes are considered.

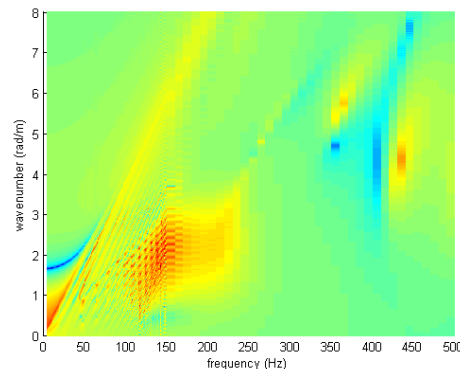


Figure 4. The f - k map for buried water-filled pipe.

3.4. Two empty pipes buried next to each other

The strong coupling between plastic pipes and soil makes it possible that nearby structures, such as building foundations and other pipes, can have an influence on the wave propagation in the pipe. Here, two empty pipes (same properties in Table 1) were buried 1m under the ground (same properties in Table 2) surface and 0.3 m (center to center) apart from each other. A point force is placed on the top outer boundary of one of the pipes. The f - k maps obtained from responses at each pipe are shown in Fig.5 and Fig.6 respectively. From the figures, although the scales of responses are different, there is no surprise that the dispersion curve recognized from the strongest mode is exactly the same.

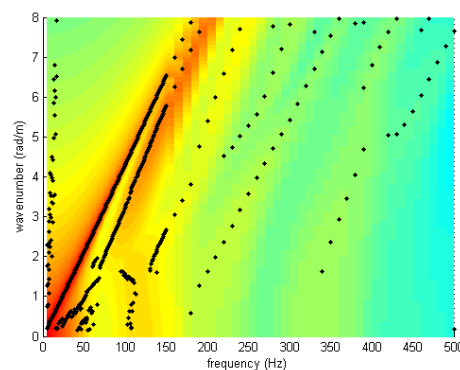


Figure 5. The f - k map for buried empty pipe with driving force placed on.

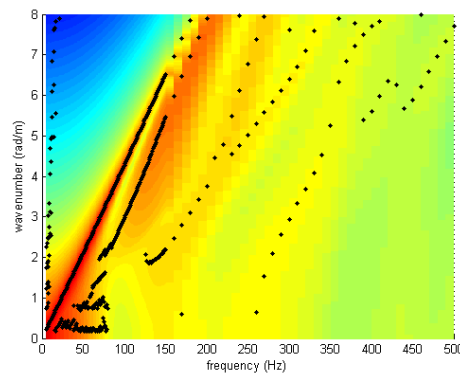


Figure 6. The f - k map for buried empty pipe without driving force placed on.

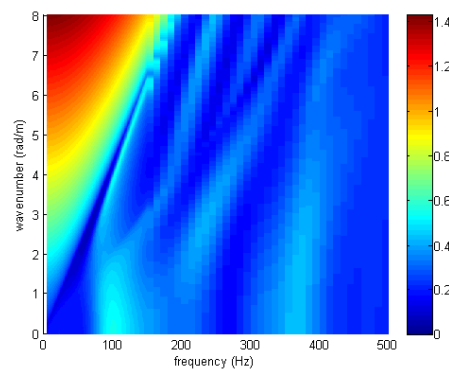


Figure 7. Difference of responses on two empty pipes buried next to each other (in dB). Driving force is only placed on one of the pipes.

Since both pipes are coupled with the soil, the soil acts as a medium to transfer energy from one to the other. The question is how much energy can be transferred. Fig. 7 shows the difference between the two maps in Fig. 5 and Fig. 6. For the frequency and wavenumber ranges calculated, the maximum difference of responses between these two pipes is about 1.5 dB. The pipe with driving force has a higher response. However, looking around the areas where highlight the dispersion curve and have most of the energy gathered, the difference is about 0 dB. Therefore, part of the energy can be transferred to the nearby pipes via the soil. The nearby pipe can potentially have same level of response as the pipe with driving force. This can significantly reduce the sound energy propagating along the original pipe.

3.5. A pipe buried next to concrete block

Pipes are often buried next to big concrete structures, such as building foundations, as seen in Fig. 8. If the coupling between soil and pipe cannot be ignored (which has been shown above), the nearby concrete structures can also have an effect on the sound propagation along the pipe. Here an empty PMMA pipe (Table 1) is buried 0.2 m away from a concrete block. The block is 1.4 m in height and 0.7 m in width. The dimensions of the block are much larger than the pipe's outer diameter 0.1 m. Material properties of the concrete are shown in Table 3. The potential modes identified from the responses on the pipe and on the block are highlighted in Figs. 9 and 10 respectively.

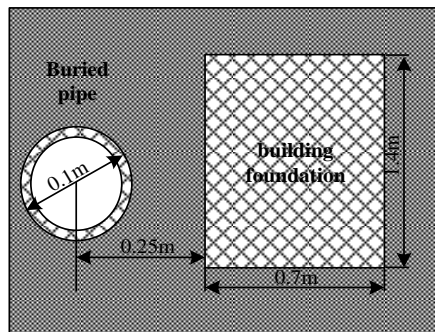


Figure 8. An empty pipe buried next to concrete block (not draw in scale).

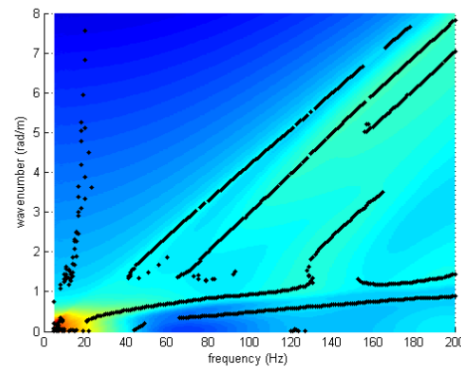


Figure 9. The f - k map for buried empty pipe with driving force placed on.

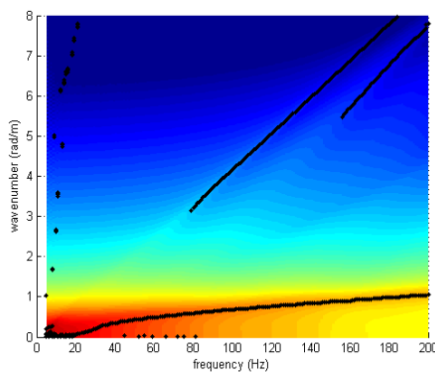


Figure 10. The f - k map for buried concrete block without driving force placed on.

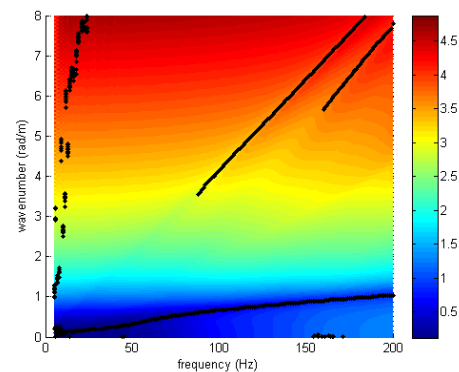


Figure 11. Difference of responses on the pipe and concrete block (in dB). Driving force is only placed on the pipe.

The difference in dB is shown in Fig. 11. Comparing to the result without the concrete block, in Fig. 3, the appearance of concrete block introduced some additional modes in the system. The main mode in Fig. 3 still exists, though it has been over taken by other modes at lower frequencies (< 50 Hz). Comparing the response levels on the pipe and the concrete, in Fig. 11, response from the pipe at the original main mode (from Fig. 3) is till about 3-5 dB larger than the response from block. This is much better than the case of two buried pipes, where the difference is about 0 dB. This can be due to the fact that the concrete block is acoustically harder than the pipe material and soil. Therefore, it acts more as a reflector for that particular mode. However it boosted other modes that take a big share of the total input energy.

Table 3. Properties of concrete block.

Parameters	Value
Young's model	$3.5 \times 10^{10} \text{ Pa}$
Poisson's ratio	0.2
density	$2.5 \times 10^3 \text{ kg/m}^3$
Loss factor	0.015

4. Conclusions

Numerical studies were carried out in this paper to investigate the influences of surrounding medium and nearby structures on buried plastic pipes which commonly used as replacement of traditional metal pipes for water transportation. Due to the acoustic properties of plastic pipe, it has a much stronger coupling with the surrounding soil. Comparing the result with and without soil, the potential propagation modes highlighted from f - k maps show very obvious difference. When water is also included in the numerical model, the propagation mode can be even more complicated when no other limits, such as limiting the displacement to axis symmetric, are given. If the plastic pipe can transfer energy into soil through the coupling, it is not difficult to imagine that the soil can act as a link between the pipe and nearby structures. In this paper two cases were investigated, including two parallel pipes and one pipe next to a concrete block. From the results, the nearby structures can have influences on the propagation mode of the pipe itself. They may introduce additional mode or highlight other weak modes under some circumstances. For the case of two parallel pipes, the response levels on the two pipes for the main mode are nearly the same. This means, if that particular mode is excited, nearly half of the energy will transmit to the other pipe via soil. This can also introduce additional error to the leak detection system, as the faulty signal might be actually from nearby pipes. The concrete block is acoustically harder than the pipe and soil. When it is considered in the model, it doesn't have significant influence on the response level of the main mode identified on the pipe, but it does introduce other modes which take a big share of the energy from the main mode.

This is only a preliminary investigation into the influence of surrounding medium and nearby structures on buried plastic pipes. Before drawing further solid conclusions, more parametric studies are needed, and water should also be considered for all the cases. However from the results presented at this stage, we can already say that: when plastic pipe is used, the property of surrounding medium and nearby structures should also be considered to determine the propagation mode.

5. References

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