Chapter 10
Combining Waves Propagation Theory, Modal Analysis and Dynamic Response to Assess the Condition of Fluid-Filled Pipes

Sebastien Perrier, Marshal D. Kafle, Gurvinder Mundi, Elia Rizkalla, and Cameron White

Abstract Water distribution networks, conveying water through thousands of miles of pipes, are critical infrastructures subjected to various structural and environmental degradation mechanisms. Timely, non-invasive, and non-destructive assessments are crucial in preventing breaks and leaks and managing the loss of these valuable resources, thereby avoiding extensive damage and repair costs. This paper explores the application of the vibroacoustic method combined with modal analysis and dynamic response techniques in evaluating the structural health of pipelines. The method includes deploying sensors to capture vibrational data that can be spaced as far as 2,000ft, applying finite element modelling to simulate pipeline behavior, and using advanced signal processing techniques to interpret the data. Until now, the technology has been tested on water mains of various pipe materials such as HDPE, PVC, Steel, Cast Iron, Ductile Iron, Asbestos Cement and Concrete for diameters ranging from 3 to 72 inches. The level of resolution acquired is typically between 6 and 15ft and varies with pipe type and diameter, as well as the distance between the sensors.

Keywords Pipeline Condition Assessment · Coupled Waves · Vibro-Acoustics · Dynamic / Modal Response Analysis

Introduction

Pipes are vital to modern society for transporting and distributing drinking water and wastewater. Capital budget constraints, pipe age, and other environmental factors have all contributed to pipe degradation, and between 2012 and 2018, the overall water main break rates increased by 27% [1]. Acoustic methods in fluid-filled pipes have been widely used for decades to acoustically monitor leaks [2]. For condition assessment, starting in the early 2000s, the Moens-Korteweg equation [2] has also been applied to fluid-filled pipes, such as watermains, to model the relationship between wave speed and the elasticity of the wall, allowing to assess the average degradation of pipes, typically over 300 to 600ft. While this approach has provided valuable information to pipeline owners and asset managers, there is a need for more granular information to make the right decision in terms of repair, rehabilitation or replacement of these 20 to 40-foot-long buried assets. This paper discusses the combination of modal analysis and dynamic response techniques with the vibroacoustic wave theory to evaluate the condition of the fluid-filled pipes and generate that finer resolution, which is otherwise incredibly challenging if using wave speed-based methods only.

Results from experimental case studies demonstrate the efficacy of this integrated approach in detecting and localizing damage within pipeline structures. The findings suggest that combining modal analysis and dynamic response techniques can significantly enhance the early detection of faults, thus reducing the risk of catastrophic failures and extending the operational lifespan of pipelines. This technology underscores the potential of non-destructive evaluation methods as robust tools for proactively managing pipeline infrastructure.

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Brandon Dilworth et al. (eds.), *Topics in Modal Analysis & Parameter Identification I, Vol. 9*, Conference Proceedings of the Society for Experimental Mechanics Series, https://doi.org/10.13052/97887-438-0154-2_10

Background

The coupled wave equation of motion governs the propagation of acoustic waves through a material medium that interacts with the structure, such as a viscoelastic pipe containing fluid. In this case, both the medium and the mechanical properties of the pipe play a role in how the wave propagates. The coupled eigenfrequencies are the frequencies at which the fluid-structure system resonates and are crucial pieces of information in the assessment of the pipe condition.

The modal analysis determines the pipe's eigenfrequencies and mode shapes. From the baseline from the undamaged pipes, the deviation in dynamic properties or indicators, such as shifts in natural frequency and mode shapes, suggests deterioration in pipes. The thinning walls are more flexible due to decreases in the stiffness of the pipe, leading to lower eigenfrequencies and increased vibrational energy. For simplicity, the pipe can be modeled as a cylindrical beam, and the eigenfrequency f_n of the mode n can be expressed as [3]:

$$f_n = \frac{\lambda_n^2}{2\pi L^2}\sqrt{\frac{EI}{\rho A}}$$

where, λ is mode shape constant, L is the length of the pipe, E is the Young's modulus, I is the moment of inertia, ρ is the density of the material and A is the cross-sectional area of the pipe. The combined fluid-structure interaction (FSI) is more complex and involves solving the wave equation for both the pipe wall and the fluid. In such cases, the eigenfrequencies can be obtained via experimental modal analysis or modeling the pipe numerically.

The dynamic response technique involves measuring the response of the pipeline using accelerometers when subjected to dynamic loads; the loads are generated using an external device. For a simple harmonic excitation $F(t) = F_0 \sin(\omega t)$, the dynamic response at frequency ω is [4]:

$$X(\omega) = \frac{F_0}{\sqrt{(k - m\omega^2)^2 + (c\omega)^2}}$$

where, $X(\omega)$ is the response at frequency ω, F_0 is the magnitude of external force, m, k, c are mass, stiffness and damping of the system which are functions of the pipe wall thickness.

The response can be fed into the signal processing tools, which give the dominant frequencies at which the pipeline is dynamically responding. Comparing and matching the response with the eigenfrequencies helps access the indicators to quantify the level of degradation.

Analysis of Eigenfrequencies using COMSOL

For numerical estimation of the eigenfrequencies of a coupled wave, an FSI analysis is carried out using a COMSOL platform. The study comprises a 3 m (10 ft) ductile iron pipe with a nominal bore diameter of 300 mm (12 in) as well as a 2D model with the same diameter and a parametric sweep of the wall thickness between 8 and 13 mm (1/3 and 1/2 in) with 1 mm (3/64 in) increments. The vibroacoustic-structure interfaces ensure a proper connection between acoustic pressure and the displacement of elastic material. The radial mode shape for a pipe with a wall thickness of 13 mm (1/2 in) is shown in Fig. 1.

The frequency shift for a radial mode as the wall thickness is reduced is observed in a 2D model (shown in Fig. 2(a)), with the results from the 3D case overlapping nicely. A similar trend is observed in the average of 8 modes for the 3D case. This reinforces the theory explained in the background section that the deviation in indicators such as eigenfrequencies can be analyzed and compared with the baseline (undamaged) to assess the level of pipe wall degradation. This result is further matched with the experimentally measured response, to obtain further interpretation of the data.

Field Result – Case Study

The City of Gresham, Oregon, with a population of 110,000 people, manages over 240 miles of water mains through a proactive, risk-based approach to maintain reliable service. As part of its long-term strategy, the City plans to restart its pipe replacement program in 2026. To prioritize pipeline replacements, Gresham assigns a Likelihood of Failure score to water mains that haven't been inspected, based on pipeline age, material, and leak/break history.

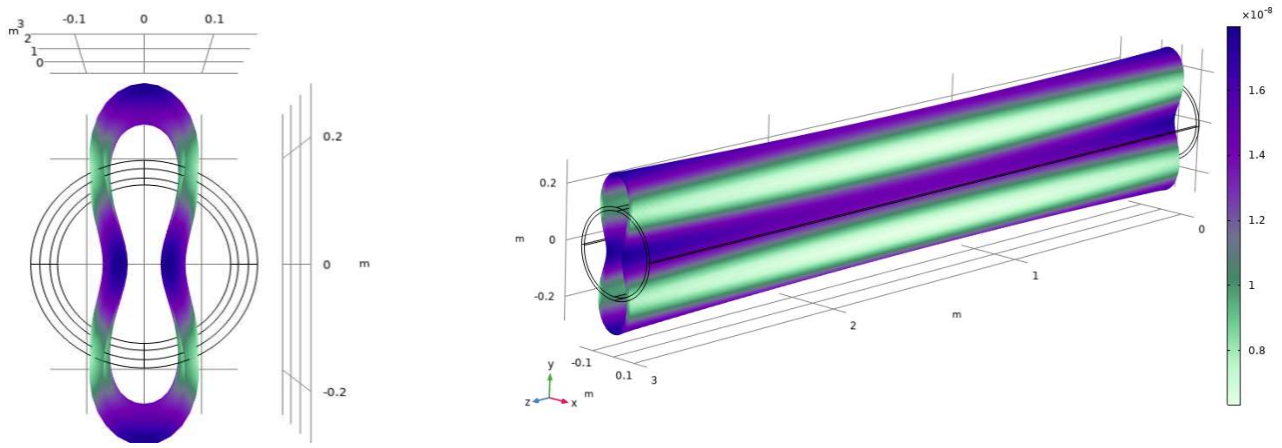

Fig. 1 Schematic of a radial mode occurring at 259 Hz.

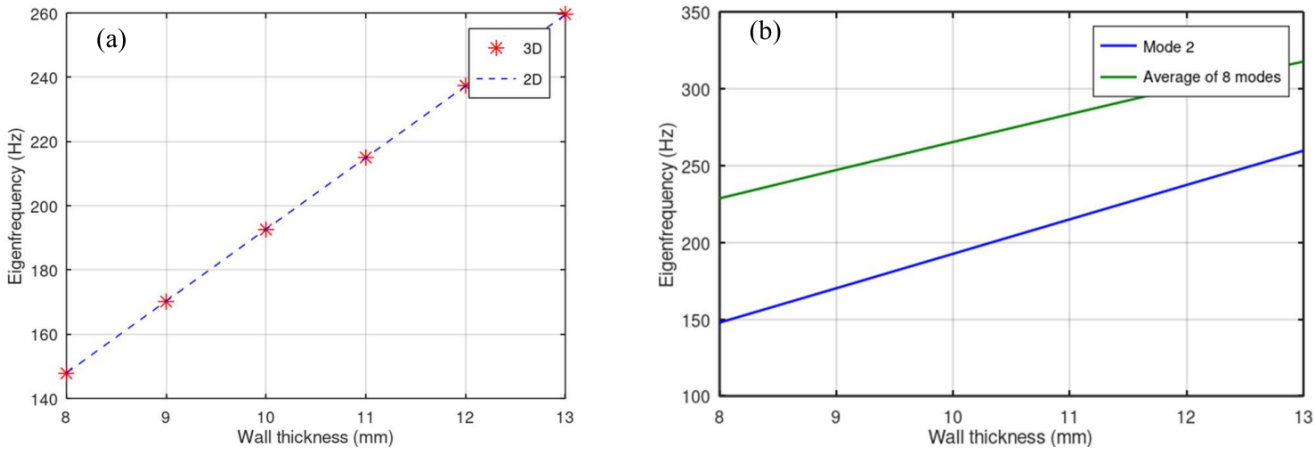

Fig. 2 The comparison of eigenfrequencies vs wall thickness: (a) between 2D and 3D model for a radial mode; (b) for mode 2 and average of 8 modes for a 3D model.

To improve decision-making and extend the life of its water mains, the City conducts condition assessments on pipelines installed before 1980. For the inspected pipes, the Likelihood of Failure score is based on estimates of Remaining Useful Life and historical leak/break data. This helps the City focus on replacing or repairing the most critical sections while keeping older but still functional segments in use.

In line with this strategy, Gresham engaged KenWave Solutions to assess four cast iron and ductile iron pipelines, ranging from 6 to 10 inches in diameter and spanning a total of 3,528 feet. KenWave's non-invasive Dynamic Response Imaging$^{\mathrm{TM}}$ (DRI$^{\mathrm{TM}}$) technology provided detailed residual wall thickness measurements with 6-foot resolution, enabling the City to identify both healthy areas and sections showing signs of increased degradation.

The DRI results identified localized changes in wall thickness between access points, enabling the City to prioritize areas requiring immediate attention. To verify these findings, Gresham excavated seven locations and used an ultrasonic gauge to scan the pipe as a general accuracy check. Additionally, two sections of pipe were removed from the most deteriorated areas and examined. The results and comparison between DRI and ultrasonic measurements are presented in the Table below.

Table 1 Validation Results

Pipeline	Pipe Type	Pipe Size (In)	Nominal Stiffness Lost (%)	DRI Residual Wall Thickness (in)	Validation Method	Measured Minimum Avg Hoop Thickness (in)
NE 5th St	Cast	6	**19%**	0.30	Slice	0.32
NE 5th St	Cast	6	**33%**	0.25	Pipe Stick	0.27
NE 5th St	Cast	6	**3%**	0.34	Slice	0.36
SE 10th Dr	Ductile	6	**0%**	0.25	Slice	0.24
SE 10th Dr	Ductile	6	**24%**	0.19	Pipe Stick	0.19
NE 23rd St	Cast	8	**10%**	0.40	Slice	0.40
NE 23rd St	Cast	8	**3%**	0.42	Slice	0.41

This process confirmed that the predicted wall thickness data was accurate.

KenWave's assessment data is now helping Gresham predict the remaining useful life of its pipelines and update the Likelihood of Failure scores for inspected sections. This information is crucial for planning future pipe replacements, ensuring efficient resource allocation and minimizing service interruptions.

Conclusion

The methodology combining waves propagation theory, modal analysis and dynamic response of watermains can provide granular longitudinal information regarding pipe wall thickness with a resolution of 2 m (6 linear feet). Comparison of changes in the wall thickness from the measured dynamic response of the pipes agreed with the validation performed on metallic distribution mains, confirming that the predicted localized wall thickness data was accurate.

Specifically, results from experimental case studies demonstrate the efficacy of this integrated approach in detecting and localizing damage within pipeline structures. The findings suggest that combining modal analysis and dynamic response techniques can significantly enhance the early detection of faults, thus reducing the risk of catastrophic failures and extending the operational lifespan of pipelines.

More projects are ongoing with several utilities worldwide with different levels of validation on various pipe materials such as HDPE, PVC, Steel, Cast Iron, Ductile Iron, Asbestos Cement and Concrete for diameters ranging from 3 to 72 inches.

This technology underscores the potential of non-destructive evaluation methods as robust tools for proactively managing pipeline infrastructure.

Acknowledgments The authors and KenWave Solutions Inc. want to acknowledge the support for this project provided by the City of Gresham.

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