ICSV14
Cairns • Australia
9-12 July, 2007

14th International Congress on Sound & Vibration

TIME-FREQUENCY ANALYSIS OF ACOUSTIC SIGNALS FOR CONDITION MONITORING OF FLUID-FILLED PIPELINES

Wenbo Duan[1], Fengshou Gu[1], Andrew Ball[1], Fenglei Jiao[2], Ke Liu[2]

[1] School of Mechanical, Aerospace and Civil Engineering,
The University of Manchester, Pariser Building, M13 9PL, UK
[2] Chinese Academy of Sciences,
21 Bei Si Huan Xi Lu, Beijing, 100084, PR China
Wenbo.Duan@postgrad.manchester.ac.uk

Abstract

In this paper, a wave propagation model is developed to investigate the wave propagation in fluid-filled steel pipe. Based on the Kennard shell equations the investigation is achieved under the conditions of coupling between the shell elastic acoustic field and the interior fluid acoustic field. Tests are conducted on fluid-filled pipeline blockage detection. An active acoustic source is used to generate acoustic pulse waves into the pipe. The position of the blockage can be obtained from the reflected transient signals. Smoothed Pseudo Wigner-Ville distribution method (SPWVD) has been used to extract the time and frequency features of the propagating waves in the coupling system. Experimental results demonstrate that the proposed approach and SPWVD are effective in detecting the position of the blockage.

1. INTRODUCTION

Pipeline leakage detection has been under investigation for the past decades. Significant economic and environmental consequences can be caused by even a small leak. Acoustic leakage detection methods have shown to be effective and are in common use in the water industry[1]. The most useful technique for locating a leak has been the cross-correlation of leak noise at two locations along the pipe[2, 3]. For the correlation technique to be effective, the propagation wave speeds and wave attenuation must be known a priori. Because of the coupling effect between the pipe wall and the contained fluid and surrounding medium, wave propagation behavior is rather complicated[4].

The analysis of harmonic wave propagation in piping systems has been studied by many authors. The waves in a fluid filled pipe, i.e., the solutions to the coupled equations of motion were originally investigated by Fuller and Fahy[5]. Real, imaginary and complex wavenumbers in all circumferential modes are calculated, and physical interpretations of the results have been offered. A concise expression for the shell power flow has been derived by Fuller [6], and energy distribution in the fluid-shell coupled system for each propagating wave of azimuthal order n has been evaluated. The analysis was then extended by Fuller to cope with forced response in infinite pipes that are excited by a radial line force[7] and by monopole sources in the fluid[8]. Brevart and Fuller[9] later derived the time domain response of an infinite fluid-filled pipe to an impulsive line force of various azimuthal distributions. The energy exchange between the structure and the fluid as the various waves propagate through the system was given. Pavic[10] derived more exact expressions of the power flow in shells, and investigated the fluid-structure interaction in relatively low frequencies by approximate dispersion equations. Muggleton, et al[11] have investigated the wavenumbers within elastic, water-filled buried pipes and the radiation from submerged shells has been concerned. The simplified forms of Kennard's equations for a thin-walled shell have been used and are only valid below the ring frequency.

The present work uses the exact forms of Kennard's shell equations which can predict wavenumbers in all circumferential modes. No approximations are made for the computation of the Bessel functions and the Hankel functions so the application can be extended to relatively high frequency range. A novel way to detect leakage or blockage has been used in the present paper. An active acoustic source is used to generate acoustic pulse waves into the pipe. The position of the leakage/blockage is obtained by the reflection transient signals. It is easier for the sound generator to activate high frequency signals, so the frequency distribution of the pulse generated by the sound generator concentrates on the high frequency region.

Tests for wavespeed and blockage in fluid-filled pipes are conducted. The reflection signal from the blockage is usually very weak unless the acoustic source is very strong or the blockage is very large. General methods such as cross-correlation method appear not ideal in detecting the position of the blockage. SPWVD is used to extract the time and frequency information of reflection transient signal which reveals the position of the blockage inside the pipe[12].

The time-frequency method has become a powerful method for the analysis of transient signals. The time-frequency has variable time-frequency resolution over the time-frequency plane by providing good time resolution at high frequencies and good frequency resolution at low frequencies[13]. Among various time-frequency distribution methods one of the most studied is the Wigner-Ville distribution. The concept was first introduced by Wigner and was re-introduced by Ville. Like Fourier transform, it requires that the time series under analysis be known at all times. The Wigner-Ville is the Fourier transform of the signal's autocorrelation function with respect to the delay variable. It can be thought of as a short-time Fourier transform where the windowing function is a time-scaled, time-reversed copy of the original signal[14-16]. Smoothed pseudo Wigner-Ville distribution is used in the present paper to evaluate the time and frequency component of the transient signal.

2. WAVENUMBER EQUATIONS

Kennard's equations are used in the present paper which describe the free, simple harmonic motion of a thin-walled cylindrical shell[17].

The normal mode shapes assumed for the displacements of the shell wall, associated with an axial wavenumber k_{ns}, are

$$u = \sum_{s=0}^{\infty}\sum_{n=0}^{\infty} U_{ns} \cos(n\theta) e^{i(\omega t - k_{ns}x + \pi/2)} \tag{1}$$

$$v = \sum_{s=0}^{\infty}\sum_{n=0}^{\infty} V_{ns} \sin(n\theta) e^{i(\omega t - k_{ns}x)} \tag{2}$$

$$w = \sum_{s=0}^{\infty}\sum_{n=0}^{\infty} W_{ns}\cos(n\theta)e^{i(\omega t - k_{ns}x)} \tag{3}$$

The internal pressure of the fluid is given by:

$$p_f = \sum_{s=0}^{\infty}\sum_{n=0}^{\infty} P_{fs}\cos(n\theta)J_n(k_{fs}^r r)e^{i(\omega t - k_{ns}x)} \tag{4}$$

The radial wavenumber k_{fs}^r is related to the fluid wavenumber k_{ns} by

$$k_{fs}^r = \sqrt{k_f{}^2 - k_{ns}{}^2} \tag{5}$$

At the boundary, the radial displacement of the fluid equals to the shell displacement. Pressure coefficients can be obtained by equating the radial velocity of the fluid at the shell wall to the radial velocity of the shell wall:

$$P_{fs} = \omega^2 \rho_f W_{ns} / k_{fs}^r J_n'(k_{fs}^r a) \tag{6}$$

Substitution of equations (1-6) into Kennard's equations gives the equations of motion of the coupled system in terms of the amplitudes of the three displacements and the acoustic pressure. The free vibrations of the coupled system can be represented in a matrix form[5]. By setting the determinant of the amplitude coefficients of the matrix to zero, the wavenumbers for a free motion solution can be found.

3. NUMERICAL SOLUTION

Expansion of the determinant given by the matrix provides the system characteristic equation. Due to the non-linear characteristics of the fluid loading term in the coupled equation, numerical methods have to be used to find the roots of the equation. Kumar and Stephens[18] provided an contour integration technique to find the roots inside the contour. Then Newton-Raphson method was utilized to calculate the exact root from the initial approximate location of the root given by the contour integration technique. Fuller[5] used a simpler and quicker method to find the approximate locations of the roots at low frequencies by using the in vacuo shell dispersion results as the initial value. Then Newton's rule was used to find the complex roots.

Note that Newton's method need to calculate the derivative of the fluid loading term, which will be cumbersome for the present paper. A simplex optimization method was used to find the complex solution of equation as an alternative[19].

The dispersion curves are obtained for a thin walled fluid-filled pipe. The properties of the shell and fluid are given in Table 1. Thickness/radius ratio of the pipe is 0.05. Results are presented in Figures 1, 2 for circumferential modes of n=0 and n=1 which exhibit all the general characteristics of wave propagating.

Table 1. Material properties.

Material	Young's modulus (N/m^2)	Poisson's ratio	Density (kg/m^3)	Free wavespeed (m/s)
Steel	19.2×10^{10}	0.3	7800	5200
Contained fluid	---	---	1000	1500

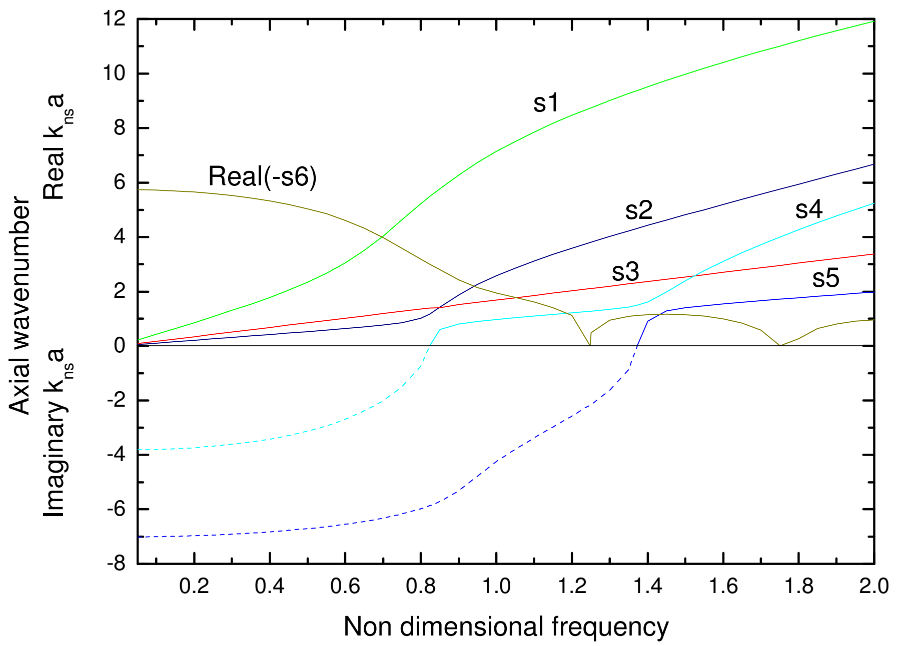

Figure 1. Wavenumbers for a fluid-filled pipe in the breathing mode.

Figure 1 shows wavenumbers in the breathing mode. The branch s1 is a fluid type wave at low frequencies. The fluid is unable to cause the shell to vibrate because of long axial wavelength. At very high frequencies, the shell and fluid motions become strongly coupled and this branch approaches the in vacuo flexural solution [5, 20]. The branch s2 is a structural-type wave at low frequencies, close to the in vacuo extensional solution. Because of the heavy fluid introduced in the system and the induced coupling phenomenon, this branch turns into a pressure release duct solution at high frequencies. The branch s3 is the torsional shell wave which is not coupled to the fluid motion. Wavespeed of this wave is constant at all the frequencies as can be clearly seen in Fig 2. The s4 wave is a decaying wave with pure imaginary wavenumbers at low frequencies and cuts on at $\Omega = 0.82$ to a propagating wave. s4 is close to an extensional in vacuo shell wave initially and the s5 wave is close to a fluid wave in a tube initially. The s6 wave represents evanescent motion with attenuated wave amplitude in the axial direction along the shell wall. The physical meaning of the wavenumbers for a fluid filled in vacuo pipe has been discussed more fully by Fuller[5].

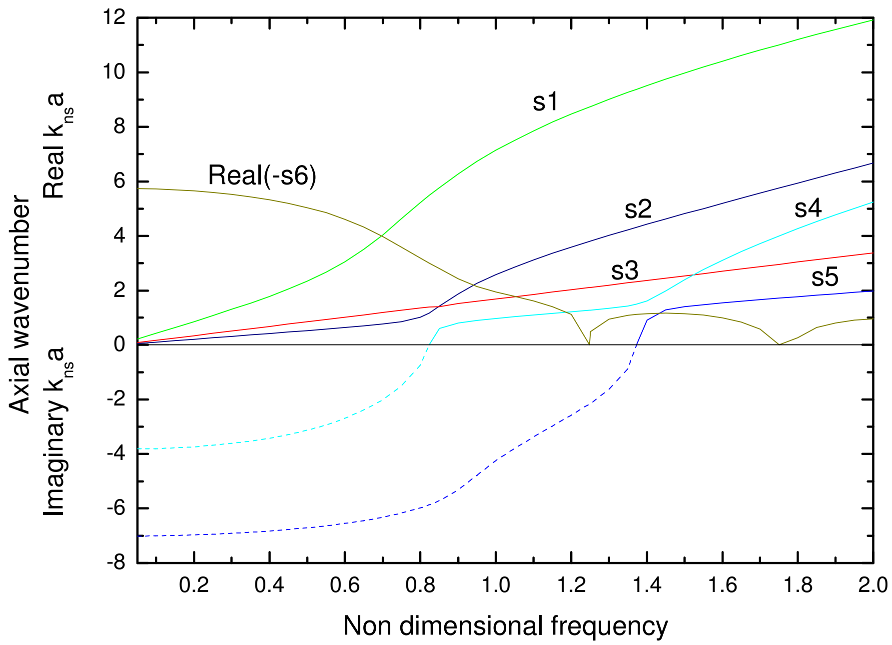

Figure 2. Wavenumbers for a fluid-filled pipe in the breathing mode.

Figure 2 shows the wavenumbers in the beam type mode. There exists only one beam type branch s1 at low frequencies. s2 wave cuts on at $\Omega = 0.592$ and this wave is close to the first rigid walled duct mode with circumferential order n=1. s3 wave cuts on at $\Omega = 0.681$ and this wave is close to the torsional shell motion. This wave changes its behavior to a fluid-type wave when it encounters branch s4. s5 wave cuts on as an extensional shell wave and it converts into a duct type wave at higher frequencies.

4. EXPERIMENTAL TEST

Several tests are conducted to get the wavespeed in the water-filled steel pipe and to pinpoint the position of the blockage. The configuration of the test rig is shown in Figure 3. Two hydrophones are mounted inside the water close to the two ends of the pipe without touching the pipe wall. The distance between the two sensors is 6.6 meters. The pipe has an internal diameter of 81mm and a thickness of 4 mm.

A pulse signal generated by the computer has been used to drive the sound generator. This impulse sound is received by the microphones in the form of transient signals. SPWVD is used to find the time and frequency characteristics of the signals. The frequency components of the pulse can be obtained from figure 4. It is clear the high frequency component carries significant portion of the pulse's energy. So these high frequency components are used for wavespeed estimation and blockage detection. Environmental noises are concentrated mainly at the low frequency region. By choosing high frequency component, the effect of the noise can be avoided greatly. The wavespeeds of different waves can be calculated by $c = d / \tau$. Where d is the distance 6.6 meters from hydrophone 1 to hydrophone 2, and τ is the traveling time of acoustic waves with different frequency components.

Dispersion characteristics can be observed in figure 4 and figure 5. As illustrated in the previous section, wavenumbers are functions of frequency, i.e., wavespeeds are functions of frequency. Thus acoustic waves with different frequency component will be traveling at different wavespeeds. Figure 8 shows the pulse traveling time at different frequencies. The pulse time-shift can be observed in signal recorded by hydrophone 2.

Figure 6 shows the time-frequency distribution of the reflection signal of the s2 fluid type wave when a blockage is inside the pipe. The blockage is a screw about 3 centimeters in diameter and 2.3 meters away from hydrophone 1. The result has been magnified to show both the initial and reflection signals together. Based on the result, the position from the blockage to hydrophone 1 can be calculated by: $d_b = c \times \tau / 2$. τ is measured from the front wave plane of the reflection signal to the front wave plane of the initial signal recorded by hydrophone 1.

Table 2 shows the calculated blockage distance at different positions. The reflection signal decreases with distance as the distance from blockage to the acoustic source increases. At position 5 and 6, the reflection signal from the blockage mixes with the reflection signal from the water-air surface at the other end of the pipe, thus makes the calculated distance inaccurate.

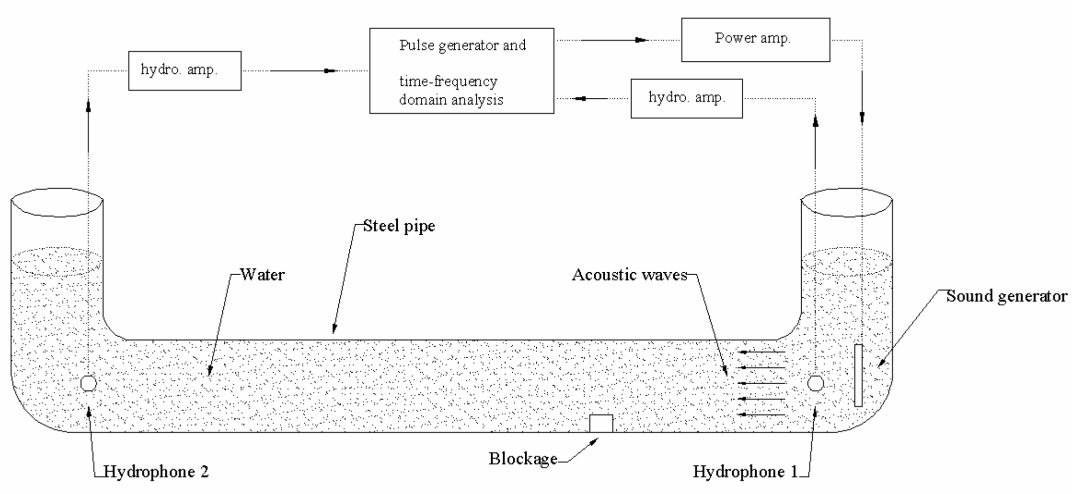

Figure 3. Test rig configuration.

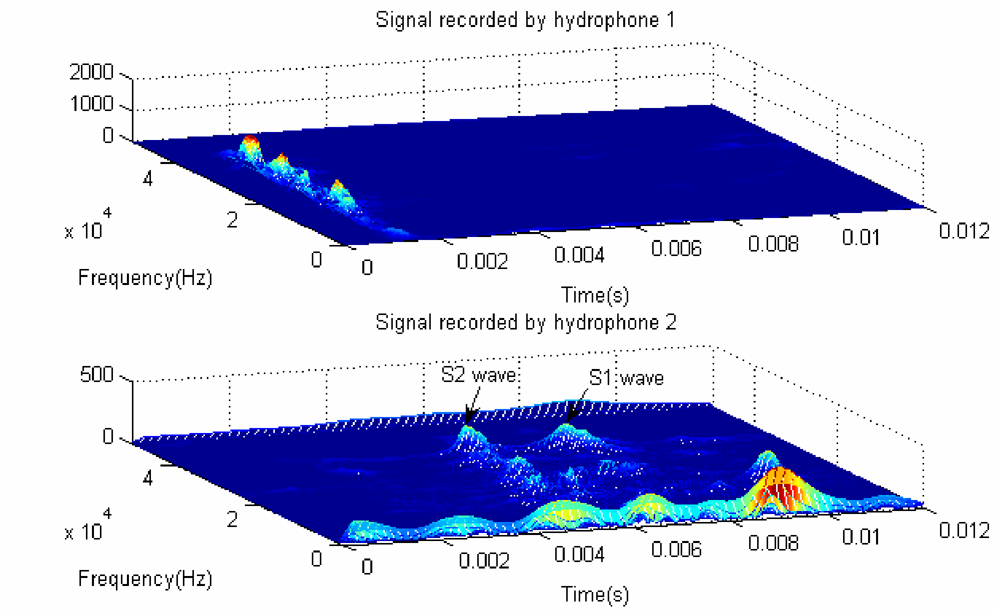

Figure 4. SPWVD of the signals from hydrophone 1 and hydrophone 2.

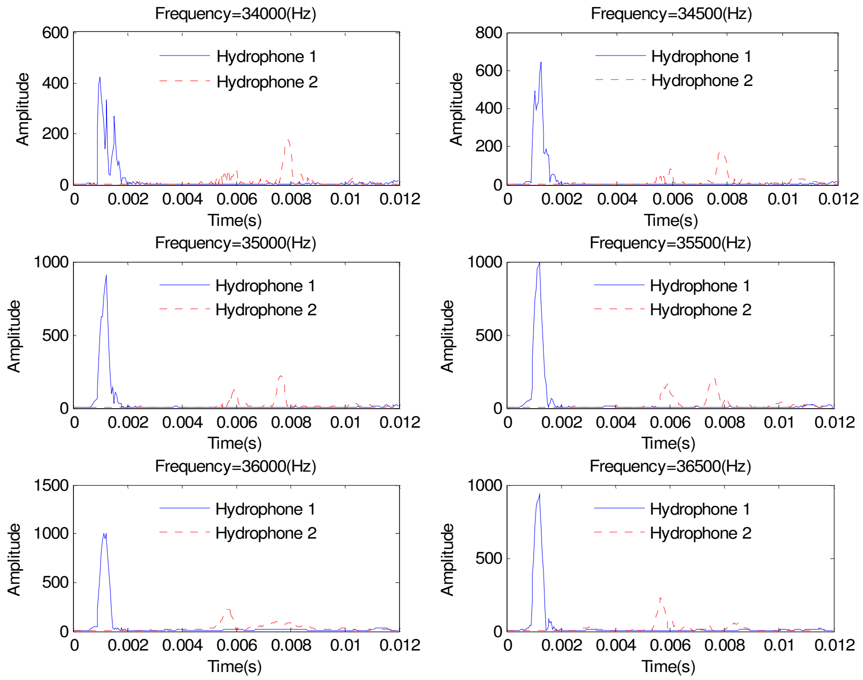

Figure 5. Dispersion charateristics of the acoustic waves.

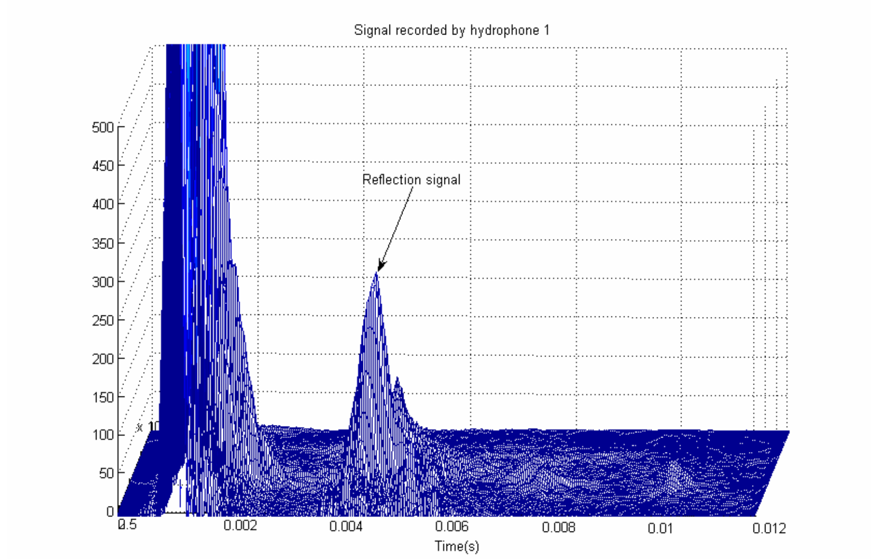

Figure 6. SPWVD of the signal from hydrophone 1 for blockage detection.

Table 2. Calculated and actual distances from the blockage to hydrophone 1.

Blockage position	1	2	3	4	5	6
Actual distance	1.3	2.3	3.3	4.3	5.3	6.3
Calculated distance	1.197	2.238	3.57	4.477	6.256	6.6

5. CONCLUSION

In this paper, axisymmetric waves in a fluid-filled, steel pipe have been studied. Dispersion curves for various waves in the circumferential breathing mode and beam type mode have been obtained. General characteristics of waves propagating in fluid-filled buried pipes have been exhibited.

A novel way to detect leakage/blockage has been used based on the theoretical investigation. An acoustic source was used to generate acoustic waves into the pipe system. The position of the leakage/blockage was obtained from the reflection signal of the injected acoustic wave. Smoothed pseudo Wigner-Ville distribution method has been used to reveal the position and frequency components of the pulse. Wavespeeds are obtained with relation to different frequencies. Experiments have shown calculated blockage distance matches well with actual blockage distance.

REFERENCES

[1]. Fuchs, H.V. and R. Riehle, *Ten years of experience with leak detection by acoustic signal analysis.* Applied Acoustics, 1991. **33**(1): p. 1-19.

[2]. Gao, Y., et al., *A Model of the Correlation Function of Leak Noise in Buried Plastic Pipes.* Journal of Sound and Vibration, 2004. **277**(1-2): p. 133-148.

[3]. Gao, Y., M.J. Brennan, and P.F. Joseph, *A Comparison of Time Delay Estimators for the Detection of Leak Noise Signals in Plastic Water Distribution Pipes.* Journal of Sound and Vibration, 2006. **292**(3-5): p. 552-570.

[4]. Junger, M.C. and D. Feit, *Sound, Structures, and Their Interaction*. 1986, Cambridge: The MIT Press.

[5]. Fuller, C.R. and F.J. Fahy, *Characteristics of wave propagation and energy distributions in cylindrical elastic shells filled with fluid.* Journal of Sound and Vibration, 1982. **81**(4): p. 501-518.

[6]. Fuller, C.R., *The effects of wall discontinuities on the propagation of flexural waves in cylindrical shells.* Journal of Sound and Vibration, 1981. **75**(2): p. 207-228.

[7]. Fuller, C.R., *The input mobility of an infinite circular cylindrical elastic shell filled with fluid.* Journal of Sound and Vibration, 1983. **87**(3): p. 409-427.

[8]. Fuller, C.R., *Monopole excitation of vibrations in an infinite cylindrical elastic shell filled with fluid.* Journal of Sound and Vibration, 1984. **96**(1): p. 101-110.

[9]. Brevart, B.J. and C.R. Fuller, *Energy exchange between the coupled media of impulsively excited, fluid-filled, elastic cylinders.* Journal of Sound and Vibration, 1996. **190**(5): p. 763-774.

[10]. Pavic, G., *Vibroacoustic energy flow through straight pipes.* Journal of Sound and Vibration, 1991. **154**(3): p. 411-429.

[11]. Muggleton, J.M., M.J. Brennan, and R.J. Pinnington, *Wavenumber prediction of waves in buried pipes for water leak detection.* Journal of Sound and Vibration, 2002. **249**(5): p. 939-954.

[12]. Fengshou, G. and A.D. Ball, *Use of the Smoothed Pseudo Wigner_Ville Distribution in the Interpretation of Monitored Vibration Data.* MAINTENANCE, 1995. **10**(2): p. 16-23.

[13]. Cohen, L., *Time-frequency distributions-a review.* Proceedings of the IEEE, 1989. **77**(7): p. 941-981.

[14]. Claasen, T.A.C.M. and W.F.G. Mecklenbrauker, *The Wigner distribution—a tool for time-frequency signal analysis, Part I: continuous-time signals.* Philips Journal of Research, 1980. **35**: p. 217-250.

[15]. Claasen, T.A.C.M. and W.F.G. Mecklenbrauker, *The Wigner distribution—a tool for time-frequency signal analysis, Part II: discrete-time signals.* Philips Journal of Research, 1980. **35**: p. 276-300.

[16]. Claasen, T.A.C.M. and W.F.G. Mecklenbrauker, *The Wigner distribution—a tool for time-frequency signal analysis, Part III: relations with other time-frequency signal transformations.* Philips Journal of Research, 1980. **35**: p. 372-389.

[17]. Leissa, A., *Vibration of Shells*, ed. Ⅱ. 1993: The American Institute of Physics.

[18]. Kumar, R. and R.W.B. Stephens, *Dispersion of flexural waves in circular cylindrical shells.* Proceedings of the Royal Society of London, 1972. **A329**: p. 283-297.

[19]. Fletcher, R., *Practical Methods of Optimization*. 1980: John Wiley & Sons.

[20]. Brévart, B.J. and C.R. Fuller, *Active control of coupled wave propagation in fluid-filled elastic cylindrical shells* The journal of the Acoustical Society of America, 1993. **94**(3): p. 1467-1475.