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Flow Estimation in a Steel Pipe Using Guided Waves

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Abstract. In this investigation, a flow rate estimation guided wave based scheme in pipes is proposed. The effect of the fluid over the propagation of longitudinal waves has been experimentally studied by using several laminar flows of water transported by a steel pipe. Results have shown a decrease of the guided wave pattern repeatability and the signal energy as the flow rate increase as a result of the energy leakage from the pipe to the fluid. A Matlab® script is used to excite the PZT actuator via *picoscope 2208* of *Picotech*®, the captured signal is acquired also by the picoscope and the data is processed in Matlab. The test bench utilized is composed by a 1” sch 40 A-106 pipe, a needle valve and a centrifugal pump provides the flow energy. A couple of PZTs are used in a picth-catch configuration to produce and capture the longitudinal waves along the cross section of the pipe.

Introduction

Ultrasound techniques are widely used in structural monitoring, low frequency ultrasound, specifically guided waves propagating along pipes has shown be a suitable technique to detect corrosion, erosion or meaningful changes in cross sections of the waveguide. One of the advantages over other NDT methods is the capability of inspecting over long distance [1]. However, unlike bulk waves, guided waves are dispersive, which means their velocity and attenuation, are dependent upon the frequency. Additionally, there is an infinite number of guided wave modes. Thus, a careful mode selection for a specific inspection purpose should be performed exploding different capabilities of the different modes[2]. Out-of-plane longitudinal and flexural particle velocities characteristic across the thickness of the structure has a great influence on the wave propagation characteristic. Furthermore, out-of-plane displacement at the inner surface of the pipe produces normal loading on the fluid and hence energy leakage into the fluid. On the other hand, axisymmetric torsional propagation is preferred because can handle fluid loading[3][4][5]. However, generation of torsional modes has some technical and economic challenges compared to the longitudinal waves. Therefore, some research works have focused on study the effect of the interface solid-liquid in longitudinal waves in topics such as: dispersion curve [6], the sensitivity in presence of discontinuities [7], and the attenuation of the wave pattern [8][9]. In [10] it is presented an analytical model to derive the dispersion curves for pipes in flow and high temperatures conditions. Simulations shown that L(0,2) mode at low frequency is non-sensitive to the temperature and the flow speed of the flowing liquid. Additionally, in [11] it is found the presence of an extra mode, and variations in attenuation and group velocity associated to the inner and outer fluids in pipes. In this investigation, a scheme to estimate the flow rate in pipes based on the information carried by guided wave is proposed. Axisymmetric longitudinal guided waves are generated by PZT in pitch catch configuration. Variations in the guided wave pattern associated to the flow are recognized by the attenuation of the current captured signal.

The leaky waves in a pipe. Ultrasonic wave propagation in leaky pipes concentrates on guided waves whose energy leaks into the flow inside or outside of a pipe. If the structure is a hollow pipe with no damping, no evident mechanism for wave energy lost should be considered. However, since the guided wave travels along the pipe, the radial displacement at the surface of the pipe couple energy into the surroundings fluid, this motion creates a bulk wave in the fluid allowing to the energy scape. In liquids, there is not energy transmission for the shear component in wave propagation. Thus, only normal displacement and compressional stress need to be continuous at the boundary between a liquid and the internal part of the pipe [12].

Leaky waves can be explained by the coincidence principle, which establishes that an incident wave in a coupling medium may be used to excite a guided wave if the component of its wavenumber in the direction along the plate matches the wavenumber of the plate [13]. Although, the principle is invocated for guided waves generation it can be extended to the case of the leaky waves. Since the projection of the wave along the interface must match for the guided wave and the bulk wave, the leakage angle, $\boldsymbol{\theta_{leak}}$ can be determined by Eq. 1 where λ is the wavelength. A schematic representation of the Eq. 1 is illustrated in Fig. 1. Therefore, for the studied case in this work, leaky waves may be only exist when the phase velocity of the longitudinal guided wave in the pipe is greater than the ultrasound longitudinal bulk velocity of water. As shown in Fig. 2, for the bandwidth considered in the experimentation (around 100 kHZ) the longitudinal velocity of the guided wave always produces leaky bulk waves; longitudinal bulk wave of the water is around 1480 m/s.

$$\boldsymbol{\theta_{leak}} = \sin^{-1}\left(\frac{v_{l,water}}{v_{ph,l}}\right) = \sin^{-1}\left(\frac{\lambda_{water}}{\lambda_{steel}}\right) \quad (1)$$

On the other hand, because of the frequency content, bandwidth, in the launched pulse and the dispersive behavior of the lamb wave, many different escape directions result along the waveguide. This phenomenon attenuates significantly the guided wave transmitted as illustrated in Fig. 3.

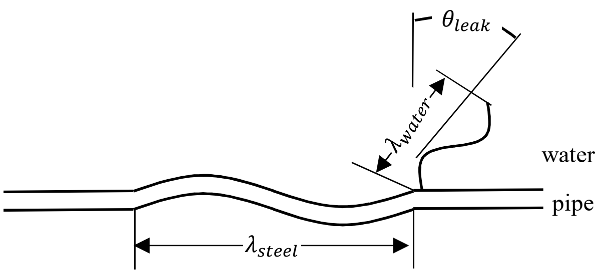

Figure 1. Schematic representation of the leaky bulk wave created by the coupling between the guided wave and the surrounding fluid.

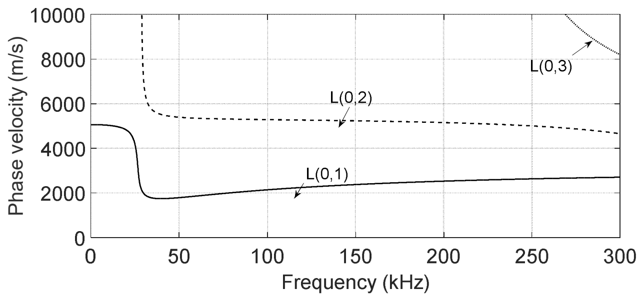

Figure 2. Dispersion curve of phase velocity for a 1” Sch 40 A-106 pipe

Experimental setup

The test bench utilized in this work is shown in Fig. 4. The installation represents a simplified scaled version of a real pump facility. During the test, only water in laminar flow is used. Data are captured only when the system reach the steady state. A centrifugal pump of 0.5 hp (Max fl 80 lpm) provides the flow energy, the different flow rates are setting by a 1” needle valve, the water is flowing in a 1” A-106 Sch 40 pipe, a 20 l. reservoir is used to ensure enough water availability in the suction. The experimental steady state flow rates are determined by catch-tank and stopwatch several times for each studied scenario. A 2208 Picoscope® is used for signal generation (Gaussian pulse signal of nine cycles) and acquisition of the guided wave. The actuator and the sensor are located at 0.5 m equidistant from the middle of the pipe and in the same vertical plane. A Matlab® script is employed to perform processing of this signal.

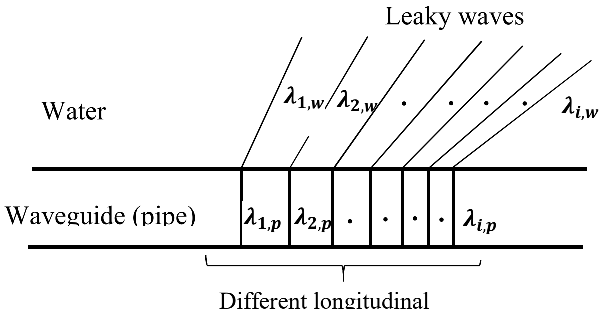

Figure 3. Pulse frequency bandwidth effect in the leaky waves

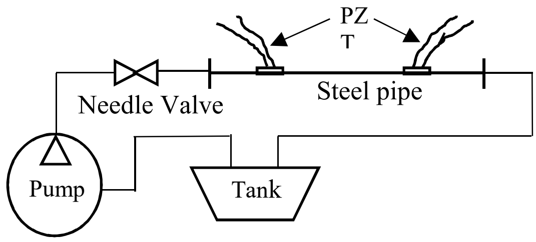

Figure 4. Scheme of the dedicated test bench for flow rate scenarios

Effect of the liquid flow inside of the pipe in the guided waves. As reported in many research works, the longitudinal guided waves pattern are affected in fluid-filled pipes [6],[7],[9],[11],[12] and even a greater influence in the wave is attributed to the liquid flowing inside the pipe [10]. Experimental tests conducted in the lab have shown a variable attenuation in the amplitude of the signal with a peak value around of 50% for a water flow of 0.33 m/s. An important observation to be mentioned is a great variability of the percentage of attenuation in the wave pattern even in steady state conditions. Because of the high variance in the captured signal in flow conditions, a mean for a set of 10 signals is applied.

Methodology

Although, steady state laminar flow condition is reached, the captured guided wave is noisy with parasite frequencies in the lower part of the spectrum excited by the water flowing and the mechanical system involved in the experimentation. Thus, an effective noise reduction scheme is implemented by a notch filter of 105 kHz of central frequency to unmask the relevant information transported by the guided wave. Several water laminar rate flows in the range between 0.18-0.33 m/s in steady state are used for the tests at room temperature, 22°C. Although, the steady state flow regime is reached, temporal variations in amplitude and phase are observed in the guided wave compared with the signal in the no-flow conditions. Thus, a mean signal of a set of 10 acquired signals are determined.

In the proposed approach, signal energy is not, strictly speaking, the same as the conventional notion of energy in physics and the other sciences. The two concepts are, however, closely related and in this investigation is used to produce the flow indicator. The energy loss by the guided wave in the interface $\boldsymbol{E_{leak}}$ caused by the leaky waves in the pipe is based on the assumption of $\boldsymbol{E_{leak}} \gg \boldsymbol{E_{hollow}}$, where $\boldsymbol{E_{hollow}}$ is the energy loss for the hollow pipe which can be considered negligible. Additionally, as the pulse energy launched $\boldsymbol{E_{l}}$ for all experiments is the same, the captured signal energy $\boldsymbol{E_{cap}}$ is an indirect measurement of $\boldsymbol{E_{leak}}$. Then, any intent to measure $\boldsymbol{E_{cap}}$ can be related to $\boldsymbol{E_{leak}}$. $\boldsymbol{E_{cap}}$ is determined, using Eq. 2, for the mean signal processed in a time window of 1 ms..

$$\boldsymbol{E_{cap}[x(n)] = \sum_{N1}^{N2} |x(n)|^2} \quad (2)$$

Analysis of results

A series of test are conducted to determine the relation between the proposed flow indicator and the experimental water flow rate. In Fig. 5, it can be observed a quadratic model which relations the captured signal energy of the guided wave and the experimental flow rate in steady state flowing inside the 1“ pipe. Althought, the relation is not linear, a decent estimation of the flow rate can be achieved using the obtained analitical model with a R-squared of 0.72.

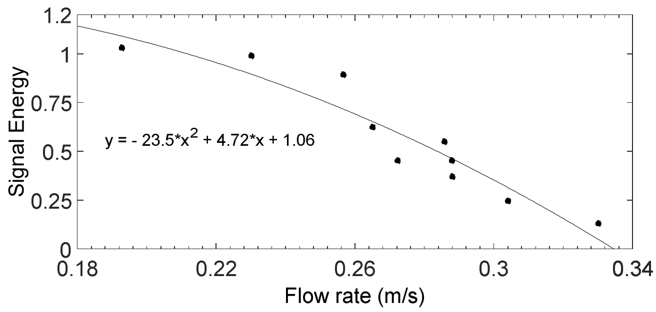

Figure 5. Mean energy of all the experiments for the flow rate cases studied

Conclusions

A methodology for flow rate estimation in metallic pipes using longitudinal guided waves is proposed. The scheme uses as a flow rate estimator the captured signal energy altered by the leaky waves in the solid-liquid interface. A preprocessing stage is implemented to reduce the low frequency noise produced by the mechanical system and to decrease the variance of the signal yielded by the multiple escape of energy attributed to a wide range of velocities present in the propagated guided wave pattern (Coincidence principle).
A quadratic relation between the signal energy loss in the guided wave and the water flow rate inside the pipe subject to a piezo-actuation is found experimentally. So, it can be proposed as a suitable value to estimate laminar flow rate in a metallic piezo-actuated pipe. An extent study considering other fluids and others flow regimens must be executed to investigate accuracy, reliability and limitation of the proposed indicator to extend the formulation proposed.

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References

[1] J. Li and J. L. Rose: Natural beam focusing of non-axisymmetric guided waves in large-diameter pipes, *Ultrasonics*, vol. 44, no. 1, (2006), pp. 35–45.

[2] A. J. Croxford, P. D. Wilcox, B. W. Drinkwater, and G. Konstantinidis: Strategies for guided-wave structural health monitoring, *Proc. R. Soc. A Math. Phys. Eng. Sci.*, vol. 463 (2007) pp. 2961–2981

[3] J. L. Rose: *Ultrasonic Waves in Solid Media*. 2014.

[4] H. Kwun, S. Y. Kim, M. S. Choi, and S. M. Walker: Torsional guided-wave attenuation in coal-tar-enamel-coated, buried piping, *NDT E Int.*, vol. 37, no. 8 (2004), pp. 663–665.

[5] J. L. Rose, Y. Cho, and M. J. Avioli: Next generation guided wave health monitoring for long range inspection of pipes, *J. Loss Prev. Process Ind.*, vol. 22, no. 6, (2009), pp. 1010–1015.

[6] H. Kwun, K. a. Bartels, and C. Dynes: Dispersion of longitudinal waves propagating in liquid-filled cylindrical shells” *J. Acoust. Soc. Am.*, vol. 105, (1999), pp. 2601.

[7] F. Li, Z. Liu, X. Sun, H. Li, and G. Meng: Propagation of guided waves in pressure vessel, *Wave Motion*, vol. 52, (2015), pp. 216–228.

[8] P. B. Nagy, F. Simonetti, and G. Instanes: Corrosion and erosion monitoring in plates and pipes using constant group velocity Lamb wave inspection” *Ultrasonics*, vol. 54, no. 7, (2014) pp. 1832–1841.

[9] W.-B. Na and H.-S. Yoon: Wave-attenuation estimation in fluid-filled steel pipes: The first longitudinal guided wave mode, *Russ. J. Nondestruct. Test.*, vol. 43, no. 8, (2007), pp.549–554.

[10] B. Zhang, H. Cui, J. Shen, and J. Trevelyan: "Influence of flow speed on guided waves in a liquid filled pipe," *IEEE Int. Ultrason. Symp. IUS*, vol. 1, no. 3, (2013), pp. 182–185.

[11] C. Aristégui, M. J. S. Lowe, and P. Cawley, "Guided waves in fluid-filled pipes surrounded by different fluids," *Ultrasonics*, vol. 39, no. 5, (2001),pp. 367–375.

[12] B. N. Pavlakovic: Leaky Guided Ultrasonic Waves in NDT, PhD *Dissertation*, (1998).

[13] M. Lowe, "Plate waves for the NDT of diffusion bonded titanium," PhD *Dissertation* (1992).