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Towards a calibration-free ultrasonic clamp-on flow meter: Pipe geometry measurements using matrix arrays

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Current ultrasonic clamp-on flow meters are manually calibrated. This process is based on manual placement of two single-element transducers along a pipe wall. Due to the usually unknown pipe properties and inhomogeneities in the pipe geometry, the axial distance of the transducers needs to be manually calibrated to align the location of the emitted beam on the receiver. In this work it is presented an automatic calibration procedure, based on matrix transducer arrays, to provide calibration information that would normally be entered into the instrument manually prior to ultrasonic clamp-on flow measurements. The calibration consists of two steps: First, along the axial direction of the pipe, Lamb waves are excited and recorded. Then, the measured time signals are combined with the Rayleigh-Lamb dispersion equation to extract pipe wall thickness and bulk wave sound speeds. Second, along the circumferential direction of the pipe, a specific Lamb wave mode is excited and recorded, from which the pipe diameter is estimated. The potential of both calibration procedures is shown, and the necessity of a matrix transducer array (i.e. small elements) is highlighted.

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1. INTRODUCTION

Standard ultrasonic clamp-on flow meters consist of two single-element transducers placed on the wall of a pipe. An angled wedge is usually placed between the transducer and the pipe wall. Each transducer can excite a longitudinal wave in the wedge. At the interface between the wedge and the pipe wall, wave mode conversion occurs, i.e. a shear wave is generated in the pipe wall. This shear wave refracts into the liquid as a longitudinal wave (Fig. 1). This wave bounces inside the pipe wall a number of times (typically 1-3) before being recorded by the other transducer. The transit time difference between the waves generated by both transducers (also known as upstream and downstream signals) is then directly proportional to the flow speed.[1] In contrast to their in-line counterparts, ultrasonic clamp-on flow meters can be installed without perforating the pipe wall or interrupting the flow.[2,3]

Ultrasonic clamp-on flow meters have to be manually calibrated to properly align the propagating beams. Such a calibration process starts by placing the transducers at a certain axial distance along the pipe wall. This initial separation distance is based on a-priori and often inaccurate values of the acoustic bulk wave speed and wall thickness of the pipe, as well as of the sound speed of the liquid. Then, while one of the transducers is fixed, the other is manually adjusted until the highest signal level is measured. This overall calibration process is very troublesome and time consuming.

Using a pair of matrix transducer arrays may potentially automate the calibration procedure of clamp-on flow sensors. First, to measure the sound speed and the thickness of the pipe wall, Lamb waves in the axial direction can be excited and measured. Second, to measure pipe diameter, a particular circumferential Lamb wave mode can be excited and measured. Finally, electronic beam steering can be used to fine-tune the travel path of the acoustic beam and therefore account for the specific parameters of the pipe and the fluid. This proposed auto-calibration procedure requires no knowledge from the operator on the pipe properties and geometry, and is potentially faster than the current manual procedure. Furthermore, it decreases the probability of user error.

In this research we present calibration procedures to estimate bulk wave speeds, wall thickness and diameter of a pipe, and the importance of using matrix transducer arrays to perform such calibration.

2. PIPE AUTO-CALIBRATION PROCEDURES USING CLAMP-ON MATRIX TRANSDUCERS

In this section, calibration procedures of pipe properties using a matrix transducer array are described.

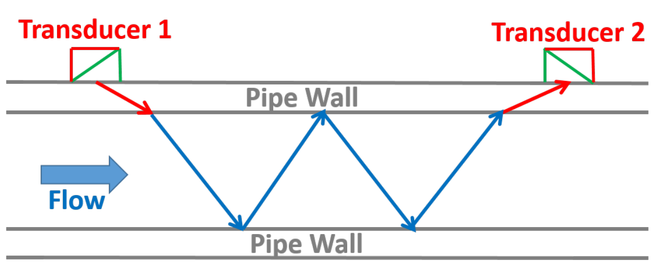

Figure 1: Path of an acoustic wave during an ultrasonic clamp-on flow measurement in a downstream direction. An acoustic beam propagates from the left transducer through the pipe wall, and refracts as a longitudinal wave into the flowing liquid. After a certain number of reflections within the pipe (here three), the beam gets recorded by the right transducer. The reverse path is traced in an upstream direction (not shown here).

A. PIPE WALL BULK WAVE SOUND SPEEDS & THICKNESS

Let us consider two matrix arrays mounted on top of a pipe wall. A cross-section of the geometry along the axial direction is given in Fig. 2a. For each matrix array, one row of elements is visible in the figure. Driving one or more transducer elements of one array excites Lamb waves in the pipe wall, which propagate and can be recorded by all the elements of the other array.

A 2D Fast Fourier Transform (FFT) can be applied on the recorded spatio-temporal data (Fig. 2b), and the resulting dispersion of the propagating Lamb wave modes can be visualized (Fig. 2c). The presented data is actually for a flat stainless steel plate ($c_l = 5800\,\mathrm{m/s}$, $c_s = 3100\,\mathrm{m/s}$) with a thickness of $d = 1\,\mathrm{mm}$, which forms a good approximation in the current case of a thin pipe. These dispersion curves present a trend that can be predicted by the Rayleigh-Lamb dispersion equations, which are extensively described in literature and are dependent on the longitudinal and shear wave speed of the pipe wall (c_l and c_s, respectively) and its thickness (d). Matching such equations to the data in Fig. 2c, can be used to extract the desired pipe properties. Two approaches can be used to achieve the matching: curve-fitting or inversion algorithms.[4–6] In this case, experimentally measured dispersion curves are fitted to simulated dispersion curves that are dependent on pipe geometry and mechanical properties.

B. PIPE DIAMETER

From the Lamb wave dispersion curves, the pipe diameter can be measured by excitation of a particular wave mode using proper beam steering in the circumferential direction. The required steering angle can be predicted via Snell's law. In the circumferential direction, a wave mode can propagate multiple times around the pipe. Measuring the arrival time of these consecutive round trips can be used to compute the pipe diameter.

Alternatively, a single array element can be excited provided that within the excitation bandwidth the potentially propagating wave modes have very different group velocities.

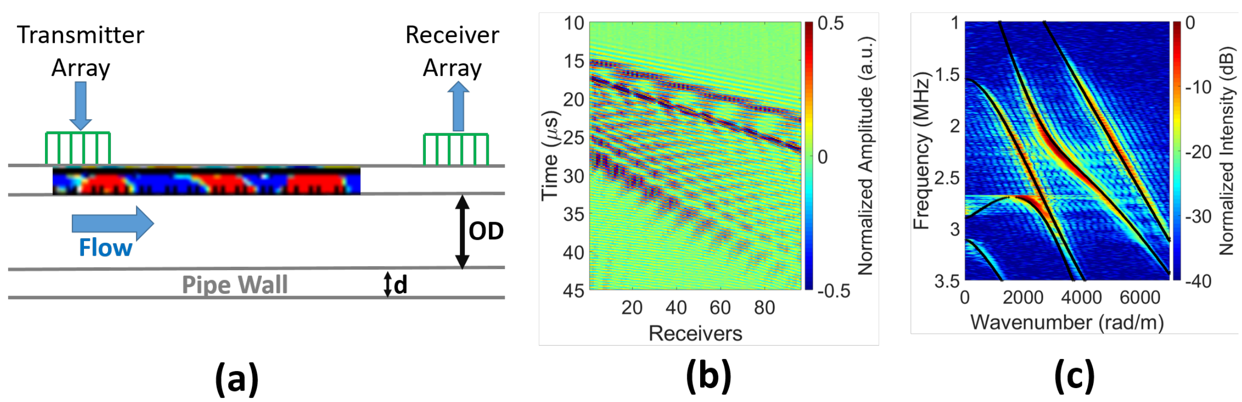

Figure 2: (a) Axial cross-section of a clamp-on flow measurement setting using a pair of matrix transducer arrays on a pipe wall with outer diameter OD and thickness d. (b) Measured time signals after excitation of Lamb waves on a flat stainless steel plate ($c_l = 5800\,\mathrm{m/s}$, $c_s = 3100\,\mathrm{m/s}$) with a thickness $d = 1\,\mathrm{mm}$. (c) Magnitude of a 2D Fast Fourier Transform performed on the space-time signals in (b). Notice the different trends of the dispersion curves. Each curve represents a Lamb wave mode. The black lines represent analytical dispersion curves predicted by the Rayleigh-Lamb equation for the stainless steel plate.

i. Measurement Procedure

Considering a normal cross-section of the pipe (Fig. 3), the length of the propagation path of a Lamb wave mode would be π times the average pipe diameter. Provided that the wave mode propagates with a sound speed c_m that is known from the previous calibration step, and its measured arrival time after propagating a full circumference is t_m, the outer diameter of the pipe can be estimated as:

$$OD = \frac{c_m t_m}{\pi} + d \tag{1}$$

Since the wave mode is dispersive, the measured signal has to be corrected. Dispersion compensation of Lamb waves can be done in the Fourier domain[7] by phase-shifting all frequency components of the measured signal, $f(t)$, to the same arrival time t_f:

$$f_{\text{corrected}}(t) = \mathfrak{F}^{-1}\left\{f(\omega)\exp\left[\omega t_f\left(\frac{c_f}{c(\omega)} - 1\right)\right]\right\} \tag{2}$$

where $f(\omega)$ represents the Fourier transform of the measured dispersive wave mode (signal), c_f represents the measured phase velocity of the dispersive wave mode at a given frequency f, and $c(\omega)$ represent the phase speed of the wave mode computed from the bulk sound speeds and thickness estimated in Section 3.A.

For the recorded frequency bandwidth, with Eq. (2) the phase velocity dispersion curve of the propagating wave mode is effectively flattened-out. Therefore, group speed and phase speed become the same, and more accurate values can be used in Eq. (1) to finally estimate pipe diameter.

ii. Large versus Small Transducer Elements

Single-element transducers have a much larger aperture compared to a transducer array element (Fig. 4a). The coupled resonance of the transducer and the pipe wall can cause ringing effects, which can become significant when a large transducer is used. These effects can overlap the time signal corresponding to propagating Lamb wave modes (Fig. 4b). Furthermore, a large transducer smears-out the dispersion effect of the propagating Lamb waves in the pipe wall (Fig. 4c), which hinders their identification for posterior dispersion correction. Pipe wall ringing and smearing-out of the dispersion were indeed observed in measured data using a large (single-element) transducer with a 10 mm diameter.

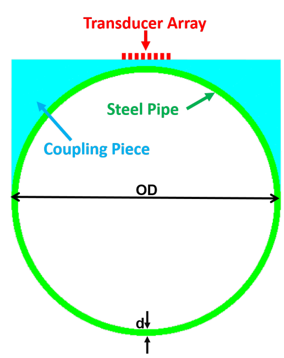

Figure 3: Tangential cross-section of a clamp-on flow measurement setting for a matrix transducer array on a pipe wall with outer diameter OD and thickness d. Proper beam steering is able to excite a particular Lamb wave mode that can propagate around the circumference of the pipe. The arrival time of such wave mode is directly related to the desired pipe diameter.

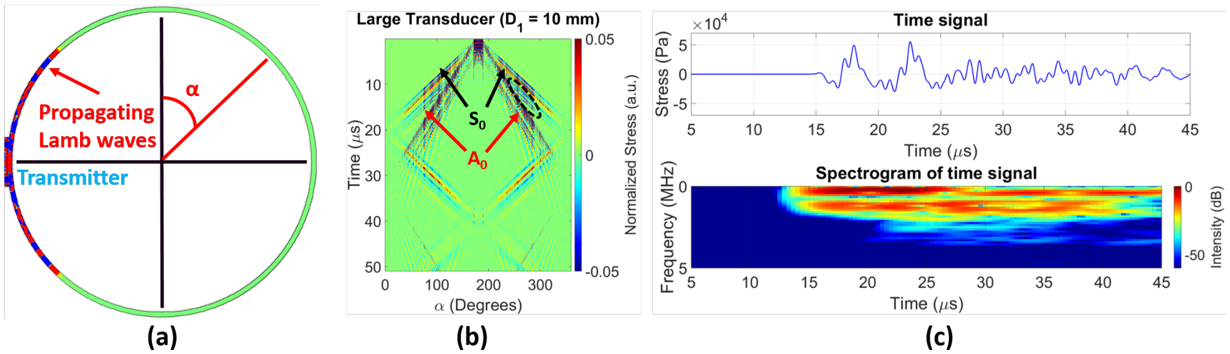

Figure 4: (a) Finite Element simulation for a large transducer (*$10\,\mathrm{mm}$ *diameter,* $1\,\mathrm{mm}$ *thickness) placed on a stainless steel pipe wall with a thickness of* $1\,\mathrm{mm}$ *and an outer diameter of* $63.5\,\mathrm{mm}$*, and excited with a 2-cycle sine pulse with a center frequency of* $1\,\mathrm{MHz}$*. Receivers were placed around the circumference of the pipe. (b) Angle-time signals recorded. Notice the two zero-order Lamb wave modes (*S_0 *and* A_0*), as well as the overlapping effect of pipe wall ringing (black oval). (c) Time signal received by a transducer with an aperture of* $10\,\mathrm{mm}$*, and its respective spectrogram, in which no wave mode or dispersion trend can be identified.

In contrast, the ringing effect in the pipe wall after excitation of a transducer array element is much shorter (Fig. 5a). Moreover, due to the point-like receiver aperture of the transducer array element, no smearing effect of the dispersive wave(s) is induced, which provides a signal with the proper characteristics to estimate pipe diameter after dispersion correction (Fig. 5b).

3. DISCUSSION

For estimating the bulk wave sound speeds and the thickness of the pipe wall, it is recommended to excite the transducer array elements (and therefore the pipe wall) using a time signal with the broadest frequency band possible. This might best reveal the shape of the dispersion curves, and a more accurate fitting/inversion process for finding the pipe sound speeds and the wall thickness can be achieved.

It was mentioned earlier that large transducer apertures, in combination with ringing of thin pipe walls, are a challenge for calibrating pipe diameter. This was demonstrated in simulations and measurements of two stainless steel pipes ($OD = 63.5\,\mathrm{mm}$ and 93mm, $d = 1.6\,\mathrm{mm}$ and 2.1mm, respectively) using disc transducers (10 mm diameter, 1 mm thickness) as transmitter and receiver. This motivates the use of a matrix array. From simulations of small transducer array elements, we were able to measure pipe diameters with a discrepancy of 2.2% from the real values. Nevertheless, the Finite Element geometry of a circular pipe still consisted of rectangular elements. This approximates the circular path of the waves by a staircase-like path instead, which might add an additional error in estimating pipe diameter since this staircase-like geometry translates into slightly different dispersion curves for the propagating wave modes than those computed for a proper circular geometry.

To actually estimate the accuracy of the method, a plate was considered, for which the travel path is not distorted due to the shape of the Finite Elements. A stainless steel plate with a thickness of 1 mm was considered. Exciting a small transducer array element (0.15 mm diameter, 1 mm thickness) with a 2-cycle sine wave with a center frequency of 1 MHz, the zero-order Lamb wave modes (S_0 and A_0) were generated in the plate and measured at a distance of 22.9 cm from the source. The S_0 mode was windowed-out in time and, after dispersion correction, the computed travel path was 23.1 cm, which represents a discrepancy of 0.8% with the real value.

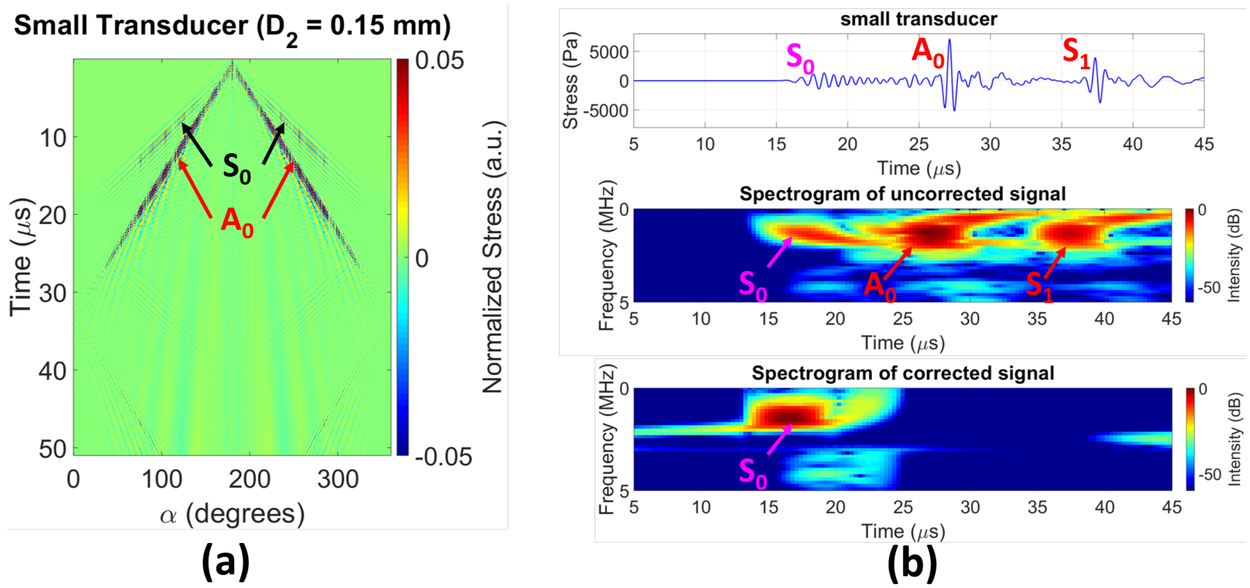

Figure 5:** **(a) Simulated time signals for locations around a stainless steel pipe wall with a thickness of** $1\,\mathrm{mm}$ **and an outer diameter of** $63.5\,\mathrm{mm}$**, after exciting it with a small (**$0.15\,\mathrm{mm}$ **diameter,** $1\,\mathrm{mm}$ **thickness) transducer array element. The transducer element was excited with a 2-cycle sine pulse with a center frequency of** $1\,\mathrm{MHz}$**. Notice the two zero-order Lamb wave modes (**S_0 **and** A_0**) and the reduced effect of pipe wall ringing. (b) Time signal recorded with an aperture of** $0.15\,\mathrm{mm}$ **and its respective spectrogram before and after dispersion correction of the fastest propagating Lamb wave mode (**S_0**).

Due to the high sensitivity of Eqs. (1) and (2) on the input sound speeds, to estimate the pipe diameter it is recommended to operate, whenever possible, in a frequency band with low dispersion of the wave mode of interest.

4. CONCLUSION

In this work we reported on two calibration procedures to estimate sound speeds, wall thickness and diameter of a pipe using matrix transducer arrays that may be used in a clamp-on flow meter. These quantities are necessary for automatic beam alignment by adjustment of the steering angle in transmission, and may render manual calibration procedures in clamp-on flow meters unnecessary. Furthermore, it was shown that small transducer elements, as compared to large single-element transducers, are more advantageous for the described methods.

REFERENCES

[1] D. W. Spitzer, “Flow Measurement: practical guides for measurement and control”, *ISA*, (1991).

[2] J. C. Wendoloski, “On the theory of acoustic flow measurement”, *J. Acoust. Soc. Am.* **110**, 724-737 (2001).

[3] R. C. Baker, “Flow measurement handbook: industrial designs, operating principles, performance, and applications”, *Cambridge University Press*, (2016).

[4] M. R. Karim, A. K. Mal, and Y. Bar-Cohen, “Inversion of leaky Lamb wave data by simplex algorithm”, *J. Acoust. Soc. Am.* **88**, 482-491 (1990).

[5] O. Behrend, A. Kulik, and G. Gremaud, “Characterization of thin films using numerical inversion of the generalized Lamb wave dispersion relation”, *Appl. Phys. Lett.* **62**, 2787-2789 (1993).

[6] W. P. Rogers, “Elastic property measurement using Rayleigh-Lamb waves”, *Res. Nondestruct. Eval.* **6**, 185-208 (1995).

[7] R. Sicard, J. Goyette, and D. Zellouf, “A numerical dispersion compensation technique for time recompression of Lamb wave signals”, *Ultrasonics* **40**, 727-732 (2002).