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DOI
10.1109/ULTSYM.2019.8925680

Publication date
2019

Document Version
Accepted author manuscript

Published in
2019 IEEE International Ultrasonics Symposium, IUS 2019

Citation (APA)
Massaad, J., Willigen, D. V., Van Neer, P., De Jong, N., Pertijs, M., & Verweij, M. (2019). Acoustic Design of a Transducer Array for Ultrasonic Clamp-on Flow Metering. In S. Cochran, & M. Lucas (Eds.), *2019 IEEE International Ultrasonics Symposium, IUS 2019* (Vol. 2019-October, pp. 1133-1136). Article 8925680 IEEE. https://doi.org/10.1109/ULTSYM.2019.8925680

Acoustic Design of a Transducer Array for Ultrasonic Clamp-on Flow Metering

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***Abstract*—Current ultrasonic clamp-on flow meters are based on single-element transducers that require manual calibration by aligning these to a fixed acoustic path. Moreover, the size and operational frequency of the transducers cannot be adapted to the parameters of the pipe and the liquid, which are in practice not precisely known a priory. A set of two transducer arrays could be used to solve these issues. With an array, properties of the pipe and the liquid can be estimated before measuring flow. Furthermore, electronic beam steering can be used for auto-alignment of the acoustic beam, reducing the need for manual calibration. Moreover, an array allows for the use of signal processing to suppress the effects of spurious Lamb waves propagating in the pipe wall. This research work describes the acoustic design process of a transducer array for ultrasonic clamp-on flow measurements for a wide range of conditions. First, performance requirements are defined. Then, the design models are presented, and a step by step process of the acoustic stack design of the transducer array is described. At each design step, material dimensions are optimized to achieve a thickness resonance mode at 1 MHz within a bandwidth of interest between 0.2 MHz and 2 MHz. Finally, the expected performance of the designed array is reported, based on simulation results.**

I. INTRODUCTION

Current ultrasonic clamp-on flow meters consist of two single-element transducers placed axially on a pipe, with a fixed-angled wedge acting as coupling piece (Fig. 1). The main advantage of clamp-on flow meters is the fact that these can be installed without interruption of the flow and/or the addition of extra pipeline sections [1], [2]. Moreover, since the pipe walls are not punctured when placing this type of flow meters, installation risks and safety conditions are improved relative to their in-line counterparts.

Nevertheless, these kind of meters have disadvantages. They have to be manually aligned depending on pipe and liquid properties, including pipe geometry. These parameters are not always known with acceptable certainty, and this makes the installation process cumbersome. Furthermore, Lamb waves could be excited in the pipe wall and interfere with the longitudinal wave that refracts from the liquid. This problem is tackled by either limiting the incidence angle of the acoustic beam on the pipe wall such that the problematic Lamb waves can be windowed-out in time domain from the longitudinal wave refracting from the liquid, and/or by placing an absorbing layer between both transducers. The first solution may limit the refraction angle of the acoustic wave in the liquid and therefore its sensitivity to the flow, while the second solution is difficult to implement in harsh environments and in poorly isolated areas.

A pair of transducer arrays has the potential to solve these issues. By using electronic beam steering, automatic alignment of the transducers can be achieved without the use of fixed-angle wedges and manual calibration of inter-transducer distance. Moreover, with a transducer array it is possible to measure pipe and liquid properties prior to flow measurements. Furthermore, clever manipulation of the PZT-elements unlocks the possibility of suppressing the spurious Lamb waves, either in transmission or in reception.

In this research work we present the acoustic design process of a transducer array for performing ultrasonic clamp-on flow measurements for a wide range of liquids.

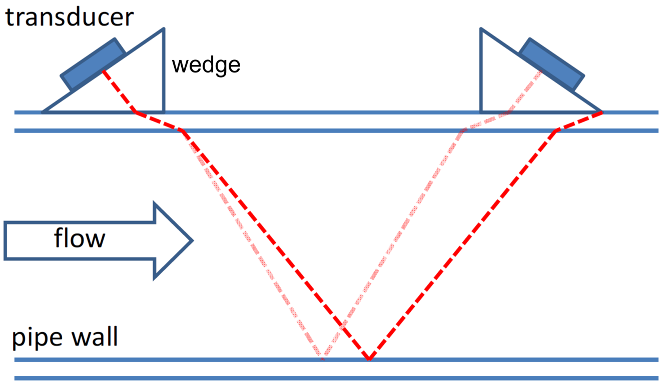

Fig. 1. Geometry of current clamp-on flow meters. Due to uncertainties in pipe and liquid properties, the transducers have to be manually aligned along the pipe to receive the acoustic beam in the right position. The bright red line shows the path of the acoustic beam for a wrong alignment of the transducers. The pink line shows the path for a correct alignment.

II. REQUIREMENTS

In this section, the requirements of an operational transducer array for ultrasonic clamp-on flow measurements are presented.

A. Flow Measurement Requirements

1) Accuracy: A liquid flow meter with decent performance should measure flow speeds $\geq$1 m/s with an accuracy of 1%.

2) Liquid Range: It is important for our flow meter to work in different conditions. Therefore, the flow meter should work for a wide range of liquids, i.e. with sound speeds ranging from 1000 - 2000 m/s and attenuation coefficients (α) of up to 1 dB/MHz.cm.

3) Suitability for Auto-calibration: Our flow meter should be able to measure pipe and liquid properties prior to flow measurements.

B. Transducer Array Requirements

1) Frequency Range: To measure flow for all desired liquids, and within pipes with inner diameters (ID) ranging from 25 to 100 mm, it is important to operate within a certain frequency range to achieve enough signal-to-noise ratio (SNR). Industrial practice shows that a frequency range between 0.2 - 2 MHz is optimal.

2) Pitch and Number of Elements: It is important to steer an acoustic beam without grating lobes through the pipe wall, since these would excite more Lamb waves. Also, it is important to properly sample all possible Lamb waves that could get excited such that they could get filtered-out in the Fourier domain. Therefore, an according array pitch is necessary.

Provided that we will consider pipe wall thicknesses up to 5 mm, the slowest Lamb wave mode that could propagate at the highest considered frequency (2 MHz) would have a phase velocity of 2880 m/s. In this case, an array pitch of half a wavelength, i.e. 0.72 mm, would be required.

On the other hand, from simulations we found that to achieve the desired flow measurement accuracy, it is necessary for the Lamb waves to have amplitudes that are 55 dB below the longitudinal wave that refracts from the liquid. We found that 37 array elements are enough to achieve this.

3) SNR: From industry experience, a minimum single-trace SNR of 20 dB is required.

III. MODELLING

A. Signal Level

From the path of an acoustic wave in a clamp-on flow metering situation, such as in Fig. 1, the signal level of the longitudinal wave used for flow measurements is predicted by the sonar equation

$$V_{open} = V_{in} T_t T_r T (RW)^{2b-1} W \tag{1}$$

where, V_{open} is the voltage measured at the receiver transducer, V_{in} is the input voltage on the transmitter transducer, which we take to be 5 V, T_t and T_r are the transmit and receive transfer functions of the transducer array, respectively, T is the joint multiplication of all transmission coefficients at all interfaces through which the acoustic wave propagates, R is the reflection coefficient of the liquid-pipe interface, b is the number of bounces (v-shapes) of the acoustic wave within the pipe before being recorded at the receiver array, and W is the amplitude decay due to propagation and attenuation per bounce. In fact, $W = AGD$, where A is the attenuation factor of the liquid, G is the focusing gain factor (set equal to 1), and D accounts for the diffraction of the propagating wave through the liquid. All these factors are per bounce, and the last factor is computed as given in [3].

On the other hand, noise was assumed to be thermal, and produced by the PZT element. Therefore, the Johnson-Nyquist equation [6] was used to estimate noise as

$$v_n = \sqrt{4 k_b T R \Delta f} \tag{2}$$

In Eq. 2, v_n represents the root-mean-square (RMS) noise produced by the PZT element, k_b represents Boltzmann's constant, T is the absolute temperature, R is the real component of the electrical impedance of the PZT element, and Δf represents the frequency bandwidth over which the noise is estimated.

Equations 1 and 2 are a direct indication of whether the transducer array fulfils the previously described requirements, since they are directly related to the expected SNR, in decibels, as

$$SNR = 20 \log \frac{V_{open}}{v_n} \tag{3}$$

B. FEM

The software package PZFlex (Onscale, Redwood City, CA, USA) was used to model material properties as well as wave propagation. In such model, the continuum mechanics equations are solved in solid materials, as well as in liquids. Full piezo-electricity equations are implemented for the piezo-materials. A visco-elastic model is used to implement losses, which are regarded to be approximately linear over a wide frequency range. Linear wave propagation is assumed everywhere. Gluing and/or soldering layers are not included in the model.

IV. ACOUSTIC STACK DESIGN

A. Center Frequency

To cover the required bandwidth (0.2 - 2 MHz), there should be a peak thickness resonance mode in the middle, around 1 MHz. Moreover, all modes with lateral resonances are desired to be away from the main thickness resonance by, at least, a factor of three [4].

B. Efficiency, Sensitivity, Bandwidth and Element Size

1) PZT Material: To maximize the signal level, a piezo-material with a high dielectric constant (ϵ_{33}^S) and a high coupling factor (k_{33}) is desired. As a result, HK1HD (TRS Technologies, State College, PA, USA) was chosen as the

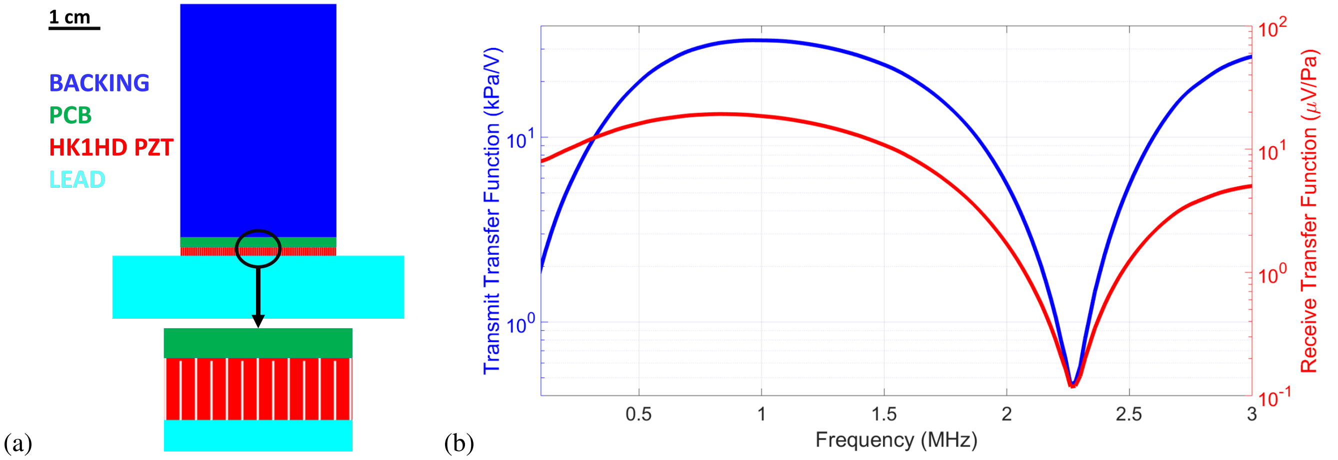

Fig. 2. (a) Final acoustic stack of a transducer array for clamp-on flow measurements. The close-up of the transducer array shows how the HK1HD PZT elements are arranged on top of the flat lead coupling piece after sub-dicing. (b) Simulated transfer functions. There is an absence of lateral resonance modes within the bandwidth of interest (0.2 - 2 MHz) and a clear thickness resonance peaking around 1 MHz.

optimal, since it maximizes SNR according to Eq. 3. This material has a dielectric constant of 2760, and a coupling factor of 0.75.

2) PZT-Pipe Coupling: Finite Element simulations of an HK1HD PZT element on top of a steel half space were performed to optimize its dimensions such that the desired resonance profile (1 MHz center frequency and no lateral modes within the 0.2 -2 MHz bandwidth) was achieved. A PZT with a thickness of $0.17\lambda_{PZT}$ (λ_{PZT} = 4.1 mm) and a width of 0.42 mm fulfils these requirements.

3) PCB and Backing Layers: On the opposite side of the PZT, a PCB layer (modelled as mainly made of FR4 material) with a standard thickness of 1.6 mm was placed on the PZT element. This layer has the purpose of wiring-out the electrical signals generated by the PZT.

Moreover, to minimize the presence of guided and transmitted waves in the PCB, an absorbing backing material was placed on top of the PCB layer. The acoustic impedance of such backing material was chosen to be the same as that of the PCB ($Z = 6.7\,\mathrm{MRayl}$), which is a relatively soft backing material. From practical experience, its attenuation coefficient was set to 5 dB/MHz.cm. Finally, its thickness was set to 4 cm to ensure a 40 dB attenuation of waves after a two-way travel path through it.

The addition of both of these layers shifted the resonance frequency of the system. Therefore, PZT thickness had to be optimized once more to ensure a thickness resonance mode at 1 MHz. The piezo-material thickness was now set at $0.20\lambda_{PZT}$.

4) Coupling Piece and Wave Interference: Current clamp-on flow meters exploit the excitation of shear waves in the pipe wall to achieve higher refraction angles in the liquids and increase the sensitivity to flow. The way to excite such waves is by impinging a longitudinal wave on the pipe wall beyond the critical angle. Without a coupling layer between the transducer and the pipe wall, such an angle is impractically high and therefore difficult to achieve due to the similar sound speed values of both materials. Therefore, plastic wedges that have a much lower sound speed are commonly used. With these, shear waves in the pipe wall are excited at much lower angles.

However, a plastic coupling layer (wedge) has a low acoustic impedance relative to the impedance of the piezo-material and the steel pipe wall. To optimize the energy transfer into the liquid, an alternative coupling material was selected. It had roughly the same sound speed as plastic ($c_{plastic}$=2290 m/s) but a much higher density ($\rho_{plastic}$=1240 kg/m^3). Lead (c_p=2200 m/s, ρ=11200 kg/m^3) was chosen as the appropriate material.

The top and bottom surfaces of this coupling piece are parallel to the pipe axis (i.e. not an angled wedge), and its thickness was set to 1.1 cm at the center of the array (and therefore thicker towards the edges). This thickness is enough to ensure proper wave mode conversion of the longest possible wavelength from the lead into the pipe wall. Furthermore, the addition of this new layer obliged to increase the PZT thickness from 0.20 to $0.35\lambda_{PZT}$ to ensure a thickness resonance mode at 1 MHz.

As a follow-up, all 37 PZT elements were now considered in the simulations. The PCB and backing materials had a width equal to the array aperture, and the width of the lead coupling piece was enough so as to be able to steer the acoustic beam up to 45°.

The performance of 37 HK1HD PZT elements showed the interference effect of a propagating Rayleigh-like wave on the surface of the coupling layer, which was avoided by increasing the width of the elements from 0.42 to 0.62 mm.

5) Sub-dicing: The increased widths of the elements inevitably shifted the lateral resonance mode towards a lower frequency of around 2.2 MHz, which was very close to the bandwidth of interest (0.2 - 2 MHz). Therefore, it was necessary to shift it back to a frequency of at least 3 MHz.

This was achieved by sub-dicing the PZT elements.

Effects of sub-dicing the PZT elements on the performance improvement of a transducer array are known [5]. Effectively, lateral resonance modes shift towards higher frequencies. The width of the sub-dicing kerf was kept to 50 µm (as well as the kerf of the array). A sub-dicing depth of 95% of the thickness of the PZT element shifted the lateral resonance mode to 3 MHz. Fig. 2 shows the layering of the final acoustic stack and its performance. At resonance, it can be observed that transmit and receive transfer functions report approximately 33 kPa/V and 18 µV/Pa, respectively. Furthermore, a -6 dB bandwidth of approximately 60% (0.28 - 1.92 MHz) is expected.

6) Noise Level: From FEM simulations of the acoustic stack shown in Fig. 2a, the real part of the electrical impedance was extracted, and within the bandwidth of interest (0.2 - 2 MHz) it was estimated, according Eq. 2, that the expected average thermal noise produced by a PZT element, at room temperature, should be in the order of 1.1 μV_{RMS}. Provided the required 20 dB of SNR, this translates into a minimum required value of 11 µV for V_{open} in Eq. 1 to perform a useful flow measurement.

7) Suitability for Many Liquids: With the performance values of Fig. 2b, the expected signal levels were computed with Eq. 1 for the case in which longitudinal waves are excited in the pipe wall and no wave mode conversion takes place. Also, six bounces (v-shapes) of the acoustic beam within the pipe were assumed.

Figure 3 shows that, at resonance, the SNR from the designed transducer array for ultrasonic clamp-on flow measurements is expected to be high enough ($\geq$20 dB) to be able to operate for all the considered liquids. A relatively small region of Fig. 3 shows SNR levels lower than 20 dB. This region is related to highly attenuating liquids, and other techniques to improve SNR might be used in these situations, such as more averaging, a higher input voltage, and/or less bounces of the longitudinal wave within the pipe.

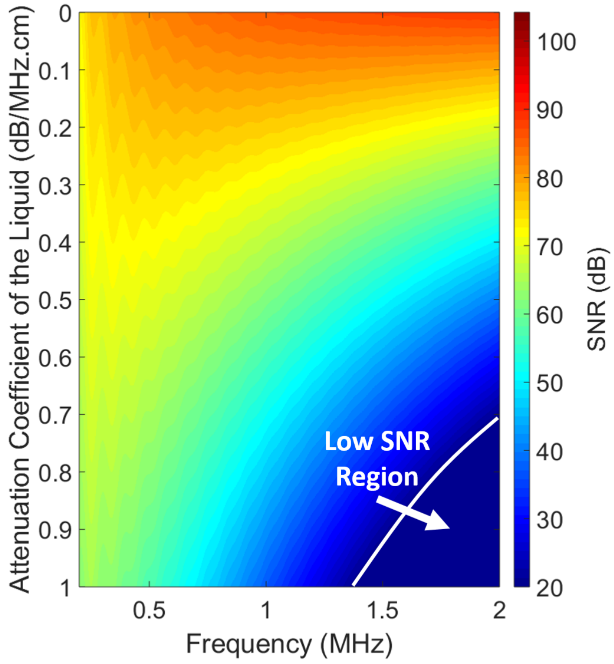

Fig. 3. Expected SNR from the designed transducer array for ultrasonic clamp-on flow measurements. assuming a longitudinal wave in the pipe wall and six bounces within the pipe. At 1 MHz, the signal level is above the noise (1.1 μV_{RMS}) by a factor $\geq$20 dB for the whole range of considered liquids. The framed red area corresponds to SNR levels below 20 dB.

V. CONCLUSIONS

A transducer array for ultrasonic clamp-on flow measurements has been designed. Its aperture and array nature have the potential to deal with Lamb waves in the pipe wall without compromising beam sensitivity to the flow, and also to perform auto-calibration of pipe and liquid properties. Furthermore, the designed array is expected to operate with high enough SNR within a wide range of liquids.

ACKNOWLEDGMENT

This work is part of the research programme FLOW+, which is financed by the Dutch Technology Foundation STW (project 15031) and industrial partners Bronkhorst and KROHNE.

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