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Flow measurement based on two-dimensional flexural ultrasonic phased arrays

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Transit-time flow measurement is a technology which has been increasingly utilized in recent years, in industries such as petrochemical, water, and gas. In general, this method of flow measurement employs two ultrasonic transducers, one situated upstream, and the other downstream. The fluid flow is then characterized via transmission and detection of ultrasound using the transducers. However, there are notable limitations of the transit-time method, including drift of the propagation direction of the ultrasonic beam. This is termed the sound drift effect. This paper reports on the latest developments of ultrasonic phased arrays, which are a potentially robust and economic solution to compensating for this sound drift effect. The design and fabrication of phased arrays is discussed, and experimental flow measurement results are reported, utilizing flow rates from 0 to 2500 m3/h. The results show that the compensation of the sound drift effect has been achieved, demonstrating the feasibility of phased arrays for accurate ultrasonic flow measurement.

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1. INTRODUCTION

Flow measurement based on transit-time ultrasonic technology has become increasingly popular in the natural gas, petrochemical, water, and food industries. In this method, two ultrasonic transducers, facing each other, are placed upstream and downstream separately, where the average flow velocity can be deduced through the measurement of the time difference between upstream and downstream propagation of ultrasonic beams. However, the signal-to-noise ratio (SNR) of the ultrasonic signals frequently suffers from the sound drift effect, thereby reducing the detection probability of the time of arrival (ToA) and the measurement range[1]. Installation-induced errors of the transducers can further reduce the accuracy of flow measurement. In this paper, we present a demonstration of the benefits of an ultrasonic flow measurement method based on phased array technology. An advantage of using a phased array is that the change in the propagation direction of ultrasonic beams caused by high flow rates can be electronically and dynamically compensated using beam steering, enabling an optimum SNR, a wider range of measurement, and measurement using multiple ultrasonic paths.

Flexural ultrasonic transducers operate by exploiting plate bending modes, enabling the generation and reception of ultrasound in fluids of low acoustic impedance such as air and water, with high transduction efficiency, robustness and relatively low cost. By combining flexural ultrasonic transducers with phased array technology, these advantages can be realized for flow measurement. This study demonstrates the suitability of two-dimensional flexural ultrasonic phased array technology for flow measurement.

2. METHODOLOGY

The phased-array flow demonstrator measurement system consists of a 4×4 two-dimensional ultrasonic phased array and a single ultrasonic transducer. It is proposed that in a final version of the phased array system, that only phased array transducers would be used, increasing the flexibility of the final system. The cross-section of the flow measurement configuration is illustrated in Figure 1, where transducer 1 is the single ultrasonic transducer, and array elements A, B, C and D represent a four-element linear array respectively. The single transducer faces the center of the array at an angle θ with respect to the normal direction of the array.

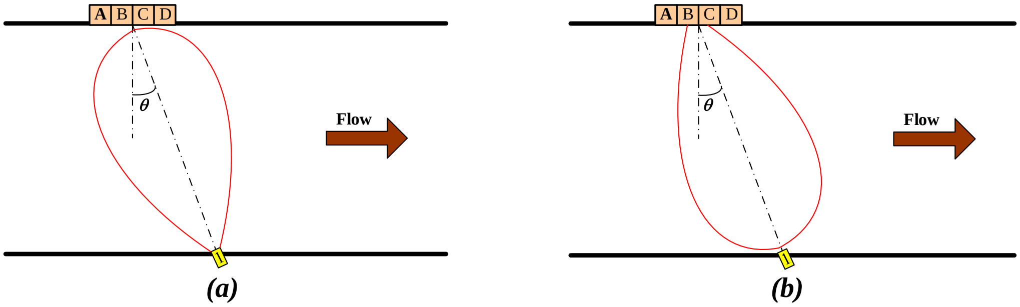


Figure 1: Cross-section of flow measurement configuration based on ultrasonic phased array technology, for ultrasonic beams travelling (a) upstream, and (b) downstream.

The beam-steering technique is applied to both the transmitting and receiving processes. When the ultrasonic beam travels upstream, the single ultrasonic transducer operates as a transmitter, and the elements of the two-dimensional array receive ultrasound simultaneously. A time delay is applied to the received ultrasonic signals, and the time-shifted signals are summed to generate a maximum amplitude signal. When the ultrasonic beam travels downstream, the element lines in the array are excited consecutively with a fixed delay, to produce constructive interference of the ultrasound waves. From this, a superimposed ultrasonic signal is received by the single ultrasonic transducer. The time delays used in the transmitting and receiving processes determine the incident angles of the ultrasonic beam with respect to the normal line of the array. In real applications, the flow velocity can vary over a relatively short time, over a wide range from laminar flow at low speeds through to turbulent flow at high speeds. To compensate for the sound beam drift effect, the optimum angles and the time delays used in the beam-forming process must be adjusted dynamically in accordance with the changing flow velocities, so that maximum SNR and greatest range of measurement can be achieved. According to the classic transit-time measurement method, the time of flight of the ultrasound travelling upstream and downstream satisfies Equation (1).

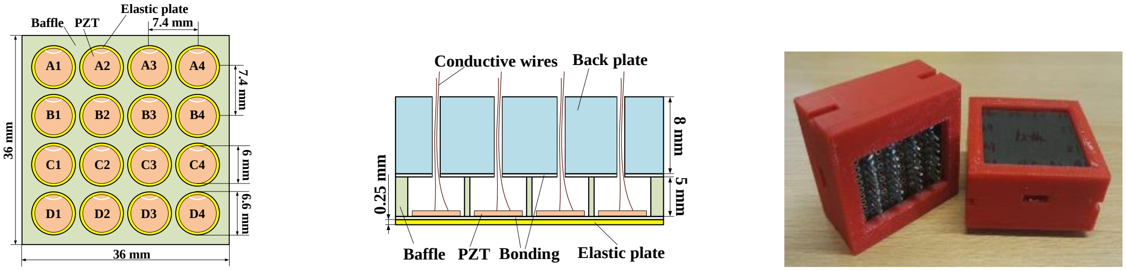
$$\begin{cases} \bar{t}_{down} = \dfrac{D}{\sin(\theta)\times[c+\bar{v}_P\cos(\theta)]} \\ \bar{t}_{up} = \dfrac{D}{\sin(\theta)\times[c-\bar{v}_P\cos(\theta)]} \end{cases} \tag{1}$$

In Equation (1), $\bar{t}_{up}$ is the average time of flight measured upstream, $\bar{t}_{down}$ is the average time of flight measured downstream, c is the velocity of ultrasound, $\bar{v}_P$ is the average flow velocity over the projection line of the ultrasonic path on the cross-section of the pipe, D is the inner diameter of the pipe, and θ is the angle between ultrasonic path and normal line of the array. Solving Equation (1), the average flow velocity over the projection line of the ultrasonic path on the cross-section of the pipe is obtained, shown by Equation (2). The average flow velocity over the cross-section of the pipe can then be calculated by Equation (3). In Equation (3), $\bar{v}_A$ is the average flow velocity over cross-section area of pipe, and k_c is the meter factor determined by the Reynolds number of the flow[2].

$$\bar{v}_P = \frac{D}{\sin(2\theta)} \times \frac{\bar{t}_{up} - \bar{t}_{down}}{\bar{t}_{up} \times \bar{t}_{down}} \tag{2}$$

$$\bar{v}_A = \bar{v}_P \times k_c \tag{3}$$

There has been previous research in the design, fabrication and characterization of phased arrays[3], and the structure of the two-dimensional flexural ultrasonic phased arrays is shown in Figure 2[3]. To help ensure a high level of consistency in the performance of array elements, a 36×36×0.25 mm^3 elastic titanium sheet was used to create the vibrating diaphragm of each of the 16 array elements. A steel baffle with 16 holes is bonded to the titanium plate, and holes with a diameter of 6.6 mm and a pitch of 7.4 mm separate the titanium sheet into 16 individual array elements. 16 piezoelectric ceramic discs, each with a diameter of 6 mm and a thickness of 0.25 mm, are bonded to the flexural elements, and conductive wires are soldered to the leads of the array (not shown in Figure 1) via the holes in a 36×36×8 mm^3 backplate. The backplate is necessary to reduce the influence of standing wave vibration on the neighboring elements, and is bonded to the baffle with epoxy adhesive. The backplate also enhances the mechanical and the electrical robustness of the array. The fabricated arrays with a 3D-printed case is shown in Figure 2(c).



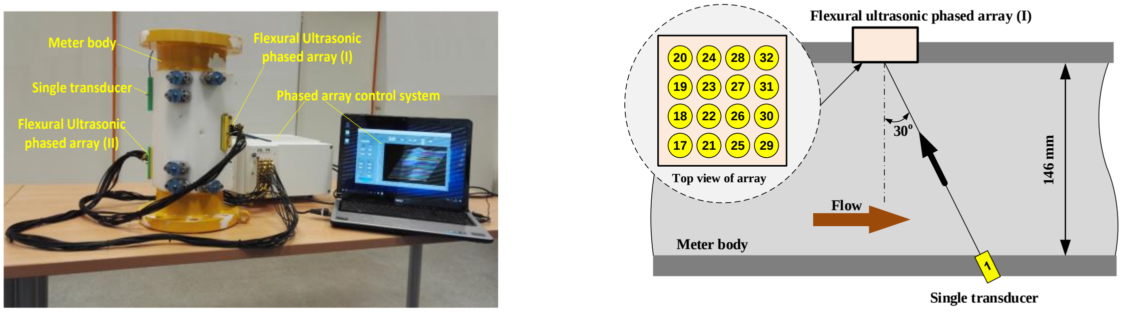
(a) *(b)* *(c)*

Figure 2: Schematic of a 4×4 flexural ultrasonic phased array, showing (a) the top, (b) the cross-section, and (c) two fabricated arrays.

The flexural elements of the array can each be considered as an individual edge-clamped elastic diaphragm vibrating in its fundamental resonant mode, generating and receiving ultrasound efficiently in low acoustic impedance media, and without the requirement for impedance matching layers, unlike some other types of air-coupled ultrasonic transducer. Through careful consideration of the baffle, the ceramic discs and the backplate, the axisymmetric (0,0) mode of each flexural element can be efficiently generated. The center frequencies, the bandwidth, the radiation pattern and the mechanical crosstalk of the individual array elements, and the array as a whole, have been characterized by an impedance analyzer, a calibrated microphone and a laser Doppler vibrometer, indicating that the center frequencies of array elements are all approximately 49 ± 1.5 kHz, and the maximum steering angle of the array is around 60˚.

3. EXPERIMENTS

A meter body produced from nylon was used to accommodate the flexural ultrasonic phased arrays and a commercial single ultrasonic transducer (PROWAVE 500MB120), as shown in Figure 3(a). The meter body has an inner diameter of 146 mm, with a flange at each end. Three 60×60 mm ports are machined into the meter body, and adapters are designed to ensure the single transducer faces array (I) at a 30˚ angle, as shown in Figure 3(b). A second array, referred to as array (II) as shown in Figure 3(a), is also included in the meter body for measurement through reflected ultrasonic paths, but not presented in this study. A 32-channel phased array controller (FIToolbox, Diagnostic Sonar, Livingston, United Kingdom) was used to control the arrays, in addition to the single transducer, and for data acquisition. Channel 1 connects with the single transducer, channels 2 to 16 connect with array (II), and channels 17 to 32 connect with array (I). Each channel is able to function either transmitting mode and receiving mode.

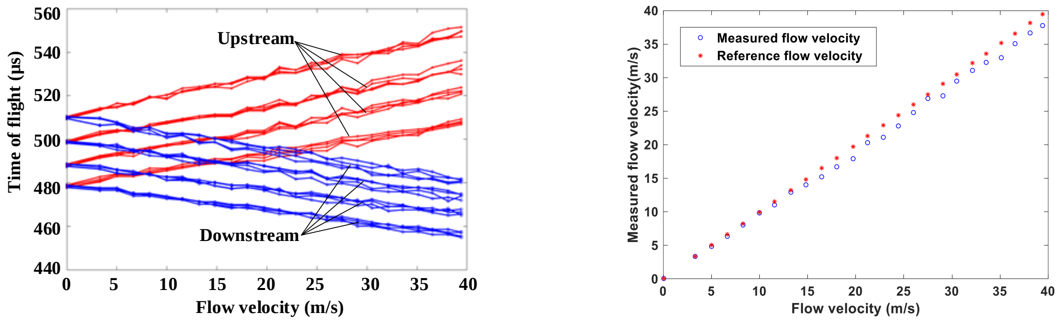


(a) *(b)*

Figure 3: (a) Experimental set-up for flow measurement, and (b) the cross-section view of meter body.

Flow experiments were performed with a commercial flow rig setup at Honeywell Process Solutions, Mainz, Germany. The rig incorporates a compressor (HVM 80-125 GR, Venti Oelde, Oelde, Germany) as the primary flow source, and a calibrated mechanical flow meter (TRZ G1600 DN200, Elster Instromet, Mainz, Germany) as the reference meter. The experiments were performed at constant room temperature, and in an open flow loop utilizing air as the flowing medium. The full matrix capture (FMC) technique was employed for data acquisition, where each channel sequentially operated in a transmitting mode, where all remaining channels functioned as receivers to enable the data acquisition of all possible ultrasonic paths. Ultrasonic signals were captured for a range of flow rates, from 0 to 2500 m^3/h in increments of 100 m^3/h. To determine the optimum time delay for each channel, the times of arrival (ToA) acquired through the FMC method are calculated using cross-correlation. The ToA variation for ultrasonic beams travelling upstream and downstream are exhibited in Figure 4(a), and indicate that the ToA increases with flow velocity for ultrasound beams travelling upstream, and decrease for those travelling downstream. The time delays of the ToA between neighboring array columns increase with flow velocity for the upstream condition, but decreases for the downstream case. The differences in the ToA are a consequence of the optimum beam steering angle.

The average flow velocity, calculated using Equations (2) and (3), from the ultrasonic phased-array flow meter is compared with the reference flow velocity, and the results are shown in Figure 4(b). In general, flow velocity measured using the phased array closely correlates with the calibrated reference for low levels of flow velocity, but greater discrepancies are shown for flow velocities exceeding 15 m/s. There are a range of factors which can account for these differences. For instance, the non-invasive nature of the ultrasonic technology introduces fewer disturbances to the velocity profile of the flow compared with the mechanical meter, and therefore the average flow velocities measured at the two flow meters are different. Also, the distance between the flow meters and the bends of the flow loop is less than 15 times of the inner diameter of the pipe, which produces different velocity profiles, and hence different average flow velocities. A measurement of the average flow velocity with improved accuracy requires a more rigorous calibration process, a sophisticated flow loop, and accurate measurement of the pressure and temperature, and a proper assessment of the system components and the density of the gas travelling through the flow meters. However, if the reference velocity obtained by the mechanical flow meter is regarded as accurate, then correction factors can be applied to the measurement results of the ultrasonic-phased-array flow meter according to Figure 4(b).



(a) ***(b)***

Figure 4: (a) ToA variation as a function of flow velocity, and (b) comparison of the measured flow velocity with the reference flow velocity.

4. CONCLUSIONS

A flow measurement process based on two-dimensional ultrasonic phased arrays is demonstrated, where compensation of the influence of the sound drift effect on the ultrasonic beams is achieved. The design, fabrication and characterization procedures of the ultrasonic phased arrays are outlined, and flow tests are conducted at a range of flow rates from 0 to 2500 m^3/h. A close correlation between the measured velocities and the reference velocities is demonstrated through the experiments, showing the feasibility of the ultrasonic phased arrays for accurate flow measurement. The investigation of flow characterized by multiple ultrasonic beam paths with arrays of this type will be undertaken in future, to achieve further improvements to flow measurement accuracy.

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