A SINGLE-CHIP FLOW SENSOR BASED ON BIMORPH PMUTS WITH DIFFERENTIAL READOUT CAPABILITIES

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ABSTRACT

This work reports the measurements of air flows for both magnitude and direction based on piezoelectric micromachined ultrasonic transducers (PMUTs) for the first time. The sensor operates in the pulse-echo mode to detect changes in flow with a measured sensitivity that is 286% of that for previously reported MUT-based flow meters, all without commanding any voltage over 5V. The enhancement is a result of four unique features reported herein: (1) the high-sensitivity bimorph structure of the fabricated PMUTs; (2) the spatial separation between the transmitter (Tx) and receiver (Rx) transducer elements; (3) the high directivity of the transmitted acoustic pulse; and (4) the differential readout. Owing to the single-chip design, our flow sensor is the first of its kind capable of measuring flow direction in addition to speed with high sensitivity.

INTRODUCTION

In the past few decades, ultrasonic flow meters have seen a vastly expanding application space, including extensive use in manufacturing process monitoring, environmental monitoring, and feedback control of HVAC systems [1],[2]. In terms of sensing technology, ultrasound presents an appealing alternative to the more conventional mechanical or pressure-based flow meters due to its ease of use, fast measurement response, and reliability over a wide range of temperatures and flow speeds. Perhaps the most convincing case for ultrasonic flow sensing, however, is the low total-life cost, which is derived from the low sensor cost, along with easy installation, and minimal maintenance [1].

Ultrasonic flow sensors have traditionally employed bulk piezoelectric transduction elements that vibrate in the thickness mode in order to transmit or receive ultrasound signals. Such transducers tend not only to be acoustically inefficient, which necessitates the use of matching layers that increase system complexity and introduce burdensome production costs [3], but can also be difficult to manufacture with small form-factors in order to measure flow in tight spaces. In contrast, micromachined ultrasonic transducers (MUTs) are an emerging alternative technology that, due to numerous recent research efforts, now offer benefits over bulk piezoelectrics including enhanced acoustic coupling with air or other gases, cost-effective batch fabrication, easy integration with CMOS circuitry, miniature size, and design flexibility [4]-[6].

Despite the prospect of these compelling advantages, MUT-based flow sensing has not yet been thoroughly explored. In [7], two different capacitive MUT (CMUT) wind speed sensors were proposed. Operating in pulse-echo mode, wherein a transmitter (Tx) CMUT element launches an ultrasonic pulse into the air that is then reflected back to a receiver (Rx) CMUT, the time of flight (TOF) or amplitude of the reflected ultrasound is collected to measure the wind speed. While achieving a high level of accuracy, the system requires impractical high voltages (over 100V DC and AC), suffers from a low TOF sensitivity of about 0.6 ns/(m/s)² that would require complex circuitry to acquire reliable measurements in real-time, and has interwoven Tx and Rx elements, resulting in a low amplitude sensitivity of 5.9%/ms¹ and precluding any differentiation of flow direction.

In contrast, we herein report on the first MUT-based, single-chip flow sensor capable of measuring both direction and speed of air flow. Using simplified analytical models and experimental testing, the novel sensor architecture is shown to derive its sensitivity most strongly from a highly directional acoustic beam pattern and spatially distinct transmitting and receiving elements. The sensor concept is tested using high-performance Aluminum Nitride bimorph PMUTs fabricated in a previous process [8] to achieve a high sensitivity of 16.9%/ms¹, which is more than 180% higher than that of previously reported MUT-based air flow sensors.

CONCEPT AND OPERATING PRINCIPLE

Overview of Sensing Mechanism

Figure 1 shows a conceptual schematic of the proposed PMUT-based, single-chip flow sensor. Operating in pulse-echo mode, the Tx PMUT element is driven electrically to launch ultrasound into the medium (air in this case), with a directional beam pattern so as to concentrate the acoustic energy into a narrow main lobe. The transverse flow carries the acoustic beam laterally, thereby affecting the pressure that is reflected back to the Rx PMUT elements from the surface at distance h. For rightwards flow in the figure, the pressure, which is proportional to the voltage, on Rx 2 will increase and the pressure on Rx 1 will decrease, and vice-versa for leftwards flow. In this way, the sensor is capable of differential readouts and detecting the direction of flow.

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Flow carries acoustic beam laterally

Figure 1: Schematic and operating principle of the proposed flow sensor.
Layout and Theoretical Acoustic Performance

As shown in Figure 2a, each PMUT element, regardless of Tx or Rx designation, is comprised of a $6 \times 28$ rectilinear array of circular PMUTs. The individual PMUTs have a radius of $a = 105 \text{ \mu m}$ for operation at a resonance frequency of 730 kHz, a pitch of $p = 460 \text{ \mu m}$, and the full element size is $2.8 \text{ mm} \times 1.3 \text{ cm}$.

As previously mentioned, it is critical to the function of the sensor that the ultrasonic output is highly directional; since the element is situated such that the air flow is in the $y$-direction, the directivity pattern of interest is in the $y$-$z$ plane. According to the acoustic product theorem [9], the directivity pattern $D_{el}(\theta)$ of the full element can be represented as:

$$D_{el}(\theta) = \frac{\sin \left( \frac{kw}{2} \sin(\theta) \right)}{N \sin \left( \frac{kp}{2} \sin(\theta) \right)} \frac{48 \sin^2(ka \sin(\theta))}{ka \sin(\theta)}, \quad (1)$$

where the first and second terms are the directivity patterns of a $w \times L$ rectangular aperture (with $L \gg \lambda$) and of a circular PMUT, respectively, $k = 2\pi/\lambda$ is the wavenumber, $N = 6$ is the number of PMUTs in the $y$-direction, and $\theta$ is the angle from the $z$-axis. Using finite element analysis, Eq. 1 has been validated by approximating each row of circular PMUTs as a long rectangular PMUT and simulating the acoustic field in the $y$-$z$ plane. As shown in Figure 2b, the two methods show strong agreement and predict a narrow 3 dB beamwidth of 9 degrees due to a large $kw$ value of about 36, and sidelobes at or below -12 dB within $\pm 45^\circ$.

In the presence of lateral flow, the main lobe is deflected by an angle of $\alpha(v) = \tan^{-1}(v/c)$, where $v$ is the flow speed and $c$ is the sound speed of the medium (343 m/s for air), and the acoustic energy is carried downstream. The relative change in pressure seen by an element of width $w$ and center position $y = y_0$ can be estimated using simple geometric arguments to integrate the steady-state far-field pressure distribution at the transducer plane as:

$$p(y_0, v) = \frac{\int_{y_0 - \frac{w}{2}}^{y_0 + \frac{w}{2}} D_{el} \left( \tan^{-1} \left( \frac{y}{2h} \right) \right) dy}{\int_{y_0 - \frac{w}{2}}^{y_0 + \frac{w}{2}} D_{el} \left( \tan^{-1} \left( \frac{y}{2h} \right) \right) dy}. \quad (2)$$

Intuitively speaking, $p$ is the flow-dependent average pressure on the Rx element normalized by the no-flow ($v = 0$ m/s) pressure, where reflections and near-field effects have been neglected for simplicity and analytic tractability.

In order to understand the expected sensor performance, Figure 2c provides the evaluation of Eq. 2 for two different reflector heights and with the downstream and upstream Rx PMUTs located at $y_0 = 5.6$ and -5.6 mm, respectively. At low positive flow velocities, as the main lobe steadily approaches the downstream and recedes from the upstream element (vice-versa for negative wind velocities), the sensor shows a nearly linear response with opposite trends for the downstream and upstream elements, thereby enabling differential measurements and evaluation of flow direction. This analysis indicates that the Rx pressure changes by about 2 and 3%/m/s for $h = 5$ and 4 cm, respectively. A slightly higher sensitivity is expected for the reflector at $h = 4$ cm due to a smaller no-flow Rx pressure, and the shallow reflector slightly widens the linear range because a higher flow velocity is required for the main lobe to reach the Rx element. The main lobe is centered on the Rx elements at $v = \pm 27$ m/s and $\pm 19$ m/s for the 4 and 5 cm reflectors, respectively, at which speed the maximum Rx pressure is achieved.

EXPERIMENTAL EVALUATION

Methods

Figure 3a shows the experimental setup used to evaluate the proposed single-chip flow sensor. The transducers are fixed in place with an aluminum reflector placed 5 cm away from their surface, and a Sunon PF92381BX DC brushless fan connected to an adjustable PWM control module generates lateral flow across the transducers. The transducers used in this work are bimorph PMUTs based on Aluminum Nitride films that were previously reported on and fabricated by our lab [8]. This unique PMUT structure doubles the amount of active piezoelectric in the diaphragm compared to conventional designs, thereby doubling both the transmit and receive responses and providing a SNR boost that allows high-fidelity pulse-echo measurements to be acquired in air.
without integrated interface electronics. The geometry and frequency of all devices are the same as those used in previous sections of this work, and an optical image of the device chip can be found in the detail of Figure 3a with two individual PMUT elements outlined. In the configuration shown, the Tx and Rx elements are spaced in the direction of flow with the Rx element downstream of the Tx element; in the Rx PMUT upstream configuration, the same elements are used but the Tx and Rx designations are switched. The off-chip readout circuit is shown in Figure 3b, which leverages a charge amplifying architecture to achieve high SNR with a simple off-the-shelf op-amp that requires only ±5V power supply rails.

Results and Discussion

Two sample pulse-echo waveforms taken with different reflector heights are displayed in Figure 4, where the Tx element is driven with a 10 V_{pp} 10-cycle 730 kHz square wave burst and each Rx signal is post-processed with a 32-order 300 kHz–1 MHz Butterworth bandpass filter in MATLAB. Early on, the Rx signals show notable

$$M = \sqrt{\int V^2 \, dt},$$

where $V$ is the Rx voltage, and the integral is evaluated within a 100 μs window that contains the full reflection. The physical significance of $M$ is that it is proportional to the square root of the energy contained within the pulse.

The sensor output with $h = 5$ cm and at different flow speeds is collected in both the Rx PMUT upstream and downstream configurations, normalized by the no-flow output, and plotted in Figure 5a, where the absolute flow speed is measured with a HoldPeak-866B digital anemometer. With the upstream and downstream configuration showing opposite linear trends, as predicted by analysis, the sensor is shown to be capable of determining the direction of flow and of differential readout. While determining flow direction is useful in itself, the differential readout is not only beneficial in its intrinsic sensitivity boost, but also in the robustness it adds to the system; for instance, differential measurement should negate the impact of factors that change the output of both upstream and downstream PMUTs in the same way - e.g., changes in ambient pressure and temperature. With a slope of -7%/ms⁻¹, the Rx PMUT upstream configuration is more sensitive than the downstream configuration, which has a slope of 2.9%/ms⁻¹. While a difference in sensitivity is predicted by the simple model previously introduced, the overall sensitivities are higher than the model predicts. Possible sources for this discrepancy are the non-uniform flow profile, including boundary layers, a slightly different directivity pattern than predicted, and the omission of near-field effects, which are expected to extend at least 2 cm from the face of the Tx PMUT.
flow sensors. As shown through analysis, simulation, and improvement over previously report as high as 16.9%. The sensor comprises a transmitter or receiver that can act as a spatially distinct transducer elements, each of which can be used for a different reflector height, exhibiting linear behavior and high sensitivity. As expected, the sensitivity increases for closer reflectors.

The measurement process is repeated for a reflector height of $h = 4$ cm, and the differential measurements, defined here as the difference between the downstream and upstream readings, for both cases are provided in Figure 5b. The differential readings exhibit linear trends with high sensitivities of 9.6%/ms$^{-1}$ and 16.9%/ms$^{-1}$ for reflector heights of 5 and 4 cm, respectively. In either case, the sensitivity of our reported sensor represents a stark improvement over the 5.9%/ms$^{-1}$ sensitivity reported by previous MUT-based air flow meters. Furthermore, as previously noted, the sensitivity boost from utilizing a closer reflector is due to the lower no-flow signal amplitude, in effect decreasing the denominator of Eq. 2. While posing this clear benefit, the reflector cannot be moved arbitrarily close to the PMUT surface, as the first reflection will become merged with the interfering signals, rendering the measurement inaccurate.

CONCLUSION

In this work, we have introduced the first PMUT-based, single-chip sensor for measurement of both direction and speed of air flow. The sensor comprises multiple spatially distinct transducer elements, each of which can act as a transmitter or receiver, and the system does not require any voltages over 5V. With a sensitivity as high as 16.9%/ms$^{-1}$, it represents a more than 180% improvement over previously reported MUT-based air flow sensors. As shown through analysis, simulation, and testing, the root of the high sensitivity lies in the high-performance PMUT architecture, the highly directional acoustic output due to the array dimensions, and most importantly, the spatial separation of elements. The differential output further boosts sensitivity and should also enhance reliability across a range of operation conditions. The increased sensitivity and functionality displayed by our flow sensor should expand the application space of MUT-based flow measurement and allow more users to take advantage of this cost-effective miniaturized approach.

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