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PMUT-Enabled Underwater Acoustic Source Localization System

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***Abstract*—The present work presents the novel application of Piezoelectric Micromachined Ultrasonic Transducer (PMUT) arrays in an Underwater Acoustic Source Localization System. Based on the difference in the time of arrival of ultrasonic bursts originating from an acoustic beacon, the system is capable of determining the direction to the source with no theoretical limitation on the angular range. A cross correlation technique is used to estimate the time of arrival difference between the received signals. Experiments are performed with the prototype submerged in liquid in a tank for arbitrary positions of a beacon, showing large potential for application of the system in a miniaturized, integrated platform for underwater source localization.**

***Index Terms*—PMUT, ultrasonic, underwater, Direction of Arrival, AVS**

I. Introduction

While there has been wide research in Piezoelectric Micromachined Ultrasonic Transducers (PMUTs) for in-air rangefinding [1], fingerprint scanning [2], imaging [3] and gesture recognition [4], it has been limited in underwater applications. Exceptions are device optimization [5] and previous work of the authors assessing PMUT capabilities for intra-body [6] and underwater data transmission [7].

Another currently active research field is Acoustic Vector Sensors (AVSs), given their capabilities for acoustic signal enhancement and Direction of Arrival (DoA) estimation [8]. Current miniaturized AVS implementations are reserved to measurements in air [9] for acoustic camera applications [10] or for DoA estimation based on orthogonal microphones [11]. The only Micro Electro Mechanical System (MEMS) implementation, suitable for underwater DoA estimation, is a sensor bio-inspired on fish organs [12].

The present work merges the use of PMUTs as underwater acoustic transducers with the source localization capabilities of AVSs. The resulting Underwater Acoustic Source Localization System (AcouLoc) offers the potential of significant miniaturization, a simpler manufacturing process and the additional capability of serving as a data transceiver. The system was designed having in mind an integrated and miniaturized PMUT-enabled underwater gadget, guiding divers towards a reference ultrasonic beacon, as a potential application (Fig. 1).

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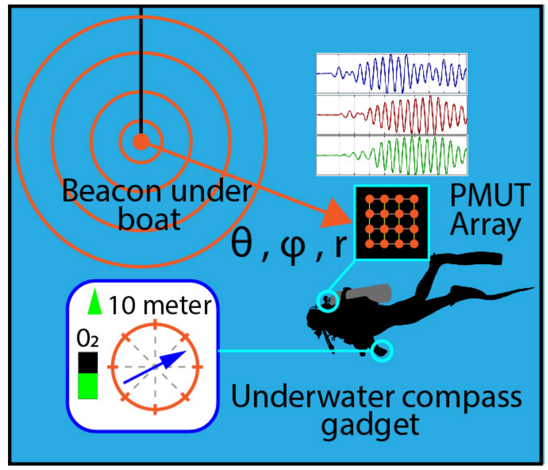

Fig. 1. Envisioned application; A PMUT-based acoustic source localization system informs divers of the relative angle and distance to a beacon placed underneath a boat or anchored on a reference location.

II. Methodology

A. Principle of Operation

The source localization system is based on geometric characteristics of the spreading of acoustic waves. An acoustic source (beacon), whose position is to be determined, emits an acoustic wave. This emission is initially assumed to be omni-directional, for simplicity. The acoustic wave spreads spherically from the beacon and, as the distance increases, the radius of the sphere defining the wave front increases. At a sufficient distance, the radius becomes so large that the curvature of the wave front starts becoming negligible. It is at such a location that the wave strikes the source localization system.

From the perspective of the AcouLoc, this incoming wave has a planar front coming at a certain angle θ relative to its face (fig. 2). In a two-dimensional simplification, the AcouLoc is formed by several receiver channels separated by a defined pitch p. Therefore, due to the angle between the wave front and the receiver's face and the finite speed of sound in the medium, one of the channels is struck before the other. A certain distance d is travelled by the wave front between the time the first and second channels are activated (t_1 and t_2 respectively). This distance can be calculated as the speed of

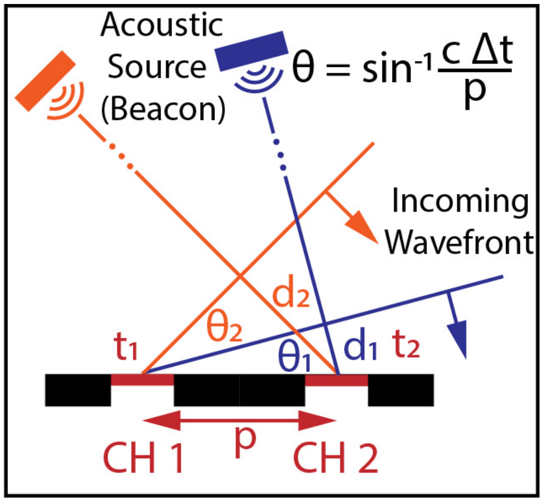

Fig. 2. Principle of operation; the relative angle to an acoustic source is calculated from the time delay between the arrival of the corresponding acoustic signals to channels with a known spacing. Distance to the source can be inferred from the received intensity with a known emitter pressure.

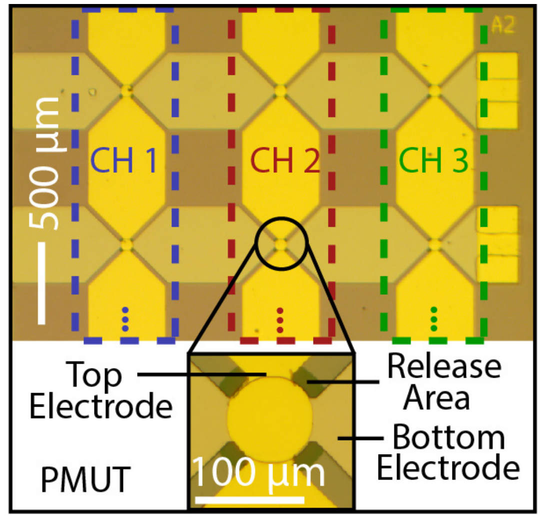

Fig. 3. Optical micrograph of fabricated devices detailing channel arrangement and element geometry.

sound c times the time delay Δt. A right triangle is formed which allows to relate the angle θ to the delay Δt through (1):

$$\theta = \sin^{-1}\left(\frac{c\Delta t}{p}\right) \tag{1}$$

Based on this relationships, it is possible to calculate the relative angle of the beacon to the receiver only by determining the time delays between the appearance of electrical signals on each of the channels.

B. PMUT Array

Fig. 3 shows an optical micrograph of a section of the PMUT array serving as the receiver in the AcouLoc. The PMUT elements are arranged in a rectangular grid where their bottom electrodes are connected in rows and their top electrodes in columns. The bottom electrode is assigned to a common ground while each column is wire-bonded to a separate channel output on a Printed Circuit Board (PCB). In this configuration, each of the columns serve as an individual channel of the AcouLoc. Even though strictly only two channels are required for the angle determination, additional channels provide the possibility of averaging the obtained time delays to increase accuracy. The particular chip implemented in this work consists of 10 rows by 10 columns, with the 10 PMUTs in each column adding to the total current output of the channel.

This configuration allows for determining the location of the beacon with one degree of angular freedom only as a demonstration of the PMUT implementation. For achieving the two angular degrees of freedom involved in three-dimensional space, an orthogonal arrangement of channel pairs can be made. The distance to the beacon can also be inferred from the amplitude of the received signal for a complete localization.

The fabrication process for the chip starts with deposition of a $1\mu m$ Silicon Dioxide (SiO_2) layer through low temperature Plasma Enhanced Chemical Vapor Deposition (PECVD). A $200nm$ Platinum bottom electrode with a $10nm$ Titanium stiction layer is then sputtered and patterned with a Lift-Off Resist (LOR) photolithography process. A $1\mu m$ Aluminum Nitride layer is then deposisted as the piezoelectric. The top electrode stack is then formed through Electron Beam deposition and consists of a $10nm$ Titanium stiction layer and a $200nm$ patterned Gold layer. A $1.2\mu m$ SiO_2 hard mask is then formed on the bottom of the wafer by PECVD, backside alignment photo-lithography and Reactive Ion Etching (RIE). Finally, Deep Reactive Ion Etching (DRIE) is used to etch cavities through the wafer and release the circular membranes.

C. Test Setup

Fig. 4 shows an overview of the experimental setup for the AcouLoc. A commercially available bulk PZT transducer serves as the acoustic beacon source and is mounted on a motorized stage for location at an arbitrary distance and angle relative to the PMUT receiver. The chip is wire-bonded to a custom PCB that leads each channel to connector cables and serves as a mechanical structure holding the device on a fixed central location. Both elements are immersed in a tank filled with dielectric oil which simulates the underwater environment while preventing any direct electrical conduction so that only the acoustic output is studied. The PZT beacon is driven by a pulser board allowing it to transmit acoustic signal bursts. The chosen frequency of operation is $2MHz$. Higher frequencies of operation allow for higher acoustic intensities but suffer from larger attenuation. The chosen frequency of the link was a good compromise for the chosen setup but large distance operation in the final application will require operation at lower frequencies to benefit from lower attenuation. The outputs of the channels in the receiver are visualized on an oscilloscope.

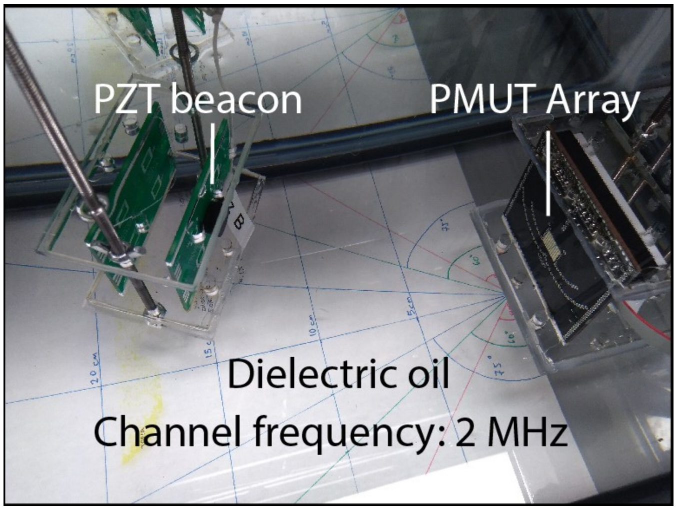

Fig. 4. In a dielectric oil tank, a PZT transducer acts as a transmitting beacon and is placed with varying distances and relative angles to the receiving PMUT array through a motorized stage.

III. Results

A bursting scheme was used on the beacon, resulting in a delayed reception of the signal according to acoustic propagation (fig. 6, top). Depending on the angle relative to the receiver, positive, null or negative delays were seen between the onset of the signals on each of the channels. Fig. 5 shows the detail of a sample measurement of the output signals resulting from a $5cm$ distance and a relative angle of 60^o. The amplitudes are normalized for easier comparison. As can be seen, the start of the output bursts is not sharp but rather has a build-up time related to the quality factor (Q) of the resonating PMUTs. This makes it unreliable to estimate the delay by direct measurement of the time separation between the appearance of the first peak on consecutive channels.

To achieve a more precise time delay measurement, a cross-correlation approach is used. While the obtained signal from a channel is fixed, the output from the consecutive one is shifted in time for a certain amount and the product of both signals is integrated. The procedure is repeated for a wide span of shifts and the cross-correlation curve is obtained characterizing the similarity of the signals for a certain shift. A maximum in correlation will indicate that the adequate shift has been used, which corresponds to the delay (fig. 6, bottom). The periodic pattern on the cross correlation function is a result of the periodicity of the burst signal; local maxima appear when the peaks are aligned, but the most correlation is found when the complete bursts align. Fig. 7 shows the distance, and the calculated delay and angle from the AcouLoc channel outputs for three arbitrary locations of the beacon. As the calculation of the relative angle is based on the time delay between the arrival of the signals, there is no theoretical limitation for the angle θ that can be measured (-90^o to $+90^o$ range), a clear advantage of the approach.

A practical limitation could be the directivity of both the beacon and the receiving transducer array. If any of both had a narrow beamwidth (high directivity), it could be possible that an acceptable received signal level would only be possible within this narrow angle range and that the signal would be lost in the noise floor out of it. Nevertheless, omni-directional acoustic transducers (projectors) are readily available as they are widely used in underwater applications [13]. On the receiver side, the directivity of an array of transducers can be high as the number of elements increases and the pitch between them decreases. However, each individual channel on the AcouLoc acts as an independent receiver so their directivity, for the angle of interest, is basically the one of a single PMUT. As the diameter of the element ($92\mu m$) is much smaller than half the wavelength ($375\mu m$), the PMUTs can be considered omni-directional [14].

IV. Conclusions

The AcouLoc was demonstrated to successfully operate in laboratory underwater source localization experiments using a commercial PZT transducer as the beacon. Arbitrary positions of the beacon were estimated in a $+/-50^o$ and $0-25cm$ range limited only by the dimensions of the tank used. A cross-correlation technique estimated the difference in time of arrival

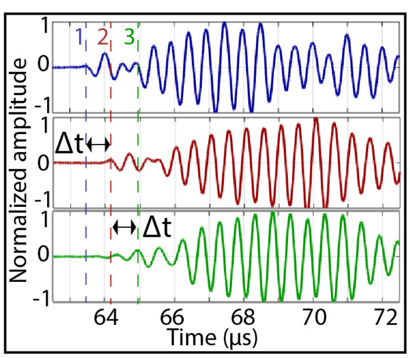

Fig. 5. Sample measurement detailing the outputs from consecutive channels and the delays among them for a $5cm$ distance and a 60^o angle.

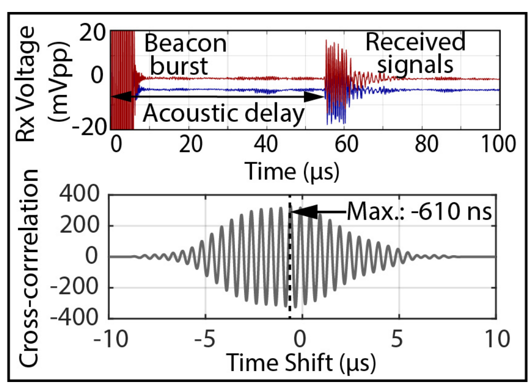

Fig. 6. Top: Bursts at the receiver channels appear delayed respect to the beacon burst according to their relative distance and the speed of sound in the medium. Bottom: Cross-correlation function obtained between channels 1 and 2 from Fig. 5

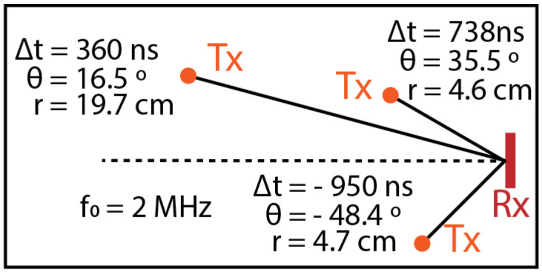

Fig. 7. Measured time delay Δt and angle θ, calculated through (1) for sample measurements at arbitrary locations of the beacon (distance r). Angle and distance of the measurement were only restricted by tank dimensions.

of ultrasonic bursts to adjacent PMUT channels within tens of nanoseconds. The $2MHz$ signal frequency used, due to the resonant frequencies of both the beacon and receiver, was appropriate for laboratory testing but will need to be reduced to mitigate attenuation in longer distance implementations. However, the results show large potential of the proposed system towards the implementation of a miniaturized, integrated platform for underwater source localization.

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