A MEMS Transducer for Ultrasonic Flaw Detection

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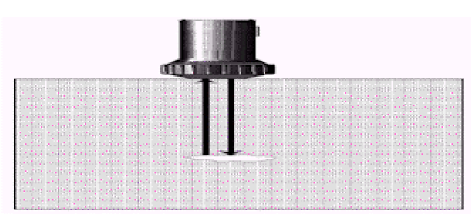
ABSTRACT

Metal structures can fail because of fatigue crack propagation or because of section loss from corrosion. Regular inspection is required to intercept such failures, and *in situ* sensors would be a superior technology for that purpose. We are developing MEMS-based transducers for ultrasonic flaw detection, to be permanently mounted at critical locations on structures. Ultrasonic testing requires the emission of a short pulse of ultrasonic energy and the detection of echoes from nearby surfaces or flaws. In a permanently mounted device, phased-array detection will be needed to scan for flaws in off-axis locations. The device we envision will use a mm-scale piezoelectric emitter and an array of MEMS capacitive diaphragm detectors. We have designed and fabricated arrays of MEMS capacitive diaphragm transducers using the MUMPS process and we report on their performance as pulse-echo detectors in direct contact with metal specimens. Our chip contains 23 sensor elements, featuring nine elements in a linear array and 14 other elements to study alternative diaphragm designs. In the linear array, each element contains 180 hexagonal diaphragms with a leg length of 49 microns, a polysilicon diaphragm thickness of 2 microns, and a gap of 2 microns. The diaphragm diameter was chosen to obtain a lowest-mode resonant frequency of approximately 4 MHz for an unloaded device, corresponding to a ultrasonic wavelength which is well-suited for flaw detection in structural applications. The unloaded elements were characterized by capacitance-voltage measurements under ambient conditions and by admittance measurements in vacuum, verifying the expected mechanical performance of the diaphragm design. Performance of the detector array was studied by bonding the chip to a test specimen and applying an ultrasonic pulse using a commercial (PZT) ultrasonic transducer. One experiment reflects an on-axis excitation in which the pulse arrives uniformly at all eight detectors. Another experiment reflects an off-axis excitation in which the pulse arrival is delayed from one detector to the next. The delay permits accurate localization of the pulse source using phased array signal processing. The results establish that MEMS transducers can function as phased array detectors for monitoring flaw conditions in metal structures.

INTRODUCTION

Steel is used in buildings, bridges, pressure piping, and industrial construction, but the safe performance of any steel structure is threatened by section loss from corrosion or wear, by crack propagation from fatigue or cyclic loading, by weld failure from overload or seismic loading, or by other discontinuities. Such flaws can develop with time, and the continued service of major structures often requires confirmation that such flaws have not developed.



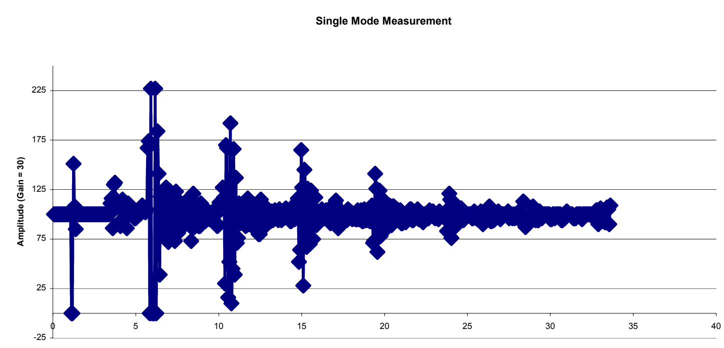


Figure 1a. Pulse-echo flaw detection (from ref [1]) Figure 1b. Results using mm-scale PZT specimen

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Ultrasonic flaw detection [1] is a versatile technology for nondestructive evaluation, but it must typically be performed by skilled personnel. The principles of pulse-echo flaw detection are depicted in Figures 1a and 1b in a through-thickness geometry. Figure 1a depicts an ultrasonic pulse generated and transmitted into the material. A typical transducer frequency is 5 MHz frequency, corresponding to a 1.2-mm wavelength in steel, which is sufficiently short to resolve flaws at that same scale. The typical transducer is a piezoelectric device, a PZT (lead-zirconium-titanate) ceramic, with a diameter much greater than the wavelength. The ultrasonic pulse will reflect from the first boundary it encounters, which in an unflawed specimen is the back surface of the steel plate. The time at which the echo returns to the front surface reveals the total travel distance, equal to twice the thickness. Figure 1b records a measurement using a mm-scale PZT sample affixed to a brass plate (velocity of sound c = 4400 m/s) with a thickness of 9.8 mm, showing successive echo returns. The time from the pulse to the return of the echo is slightly under 5 μs, correctly approximating the thickness. Ultrasonic inspection can be used in this manner to measure thickness, which would reveal any section loss, or to reveal reflections that arrive prematurely, which would signal the presence of a flaw.

Although ultrasonic flaw detection is quite versatile, there are two limitations that could be eliminated by the development of resident sensors: in current practice the inspection is performed manually, and is therefore subject to interpretation, and the process is often memoryless, which makes no use of the earlier signal history. We envision building a resident ultrasonic flaw detection system to be mounted at critical locations on metal structures, which would retain a signal history to allow signature analysis in the detection of developing flaws. We intend that the device be polled remotely using RF communications. This paper describes the design and initial testing of a MEMS capacitive (diaphragm-type) transducer array to function as the receiver in the flaw detection system. In order to scan a volume of material from a fixed position it is necessary for the transducer to function as a phased array, and experiments to demonstrate signal detection and phased array processing were a main purpose of this study.

PREVIOUS WORK

Ultrasonic pulse-echo detection is used in many other applications including range/motion sensing, embedded object detection, surface characterization, and medical ultrasound imaging. There is a considerable history of research into MEMS transducers for fluid-coupled and air-coupled applications. Our approach to designing microscale ultrasonic diaphragms was based on the important work of Khuri-Yakub at Stanford University [2-6]. One paper [2] outlines the mechanical and electrical analysis of capacitive diaphragm transducers and presents experimental results for air-coupled and fluid-coupled transmission through aluminum, showing that practical applications (including flaw detection) are feasible. Another paper [3] records in detail the fabrication steps needed to produce capacitive ultrasonic transducers suitable for immersion applications and the characterization, both experimental and analytical, of their performance. Another paper [4] presents results for nondestructive evaluation of metal specimens, in which air-coupled transducers generate and receive Lamb waves, which are useful for detecting near-surface flaws. Two other references [5,6] discuss one-dimensional transducer arrays and present initial imaging results, in which solids immersed within fluids are detected. Other investigators of MEMS ultrasonics include Schindel [7,8] with numerous contributions to immersion applications, and Eccardt [9,10], at Siemens, with the demonstration of surface micromachined transducers in a modified CMOS process. The authors [11] have recently published an earlier version of the experimental results presented herein.

DEVICE DESIGN

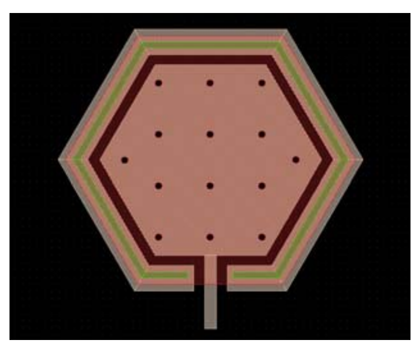


Figure 2, to the right, is a mask layout drawing for the typical diaphragm used in our device. In a MEMS capacitive transducer, when a DC bias voltage is maintained across the plates of the capacitor, diaphragm deflection produces a change in capacitance that can be detected electrically. The sensitivity of a single diaphragm increases linearly with the bias voltage and inversely with the cube of the gap dimension. Moreover, the sensitivity of any detector composed of diaphragms in parallel increases with the number of diaphragms, and therefore the most favorable utilization of area is preferred in order to obtain maximum signal strength. Accordingly, the hexagonal geometry was chosen for the individual diaphragm unit and the transducer was fabricated by the MUMPS surface micromachining process. It is constructed in the polysilicon-1 structural layer with a thickness of 2 µm; the holes are required by the MUMPS design rules for the release etch of the sacrificial layer between the polysilicon-1 layer and the substrate. The diaphragm geometry is a regular hexagon with leg length equal to 49 µm, chosen to yield a resonant frequency near 4 MHz. The elastic modulus for polysilicon is 180 GPa, the Poisson's ratio is 0.25, and the specific gravity is 2.300. MEMS fabrication processes can introduce significant residual stress, but in the MUMPS process the residual stress in the polysilicon-1 layer is only 10 MPa compression, which is quite small compared to the in-plane buckling stress. The underlying stationary electrode on the substrate is hexagonal with leg length equal to 37.5 µm, and the gap between the diaphragm and the stationary electrode is 2 µm, from which the predicted capacitance for a single diaphragm is 0.016 pf. A target capacitance of a few pf was chosen, and therefore the basic detector was fabricated as a group of 180 diaphragm units in parallel. Figure 3 is the layout drawing for a typical detector with approximate dimensions of 0.5 x 2 mm.

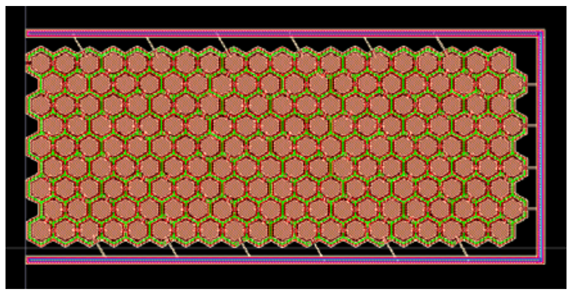


Figure 3. Typical detector

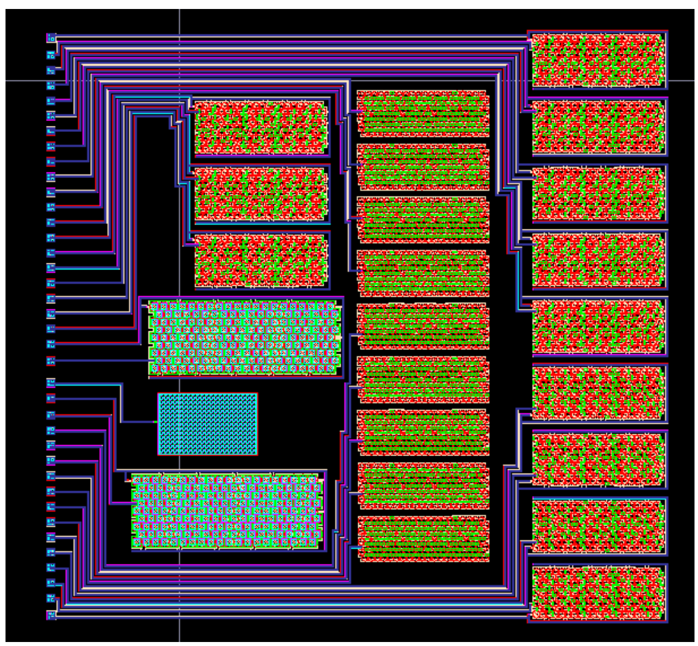


Figure 4. Layout drawing for chip

The overall layout is shown above in Figure 4. The chip is approximately 1-cm square and contains 23 detectors. The primary detector array is the set of nine in the right-hand column, spanning a 1-cm baseline for phased array implementation. The nine detectors in the middle column are an alternate design attempting to use the substrate, rather than a deposited electrode surface, as the stationary plate of the capacitor. The three detectors at the top of the left-hand column constitute variations on the diaphragm design, using closer-spaced etch release holes, to perform experiments on squeeze film damping. The two largest detectors in the left-hand column are alternate diaphragm designs constructed with two polysilicon layers, for a thickness of 4 µm, and a correspondingly larger leg dimension of 69 µm.

EXPERIMENTAL RESULTS AT SIGNAL DETECTION

To our knowledge, our tests were the first to attempt signal detection by MEMS transducers in direct contact with solids. The experiments were performed with chips bonded to plexiglass specimens using Gelest Zipcone CG silicone adhesive. Commercial ultrasonic transducers, with nominal diameters of 15 mm and rated operating frequencies of 3.5 MHz and 5 MHz, were the signal sources. Figures 5a and 5b, shown to scale, depict the specimen geometries; the MEMS chip appears on-edge as a small rectangle, and the dimension records the closest distance between the signal source and the nearest detector. In the test depicted in Figure 5a the baseline of nine detectors appears as a single point, the point closest to the transducer. Because the transducer is approximately 15 mm wide and the detector baseline is less than 10 mm long, the signal is expected to arrive simultaneously at each detector; the test is termed the on-axis geometry. In the test depicted in Figure 5b the baseline of nine detectors appears as the heavy line. The dimension shown (0.72-inch, or 18 mm) is the distance between the signal source and the nearest single detector. Therefore, the signal will reach the nine detectors along the baseline at an extreme raking angle (65^o from the normal) and with considerable delay in arrival time across the baseline; the test is termed the off-axis geometry. The main purpose of these tests was to obtain the distance and angle between the transducer and the source in Figure 5b, using phased array signal processing.

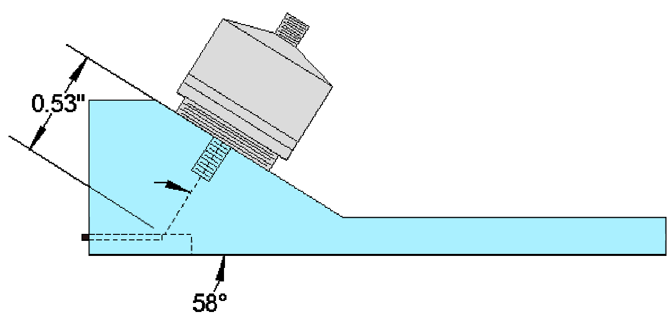


Figure 5a. Test specimen, on-axis geometry

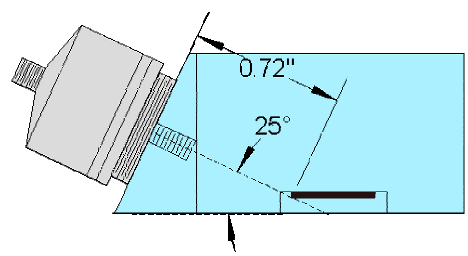
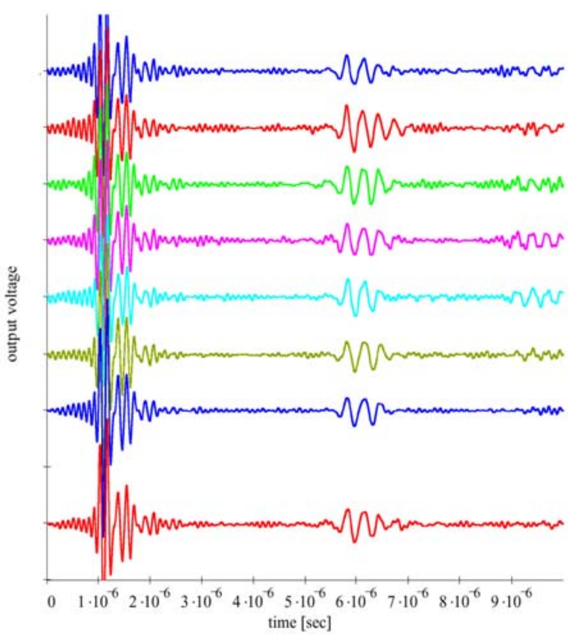


Figure 5b. Test specimen, off-axis geometry



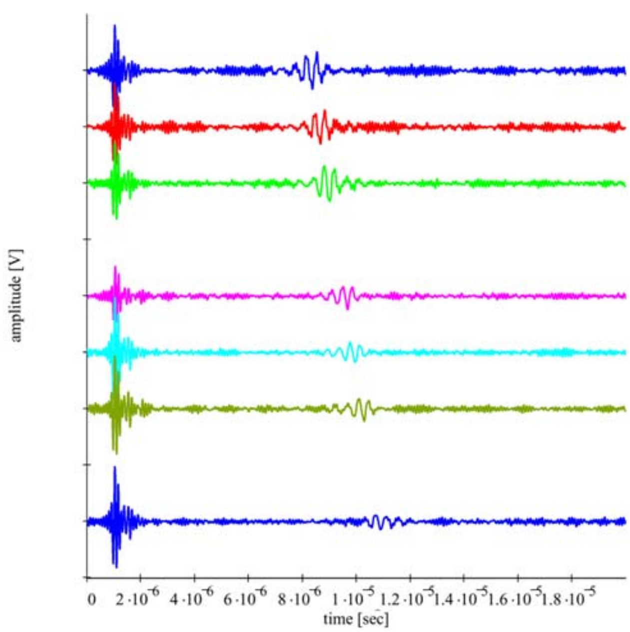


Figure 6. Experimental results, MEMS array response; Figure 6a: on-axis geometry; Figure 6b: off-axis geometry

Figure 6a shows experimental results for a pulse in the on-axis geometry illuminating the array of nine detectors from a distance of approximately 0.53-inch, or 13 mm. The signal received at each detector is displayed on the plot at the appropriate relative spatial position of each detector. We note the following:

- Each signal shows a pulse near 1 μs because of stray electrical coupling, followed by the signal arrival approximately 4.5 μs later, corresponding roughly to the specimen thickness along that travel path.
- As predicted, the arrival time is uniform at all detectors.
- The signals at each detector are relatively uniform in appearance and comparable in amplitude.

Figure 6b shows experimental results for a pulse in the off-axis geometry raking across the array of detectors.

- Only seven detectors are shown, because two detectors became non-operative over the long course of the tests.
- The signal arrives first at the closest detector, with successive delay in its arrival at each subsequent detector.
- The arrival times are consistent with the distance between the pulse source and the array.
- The delay permits localization of the source, determining the distance and angle to that source, using the principles of radar imaging.
- A simple geometric localization can be envisioned directly on Figure 6b. If a vertical line is drawn through the start of the pulses, and another straight line is drawn through the start of the received signals, those lines will intersect at a distanced which can be scaled (either from the inter-detector spacing or from the whole baseline dimension) to obtain the location of the pulse origin to the "left" of the array as it appears in Figure 5b.

A simple signal processing approach was used. Because the detectors are equally spaced, the delay between them will be constant. If each signal is shifted successively by some delay, and then all signals are added together, the sum should be maximum when the correct delay is used. Equivalently, "guessing" the distance and the angle to the source constitutes a "guess" at a delay, with which the signals can be summed, and when the best estimates of distance and angle are used the sum should be a maximum. Figure 7 depicts the results of that process, with arbitrary units, and the isolated peak represents the best estimate of distance and angle to the source. The axis projecting into the foreground represents the distance, and the axis projecting to the right represents the angle to the source. (The peaks along the distance axis represent the stray-coupled pulses, and should be ignored.)

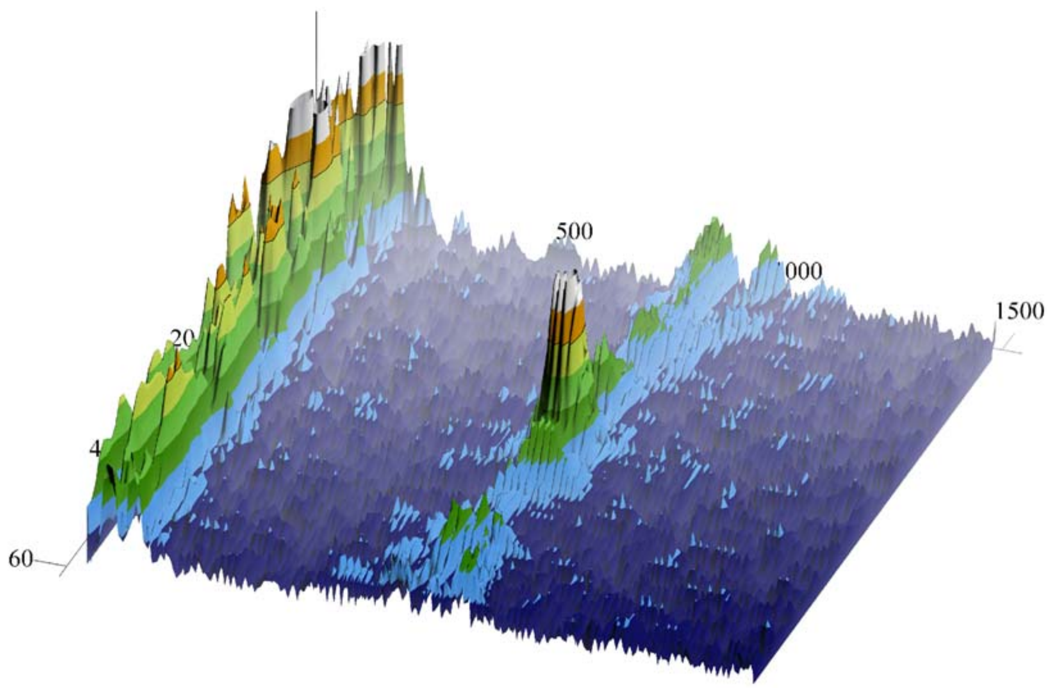


Figure 7. Results of signal processing: distance and incidence angle to source appear as the peak

CONCLUSIONS

Experimental results in Figures 6 and 7 show that MEMS capacitive (diaphragm-type) transducers can successfully detect ultrasonic pulses when in contact with a solid. The phased array implementation shows that the transducer can successfully localize a source in an off-axis geometry. This first-generation device was designed to test the feasibility of phased array detection, to evaluate design alternatives, and to conduct related experiments in diaphragm behavior. The detectors fabricated in this first device are sufficiently sensitive to detect pulses from a commercial PZT transducer. More recent results (not shown) demonstrate that the detectors are sufficiently sensitive to detect pulses from mm-scale PZT sources if geometric spreading from the signal source is kept small. However, demonstration of flaw detection in practical geometries will require greater sensitivity in order to detect signals from small sources (creating a spherical wave) after considerable geometry spreading. Currently the sensitivity is limited by the capacitor gap and the detector area, and detection limits are severely constrained by parasitic capacitances. A second-generation device is presently being fabricated with a number of design improvements to these conditions, and is expected to improve performance by an order of magnitude. Additional improvements in effective sensitivity, by orders of magnitude, can be achieved when the mechanical transducer and the electronic circuits are fabricated as an integrated system on a single chip.

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