Ultrasound Non-Destructive Evaluation/Testing using Capacitive Micromachined Ultrasound Transducer (CMUT)

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***Abstract*— Ultrasound transducers such as Capacitive Micromachined Ultrasonic Transducers (CMUT) have attracted attention recently because of their sensitivity, scalability, and compatibility with CMOS. They offer better bandwidth and sensitivity than piezoelectric transducers and have shown efficient transduction. The CMUT replaced piezoelectric transducer in some applications like imaging because of its lightness and miniaturization. In this work, the experiments were carried out to measure the length of the stainless-steel bar. Two methods were used to calculate the length of the stainless-steel bar using pulse-echo and transmission through (pitch-catch). The lengths were calculated with an error of 3.7% using the pulse-echo method and an error of 5.2% using the pitch-catch method. These experimental setups lay the foundation for ultrasonic nondestructive evaluation/testing using CMUTs. The results obtained using ultrasound signals were reliable for measuring the length and finding any defects in stainless steel.**

Keywords— Pulse-echo, non-destructive testing, pitch-catch, CMUT, ultrasound, transducers, DPR300.

I. Introduction

Conventional piezoelectric-based ultrasound transducers are the most widely chosen due to their mature technology, while their offer an inherently small bandwidth[1, 2]. Capacitive Micromachined Ultrasound Transducer (CMUT) has attracted many researchers in the last two decades. The CMUT replaced the conventional piezoelectric transducers in many different applications because they offer better bandwidth and sensitivity than piezoelectric transducers showing efficient transduction [3-7]. CMUTs are made up of two membranes like a capacitor, where one of the plates is made robust and rigid while the other membrane is made flexible and easy to vibrate [8, 9]. An AC voltage is applied in transmission mode, as illustrated in Fig. 1(a), making the electrostatic attraction forces vibrate the membrane. However, the membrane's vibration is twice the applied input frequency because the electrostatic force is unipolar; therefore, a larger amplitude of a DC bias voltage than AC voltage is applied to give the best performance of the CMUT. The membrane deflection increases as the DC input voltage increases because the electrostatic force deflects the flexible membrane, while the mechanical restoring force resists the attraction [10]. At an above-specific voltage (collapse voltage), the flexible membrane collapse to a fixed membrane and does not vibrate because the mechanical restoring force overwhelms the electrostatic force; hence the imbalance of CMUT occurs, and the CMUT breaks [11, 12]. The DC bias can be eliminated if the efficiency is not a matter. The compensation for eliminating the DC bias is reducing the AC signal to half the operating frequency, and high efficiency might be obtained. Ultrasound signals are generated in the medium due to the vibration of the membranes [13, 14].

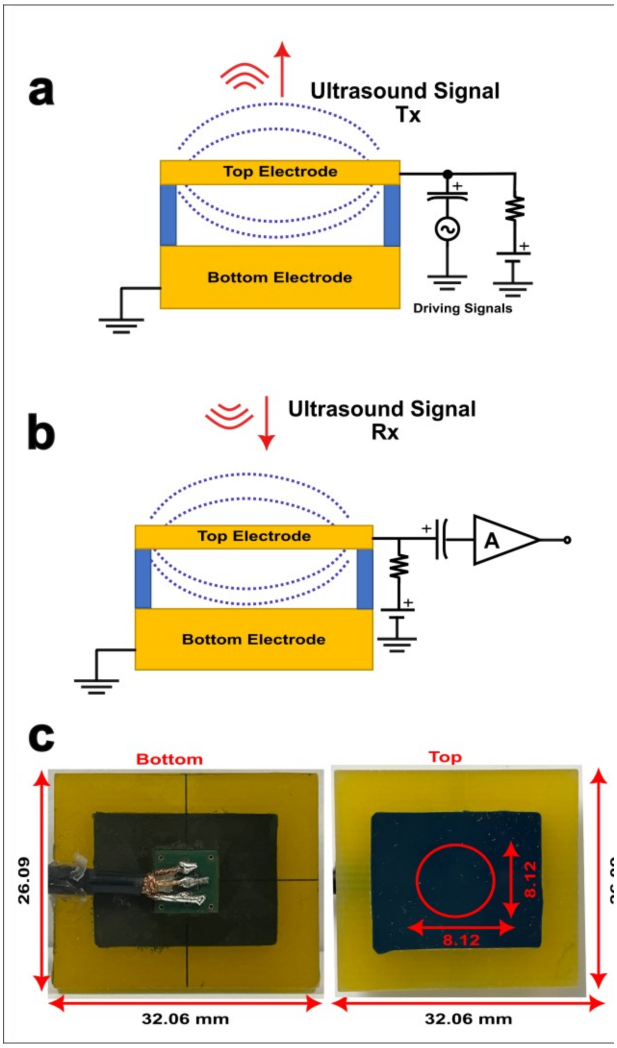

Fig. 1. (a). CMUT excitation setup in transmission mode using AC and DC signals. **(b).** CMUT excitation in the receiving mode is connected to the DC bias only. **(c)**. Top and bottom views of the typical CMUT.

In the receiving mode, the gap height of the CMUT is vibrated at the same incoming frequency as the received ultrasound waves. The incident ultrasound signals vibrate the membranes and modulate the overall capacitance of the CMUT, which also require a DC bias voltage. A condenser microphone is similar to the CMUT; its capacitance increases

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and decreases to detect ultrasound waves. A typical packaged CMUT is illustrated in Fig. 1(c).

The external electronics circuit captures and amplifies a current flow resulting from the capacitance vibration [13, 14], as illustrated in Fig. 1(b).

In a medium such as air, the higher frequency increases the attenuation of the ultrasound signal; therefore, for a given density, the ultrasound wave might not be able to travel even a small distance. The gel allows the ultrasound wave to pass through the object without interruption. Therefore, the gel eliminates impedance mismatch between the transducers and the tested objects. Moreover, for the air coupling ultrasound transducer is preferred to be in a low frequency (kHz or less) for better propagation into the medium [15].

The pulse-echo method uses the same transducer for transmitting and receiving ultrasound signals. In the pulse-echo method, a switch is required to distinguish between the transmitter and the receiver signals. Pulse-echo method is used in ultrasound imaging applications and in the non-destructive testing used to locate, measure and find the defects in the workpiece. The ultrasound signals propagate through the material in the form of waves. When the wave passes through a different medium, the ultrasound waves' energy is reflected back to the same transducer and converted into electrical signals [16]. Non- destructive testing is based on the time of flight (TOF), defined as the time required for signals to travel from the transmitter to the receiver transducer [17]. By using Eq (1), we can determine the length of an object:

$$Distance = velocity \times time \qquad (1)$$

A pitch-catch method uses two separate transducers for transmitter and receiver ultrasound signals. The pitch-catch method is faster than the pulse-echo method because the ultrasound signals travel less distance than the pulse-echo method. The time of flight is reduced by half in the pitch-catch method.

In this paper, pulse-echo and pitch-catch methods were explored to calculate the length of the stainless-steel block and compared with the measurement obtained by the Vernier Caliper. This paper is organized as follows: section II methodology, section III presents the results and discussion. In section IV, conclusions are drawn.

II. Methodology

A. Measuring the length of the stainless steel using the pulse-echo method

Unlike the piezo transducers, the CMUT required DC bias and AC signals for proper operation. Fig. 2 illustrates the complete system for the pulse-echo method using DPR300 pulser/receiver (JSR Ultrasonics), an RF attenuator (Telegartner), DC power supply (ea-ps 2042-03b), CMUT (University of Tours, France), Bias Tee and Oscilloscope (Tektronics 5 Series). DPR300 had full front-end electronics for the ultrasound system. In this work, the DPR300 was used to transmit AC signals (pulses) and receive ultrasound signals with a single element transducer. The transmitted output voltage range of the DPR300 is –100 V to –475 V; therefore, an RF attenuator of 20 dB with 50 Ω impedance was connected to the DPR300 to avoid high voltage transmission that may damage the transducer. The transmitter and receiver modes were isolated by a built-in switch in the DPR300

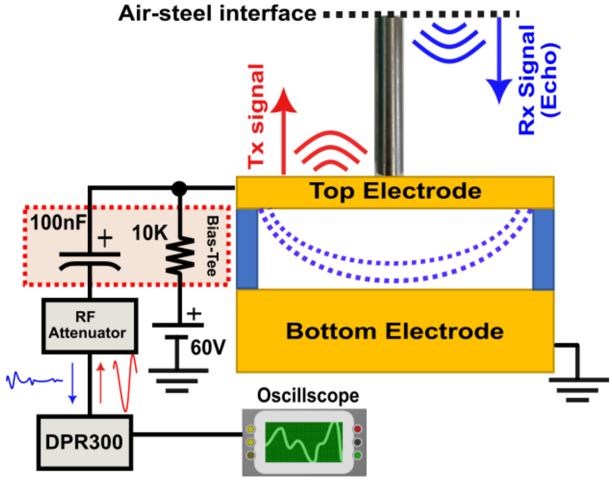

Fig.2. Pulse echo measurement setup using CMUT.

instrument. In the transmitter mode, the DPR300 sends the pulses to the CMUT to generate ultrasound waves propagating through the stainless-steel block. The attenuator reduces the output signals from the DPR300 by a factor of 10 for the transmitter mode and receives mode (–10 V to –47.5 V).

Ultrasound signals travel through the stainless steel with a constant velocity. When the signals encounter different mediums (air and steel interface) or cracks, an echo signal is reflected back to the transducer. The ultrasound echo signals are converted into electrical signals, which are attenuated with the RF attenuator. Then the signals are amplified and filtered by the DPR300 ultrasonic Pulser-Receiver. The output signals from the DPR300 are displayed on the oscilloscope. For high performance of the CMUT, the input signals were set up as follows: Vac (−40 V) from the DPR300, Vdc (60 V) from the power supply, and the bias tee values were 10 nF and 10 kΩ.

B. Measuring the length of stainless steel using the pitch-catch (through transmission) method

Further investigation was carried out to calculate the length of the stainless steel using two separate CMUTs. This

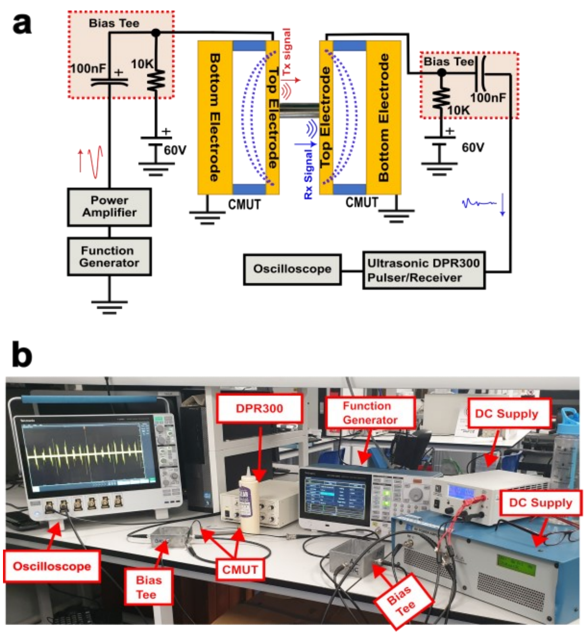

Fig. 3 (a). Pitch-catch block diagram setup for the CMUTs. **(b).** Pitch-catch measurement setup using CMUTs.

method was introduced to eliminate the attenuator. The pitch-catch method setup is illustrated in Fig.3.(a) and Fig.3.(b). The function generator (Tektronix AFG Arbitrary Function Generator 31000) sends a repeated pulse signal at an interval of 20 ms. A power amplifier (Electronics and Innovation, LTD) was used to amplify the signals from the function generator because the function generator had limited output voltage. The power amplifier amplifies the input signal at a fixed gain of 52 dB.

The amplified pulses are fed to the bias tee to separate the AC and DC input to avoid mutual interference between the signals. The output signal from the bias tee was connected to the top electrode of the CMUT to generate ultrasound waves that propagate in the stainless-steel block. The second transducer receives the propagated ultrasound waves sent from the transmitter. DPR300 device was used for receiving the electrical signal, where all the functions built-in the DPR300 have been exploited. The received parts knobs such as gain, high pass filter and low pass filter were controlled and adjusted to amplify the received signal. The received signals from the transmitter transducer are amplified and filtered in the DPR300. The output electrical signals from the DPR300 were displayed on the oscilloscope. For high performance of the CMUT, the input signals were set up as follows: Vac (-40 V) from the function generator and power amplifier, Vdc (60 V) from the DC power supply and the capacitor and resistor values in the bias tee were 10 nF and 10 kΩ respectively.

III. Results and Discussions

A. *Pulse echo measurements results*

The transmitted electrical signals generate the ultrasound signal. The ultrasound wave generated by the CMUT was at 2.5 MHz, propagating through the stainless steel. The front echo signal detected on the oscilloscope was the transmitter signal at the front interface of the stainless steel block, as shown in Fig. 4(a). The rear echo signal was the echo signal received from the end of the stainless steel surface at a time of 34.57 µs. The signals received were attenuated while propagating through the stainless steel. The stainless steel absorbed some of the ultrasound signals along the travel. The attenuation of the ultrasound wave intensity increased with distance. The amplitude received from the pulse-echo signal was less than measured with the pitch-catch method. The ultrasound signal travelled twice the length of the stainless steel (202.44 mm).

The propagation time between the transmitted and received signals was calculated using the oscilloscope. By the time of flight of the signal, the length of the stainless steel can be calculated using Eq (2) as follows:

$$D = v \times \frac{t}{2} \qquad (2)$$

D is the distance the signal travelled from the transmitter to the receiver, v is the speed of the ultrasound wave in the stainless steel (6035 m/s), and the t is the time taken for the signal to travel from the transmitter and return to the same transducer (34.57 µs).

$$D = 6035 \times \frac{34.57x10^{-6}}{2} = 104.33\,mm \qquad (3)$$

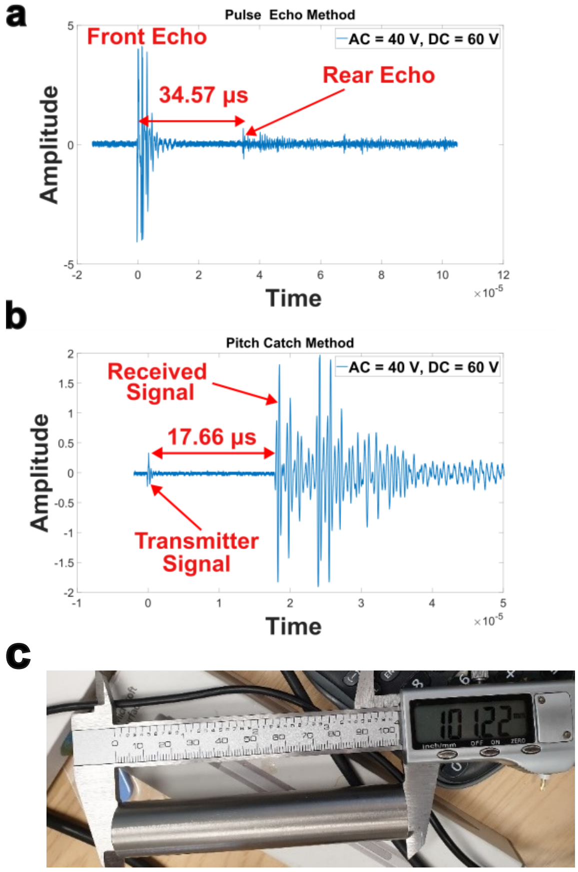

Fig. 4. (a) Received ultrasound signal plot using the pulse-echo method. **(b).** Received ultrasound signal plot using the pitch-catch method. **(c).** The actual length of the stain steel measuring using Vernier Calliper.

The time was divided by two because the echo signal travelled twice the length of the stainless steel. The actual length was measured using the Vernier Caliper, as shown in Fig. 4(c). Moreover, in this setup, the received signals were also attenuated by 20 dB due to the bidirectional RF attenuator. Therefore, for any received signals, the amplitudes were attenuated by 10.

B. *Pitch-catch measurement results*

Fig 4. (b) represents both transducers' transmitted and received signals. The transmitted signals displayed on the oscilloscope were 0 in the time domain, representing the signals sent from the transducer transmitter. The second signals represent the received signals in the received transducer.

The signal keeps bouncing back in the received transducer, and a large amplitude was obtained at the stainless steel's back surface. The bouncing signals can be reduced by applying multiple pulses to the input signal in the transmitter transducer. The second solution for reducing the bouncing signals is applying a signal in the transmitter transducer with a frequency close as possible to the natural resonance frequency of the CMUT.

The time difference between the transmitter and receiver was when the ultrasound signals travelled from the transmitter transducer to the receiver transducer. The first received signal by the receiver transducer was at 17.66 μs, where the value was half of the value obtained when the pulse-echo experiment was done. The difference between the pulse-echo experiment and the pitch-catch experiment was the time of flight and the number of transducers. The calculation of the length of the stainless steel using the pitch-catch method is as follows:

$$D = 6035 \times 17.66 \times 10^{-6} = 106.55\ mm$$

The actual length of the stainless steel was measured using the Vernier Caliper.
Table I compares the length of the stainless steel using different methods.

TABLE I: COMPARISON OF MEASUREMENT RESULTS

Method	Length (mm)	Error (%)
Actual Measurement (Vernier Caliper)	101.22	-
Pulse-Echo	104.33	3.07
Pitch-Catch	106.5	5.21

IV. CONCLUSION

CMUTS are a powerful tool for ultrasonic non-destructive testing. CMUTs required both AC and DC signals for best performance. DPR300 pulser/receiver had the full front-end electronics required to excite the transducer and receive the ultrasound signals. A single CMUT transducer was utilized for the pulse-echo method using DPR300 pulser/receiver. The signal was transmitted and received via the same transducer and calculated the length of the stainless steel. The difference between the transmitted and received signals was the time of flight used to calculate the stainless-steel length. The second experiment used a separate transducer to transmit and receive the ultrasound signals. The length of the stainless steel measured by the Vernier Caliper was calculated and validated using Pulse-Echo and Pitch-Catch methods. The electronic circuit can be reduced to a miniaturized PCB board that will replace many bulky instruments used in these experiments. An FPGA with a PCB board is an excellent option to replace the DPR300, power amplifier and function generator.

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