Title: **Acoustic emission sensing using MEMS for structural health monitoring: Demonstration of a newly designed Capacitive Micro machined Ultrasonic Transducer**

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## ABSTRACT

Among the various experimental techniques used for Structural Health Monitoring (SHM), acoustic emission (AE) allows real time monitoring of large structures with the possibility to detect, characterize and locate damages. In practice, its implementation can be complex, especially for mobile structures. The main difficulties are related to the integration of sensors in the structure, electrical interconnections, different sources of noise, the detection and processing of transient signals and the management of massive data streaming.

Generally, AE are collected through piezoelectric sensors. We propose an AE-based SHM methodology using an alternative technology in breakthrough with piezoelectric transduction: Capacitive micro-machined ultrasonic transducers (CMUTs). These sensors have many advantages. One advantage lies in the size of the sensors allowing a little intrusive integration into the material.

Following a previous work published in EWSHM'18, we report on the design, fabrication, and experimental demonstration of a new CMUT transducer specifically designed for the measurement of AE events. A data preprocessing methodology dedicated to interpret the obtained AE streaming is presented. We compare the results with standard piezoelectric sensors to detect damages during tensile tests on composite plates.

## 1 INTRODUCTION

Before 1998, conventional transducers used at highest frequency was piezoelectric material (Lead Zirconium Titanate) with 35 Mrayls acoustic impedance, which is $10^4$ bigger than acoustic impedance of air (about 0.0004 Mrayls). Thus, there is an acoustic impedance mismatching which causes loss of energy (received or emitted) if there is no matching layer. Matching layers material with low attenuation, with right acoustic impedance and are easy to work are not available.

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Haller and al [1] presented electrostatic ultrasonic transducer for the first time on 1994. The goal was to use ultrasonic transducer to generate ultrasound in air. Indeed, to achieve maximum resolution, it is necessary to operate at highest frequency, which is limited by attenuation of sound in air (about 1.2 dB/cm/MHz). On 2002, Fraser [2] presented capacitive micro-machined ultrasonic transducers for medical imaging with improved signal response. Belonging to the family of electromechanical microsystems (MEMS), they inherit in particular the advantages of microelectronics: ease in mass production, miniaturization, flexibility and therefore, integration into complex devices and different topology.

On 2006, Ozevin et al [3] developed capacitive MEMS for Structural Health Monitoring (SHM) specifically for Acoustic Emission (AE) method operate from 100 to 500 KHz. On 2009, Wright [4] optimized the sensitivity of the developed transducer by reducing disparity between capacitive MEMS –AE and conventional piezoelectric AE transducer. H Saboonchi and D Ozevin [5] compare MEMS –AE transducers manufactured using electroplating technique with piezoelectric transducers with similar frequency range (50-200 KHz). The result of experiment, show the good sensitivity of capacitive MEMS AE transducers. However, the transducers are sensitive to a unique wave direction, which can be disadvantage for damage detection inside materials. In various structure and materials, such aerospace [6], civil infrastructure [7] real time sensing has been described.

This paper examines the possibility of using a newly designed Capacitive Micro machined Ultrasonic Transducer (CMUT) for Structural Health Monitoring. Several groups have work on manufacture of CMUT [8] [9] [10] [11] [12]. We chose a Multi-User Micro-Electromechanical Systems (MEMS) Processes (MUMPs) for manufacture our CMUT transducers available in large universities and companies with lower coast.

Following a previous work published in EWSHM’18 [13], we report on the design, fabrication, and experimental demonstration of a new CMUT transducer specifically designed for the measurement of AE events. In the first section, we presented the CMUT principle and design chose. The experiment of electrical and acoustical characterization are presented on section 2 with a brief setup presentation. A comparison between CMUT-R100 manufactured and two piezoelectric transducers is finally presented.

## 2 DESIGN AND MANUFACTURING

The Capacitive Micro machined Ultrasonic Transducers (CMUT) is composed of a periodic network of elementary cells all connected in parallel by the pooling of their electrodes. All of these cells constitute a chip element, analogous to the piezoelectric transducers (Figure 1). The elementary cell has a structure close to that of a capacitor with upper movable membrane, which can move in the cavity (gap) above, which it is, suspended (Figure 1). The mechanical properties and geometry of the membrane control the bandwidth frequency.

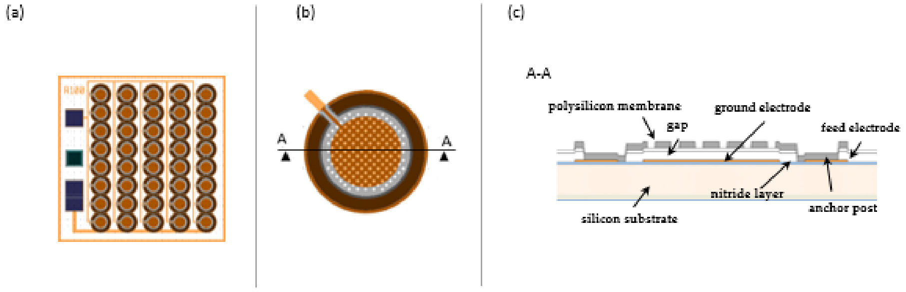

Figure 1: Chip element (a), elementary cell (b) and sectional view(c)

When Direct Current voltage $V_{DC}$ is applied to the membrane, an electrostatic force attracts the electrodes towards each other, which causes the deflection of the movable membrane towards the bottom of the cavity until equilibrium of the forces in presence (polarization of the cell). The resonance frequency and the sensitivity of CMUT are controlled with the bias voltage applied to the membrane. Conversely, an acoustic wave reaching the membrane causes a vibration, a variation of electrostatic capacitance and consequently a measurable electric current depending on the acoustic power of the incident wave.

The resonant frequency for circular plate membrane with radius $a$ are calculated using Leissa expression [14] , it is presented in previous work in P. Butaud et al [13] with radius $a = 100\ \mu m$, Young's modulus $E = 160 GPa$, the plate thickness $h = 1.3\ \mu m$, Poisson's ratio $\nu = 0.22$ and the mass density per unit area $\rho = 2330\ kg/m^3$. To control the resonance frequency $f$ and the collapse voltage $V_{collapse}$, we have to adjust the radius $a$ , indeed the density and thickness of membrane are determined by the MUMPs process.

We present the design of circular cells with 100 µm radius of the movable membrane Poly2 to cover a large frequency bandwidth, called later on a “CMUT-R100”. This characteristic are chosen as a first experiment to cover the frequency band from 280 KHz to 480 KHz. The CMUT chip element is 2.5x2.5 $mm^2$ area and 0.6 mm height with 40 elementary cells on it (figure 2).

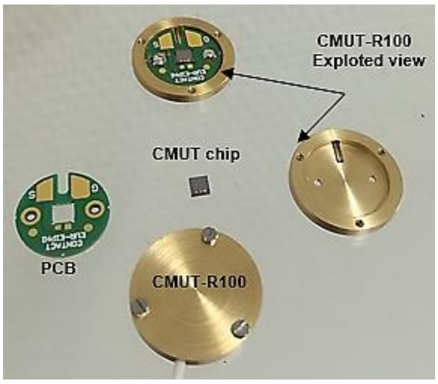

Figure 2: Prototype CMUT-R100

The experimental characterization presented at the next topic concerned elementary cell of CMUT-R100.

# 3 ELECTRO MECHANICAL CHARACTERIZATION OF CMUT

## 3.1 *Electrical characterization*

The optimum operating point of CMUT is controlled by the collapse voltage, and this parameter is critical for CMUT. The bias voltage is adjusted between 0V to collapse voltage. With a synthesizer function generator (Helwett Packard 3325 B) we applied $V_{AC}$=0.5V peak-to-peak. We measured the maximum signal amplitude of CMUT-R100 with laser Polytec vibrometer. In figure 3, we observed the amplitude signal and resonance frequency for CMUT-R100 elementary cells as function of $V_{DC}$ bias.

We can see the amplitude of vibration increases with the $V_{DC}$ bias while the frequency resonance decrease. The collapse voltage equals 85 volts $V_{DC}$.

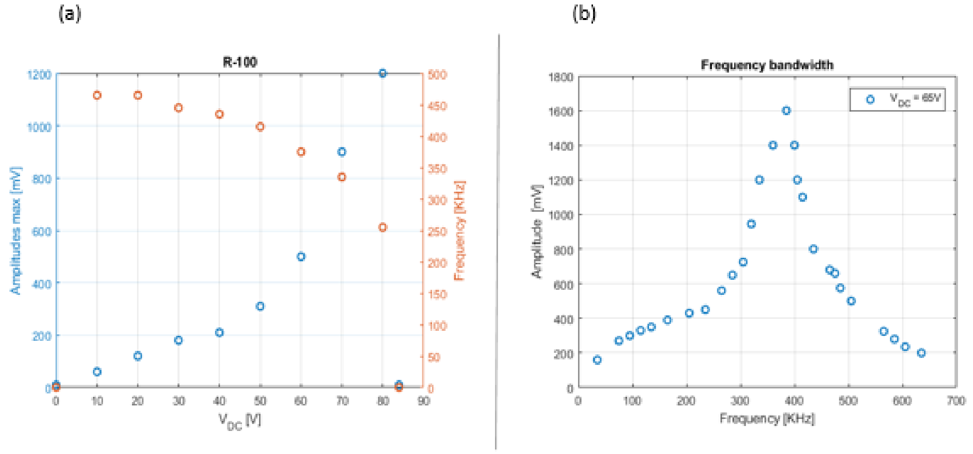

Figure 3: Maximum signal amplitude and corresponding resonance frequency as function of the $V_{DC}$ voltage (a) and CMUT-R100 frequency bandwidth at 65 Volts

In figure 3-a, we observe the dependence of resonance frequency with the DC bias. It is important to choose a DC bias, which can correspond to the desired resonance frequency. The sensitivity of CMUT correspond to the frequency bandwidth.

For bandwidth frequency characterization, we applied 80% of collapse voltage, which correspond 65 Volts. We used the same experimental setups, which is described, at the previous section. In frequency bandwidth characterization, we increased the frequency from 50 KHz to 650 KHz. We can observe in figure 3-b, the frequency bandwidth of CMUT-R100 at 65 Volts $V_{DC}$. At 50% of maximum resonance frequency amplitude, the frequency bandwidth is 195 KHz (from 300 KHz to 495 KHz) and 385 KHz for resonance frequency. The resonance frequency is dependent to the bias voltage $V_{DC}$ applied, in contrary to the bandwidth.

## 3.2 *Acoustical characterization*

For acoustical characterization, a broadband excitation at 600 KHz center frequency is generated with ultrasonic piezoelectric transducer Micro-80/E from Mistras Group Ltd with 9 mm diameter and 11 mm height. We observe the acoustic wave propagated through 30 mm width, 200 mm and 3 mm height aluminum beam with CMUT-R100 and second Micro-80/R piezoelectric sensor (Figure 4).

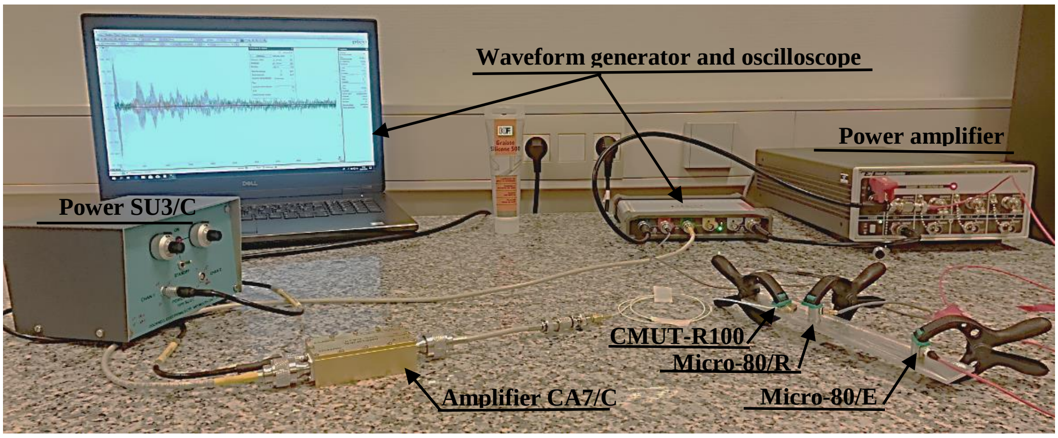

Figure 4: Acoustical characterization setup

Six sine wave windowed signal excitation is used at 600 KHz using a waveform generator picoscope 4825 with 5 Mega sample per second and amplified with Tabor Electronics 9100A with a fixed gain of 50. We applied 65Volts $V_{DC}$ on the CMUT-R100 with Cooknell SU3/C and CA7/C gain charge amplifier.

Morlet Continuous Wavelet Transform (CWT) of temporal signal is show in figure 5. In this experiment, the first piezoelectric Micro-80/E is used as source of Lamb waves. The Morlet CWT show the time arrival of the first symetric and antisymetric Lamb wave modes ($s_o$ and $a_o$) is the same for CMUT-R100 and the micro-80/R piezoelectric reception transducer. We can also notice, the frequency of the signal received is the same for both transducers with more sensitivity in CMUT-R100 (more signal detected). The difference between two transducers is the amplitude of received signal. Indeed, for the first wave mode the piezoelectric Micro-80/R transducers receive maximum amplitude 0.25 Volts against 0.03 Volts for CMUT-R100. This difference can decrease with diminution of energy loss (impedance adaptation between CMUT-R100 and plate) and/ or increasing the number of elementary cells. However, Figure 5; show clearly the feasibility of using CMUT-R100 on real time acquisition compared with Micro-80/R.

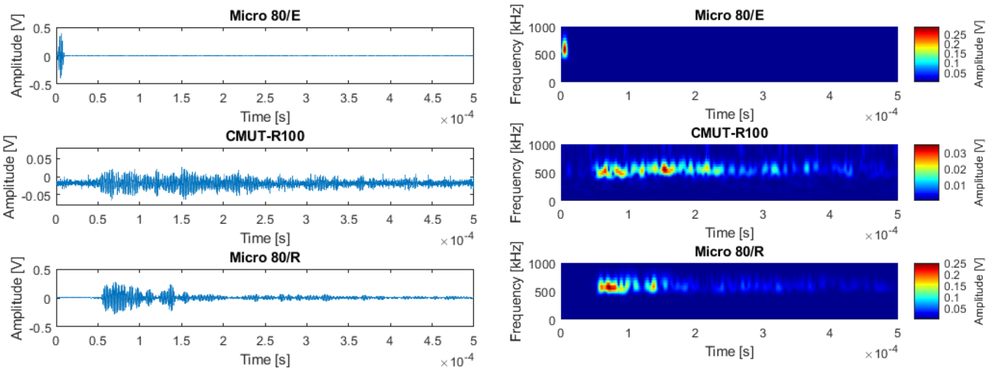

Figure 5: Temporal signal for micro-80/E (a), and detected with micro-80/R (b) and CMUT-R100 (c) and here zoom

# 4 RESULT OF CMUT UNDER TEST AND CAMPARISON WITH PIEZOELECTRIC TRANSDUCERS

After showing in previous paragraph the feasibility of using CMUT-R100 for Lamb wave detection and for AE applications. We present on the following works the first results of mechanical test using CMUT-R100 for AE detection.

## *4.1 Tensile test on flax /epoxy*

The experimental arrangement is shown in figure 6. Two piezoelectric transducers (Micro-80/E and Micro-80/R) and CMUT-R100 was placed on 240 x 25 x 2 mm unidirectional flax /epoxy composite plate manufacturing by thermo-compression. The CMUT-R100 was connected via CA7/C Charge amplifier. This receiver amplifier both applied DC voltage of 65 V for reception sensitivity of CMUT-R100 and for recorded the received signal. The signal of piezoelectric transducers as also amplified by 20 dB Mistras low noise amplifier. The waveforms were recorded by using a PC oscilloscope (picoscope 4824) by Pico technology with 20MHz bandwidth and 12-bit resolution. The three transducers was coated into the plate with industrial coupling gel (Silicon 500) and attached with a spring clamp to ensure good transmission of the signal.

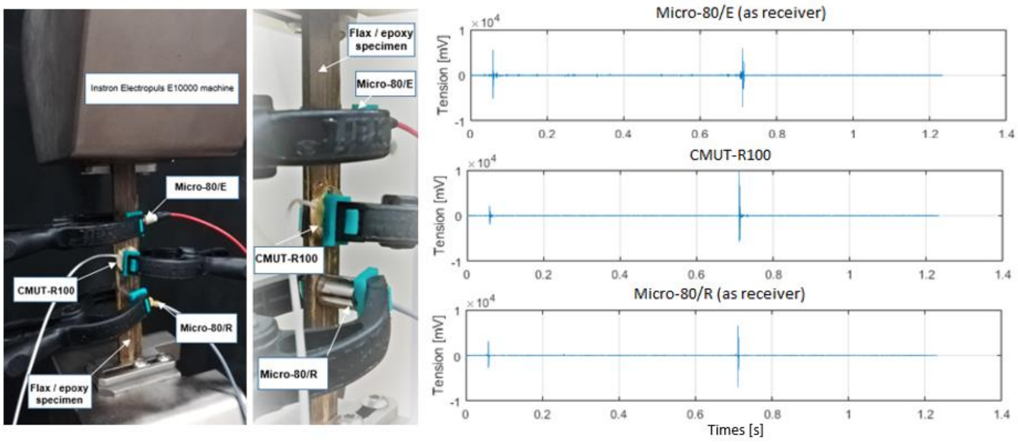

Figure 6: experimental arrangement of tensile test and AE events at the end of test

MTS Criterion machine equipped with 100 kN load sensor control 0.1 mm/s axial displacement up to failure of the flax/epoxy plates are used. Streaming data of AE signal was recorded during 50 seconds (duration of the test). With a wavelet denoising approach adapted from [15], we show on figure 7, the evolution of the AE signal amplitude and the centroid frequency detected with the three transducers.

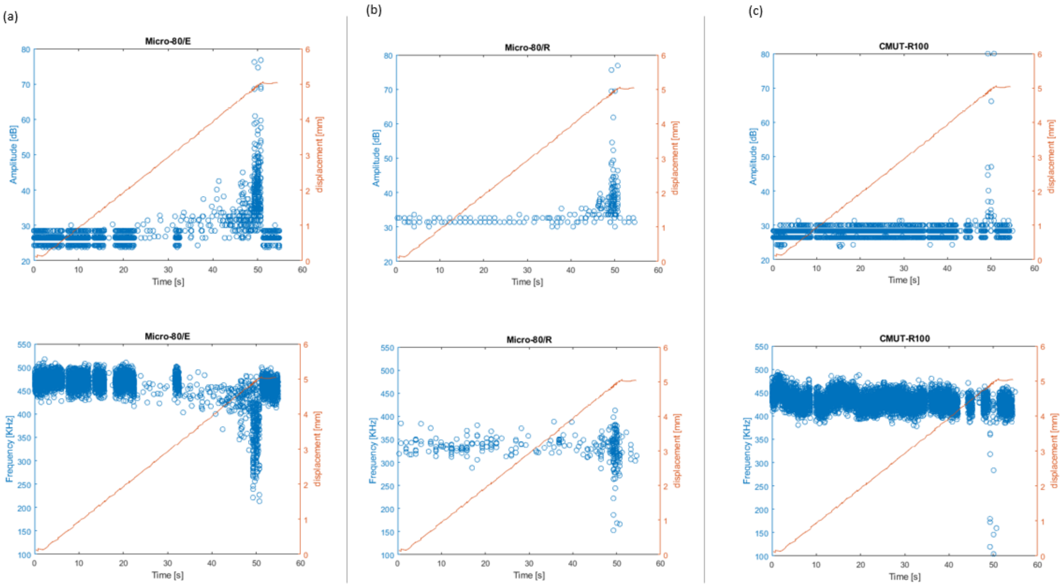

Figure 7: Amplitude and centroid frequency features of AE data streaming as function on test time (bleu) and displacement as function on time (red)

For three transducers, AE events are observed at the end of the tensile test before the failure of flax/epoxy plate. Before, amplitude is between 20 and 30 dB, which correspond to the noise of instrumentation. For the centroid frequency feature, both CMUT-R100 and Micro-80E present an important AE activity compared with Micro-80/R. Indeed, the sensitivity of Micro-80/E piezoelectric transducers bandwidth (200 to 900 KHz) is more important than Micro 80/R (300-500 KHz) and CMUT-R100 (300 to 495 KHz).

## 5 CONCLUSION

A newly designed capacitive ultrasonic micro machined transducer has been presented. The CMUT-R100 has been manufacturing from Multi-User Micro-Electromechanical Systems (MEMS) Processes (MUMPs) based on micromachining technology (run #124). For the dimension of CMUT-R100, testing has indicated good results with a good signal noise ratio. This make the CMUT-R100 good candidate for Structural Health Monitoring (SHM) and Acoustic Emission (AE) applications. Indeed, the results shown the capability of CMUT-R100 to detect Acoustic Emission on 3 mm height aluminum plate and detect symmetric and asymmetric Lamb wave. Furthermore, they have been compared with piezoelectric transducers and it shows the capability of these capacitive transducers to be an alternative solution for the detection of AE events with high potential of integration.

This paper is the first step to improve the CMUT-R100 device presented on EWSHM 2018 [13]. This study shows also the limitation of these devices. Indeed, compared with piezoelectric transducers, the amplitude of detected AE signals remains lower which can be improved by increasing the number of cells and by optimizing the electrical impedance matching according to the frequency bandwidth required.

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