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Bordering the footprint of AE sensor using a bank of sharply-defined frequency domain capacitive micromachined ultrasonic transducers

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Abstract

The Acoustic Emission (AE) technique is widely used in Structural Health Monitoring (SHM) in order to detect, in real-time, small-scale damages and to evaluate their kinetics. The piezoelectric transduction is generally favored for detecting the subnanometric displacements of the surface of a material induced by the propagation of the elastic waves generated by the sudden release of energy during damage. Yet highly sensitive, this type of sensor has a great impact on the signals collected introducing interpretation biases when assigning damage families to AE signals. In this paper, new Capacitive Micromachined Ultrasonic Transducers (CMUT) have been designed and tested with the objective to decrease the footprint of AE sensors compared to conventional piezoelectric sensor. CMUT allow getting AE sensors with wide-band and flat response making them of great interest for the collection of AE signals in SHM solutions.

1. Introduction

Structural Health Monitoring (SHM) aims at anticipating failures on mechanical structures and thus performing maintenance at the right time and place. For SHM of composite structures, the Acoustic Emission (AE) has been widely used. The objective of AE based SHM is to detect the damage of the composite and more importantly identify it: to distinguish between fiber breaking, delamination or matrix cracking for example. For this purpose, AE sensors used for SHM have to be well chosen to provide sensitive detection of structural degradation. This is especially important since several authors rely on the amplitude level (1-3) or on the frequency signature (4-6) of the AE signal to define the nature of the mechanical damage. It therefore seems essential that AE sensors used do not alter the acoustic signal generated by the damage.
The footprint of AE sensors is an issue already mentioned and discussed. A solution is to measure the transfer function of the AE sensor used (7-8) and then to perform in a second phase a deconvolution of the acoustic signal (9). Nevertheless, the deconvolution is an ill-posed problem and the results are often unstable. In order to mitigate the deconvolution limits, new inverse methods (10-11) exist. Another solution, proposed and studied in this paper, is to use AE sensors with a better-controlled footprint.
The AE sensors investigated here are Capacitive Micromachined Ultrasonic Transducers (CMUT). This kind of sensors have proven their efficiency in SHM applications in the works of Ozevin et al. (12) and Hutchins et al. (13). They have shown that, in spite of a low signal-to-noise ratio compared to the piezoelectric transducer, the CMUTs are able to detect AE events. In our work, the CMUTs of interest have been developed by Galisultanov et al. (14) and the technology is presented in the next section. An experimental setup is then proposed to border the footprint of two different AE sensors.

For that, a comparison is made between the classical piezoelectric transducer and the CMUT according to their continuous wavelet transform which can or not match the one of the AE source. Finally, conclusions on upsides and downsides of each technology are drawn.

2. Materials and methods

2.1 CMUT sensor

A CMUT is an electrostatic transducer consisting mainly of a vibrating membrane acting as a sensor/receiver of acoustic waves like a microphone. The vibroacoustic characteristics of a CMUT cell in terms of center frequency, amplitude of vibration and impedance are determined by the geometric, mechanical and electrical properties of the membrane. The chip is composed of several capacitive membranes of different diameters. The design of one membrane is presented in Figure 1.

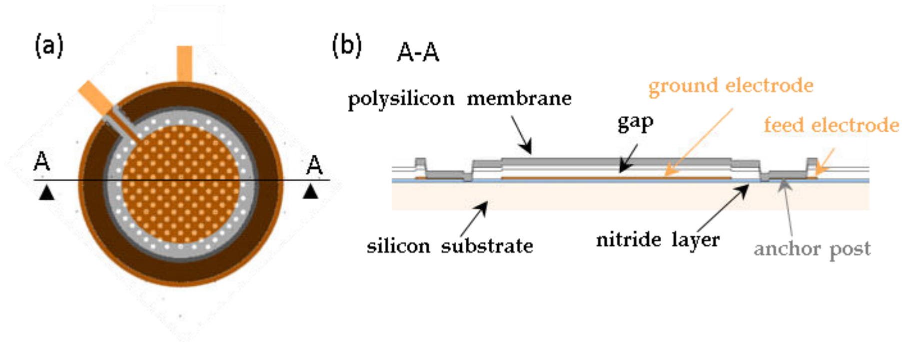

Figure 1. Top (a) and sectional (b) views of a typical membrane layout.

The diameter of the membranes varies between 50 µm and 350 µm and hence the associated resonance frequencies between 50 kHz and 2.4 MHz. The dimensions of the chip are 5×5 mm² and 0.6 mm height, with more than 60 membranes on it. The membranes are alone or associated with others by family to expect more amplitude variations under acoustic excitation. For convenience, in next sections, only results on the membrane of 150 µm are presented.

2.2 Experimental setup

Two sensors are tested: a piezoelectric sensor Micro80 from Physical Acoustics©, and the CMUT sensor from an in-house high-tech development based on MEMS technology (MUMPS). The Micro80 sensor is deemed to have a good frequency response over the range of 200-900 kHz and a resonance frequency of 325 kHz. Its dimensions are 9 mm of diameter and 11 mm of height.
In order to border the footprint of these AE sensors, a basic experimental setup is proposed based on acoustic waves propagation through an aluminum beam. The aluminum beam considered is 200 mm length, 30 mm width and 3 mm height. Both sensors are glued on the beam at 30 mm from the end (Figure 2). The Micro80 signal is recorded directly on the oscilloscope. The CMUT chip behavior is studied through a laser vibrometer (Polytec OFV-5000) pointed on the middle of the membrane of interest.

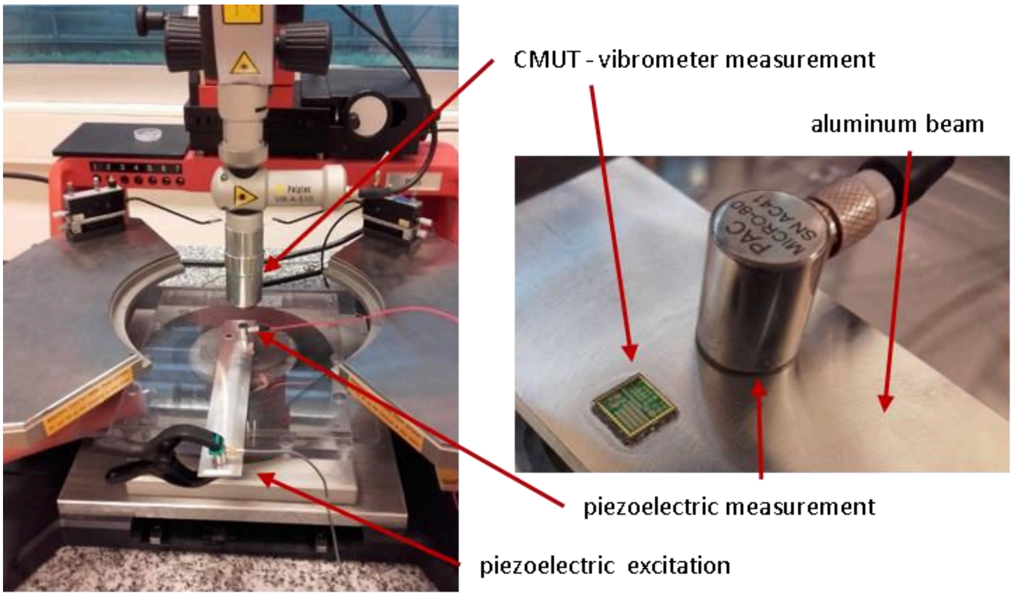

Figure 2. Experimental setup: acoustic emission through an aluminum beam, measurement with piezoelectric sensor and laser vibrometer on CMUT membranes.

Two kinds of excitations are used to characterize the sensors. Firstly, a broadband excitation is performed with a pencil lead break. Secondly, a monofrequency excitation is performed at 300, 500 or 900 kHz through a wave packet composed of five sinus periods (Figure 3). The monofrequency excitation is obtained with a piezoelectric transducer Micro80 used as transmitter, mounted on the beam, at 15 mm from the edge, with a spring clamp to ensure a permanent contact. The input signal of the transducer is created using a waveform generator (Tabor Electronics 5064, 100 MS/s) and a power amplifier (Tabor Electronics 9400, with a fixed gain of 50).

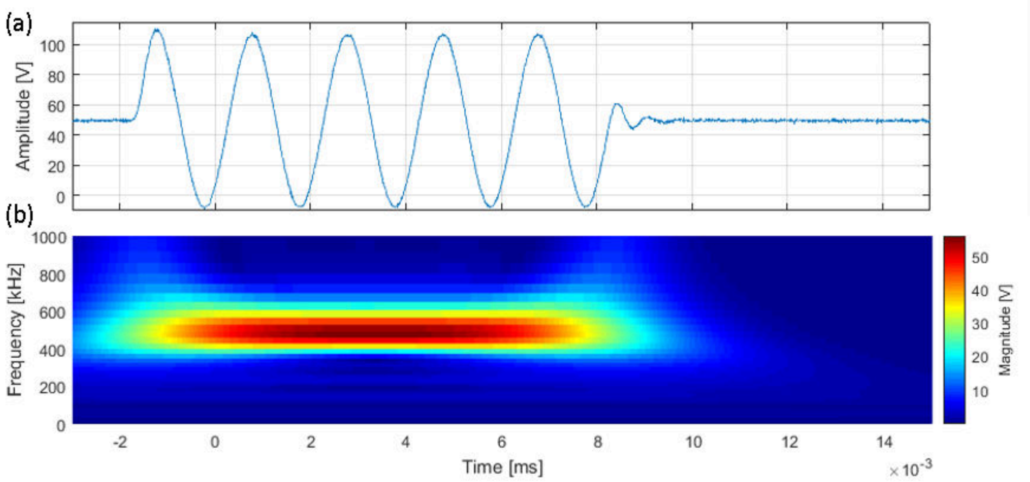

Figure 3. Excitation (a) temporal signal at 500 kHz (b) Morlet continuous wavelet transform

It has to be mentioned that the transducer will have an impact on the input signal, and so the excitation will not be perfectly known, nor pure in the frequency domain. In the next section, for convenience, only results at 500 kHz are presented, but the conclusions are the same for the other frequencies. The Figure 3 presents the monofrequency excitation at 500 kHz: in the top, the temporal signal, in the bottom, the Morlet continuous wavelet transform (obtained with the cwt function of Matlab®).

3. Experimental results

3.1 Pencil lead break excitation

In this part, the behavior of the two sensors is studied in respect to a broadband excitation. This excitation is obtained with a pencil lead break performed on the aluminum beam.

3.1.1 Piezoelectric Micro80 response

The Figure 4 shows the temporal signal measured with the Micro80 piezoelectric transducer and presents the associated Morlet Continuous Wavelet Transform (CWT) of this signal. As the excitation is a broadband excitation, it should be expected a CWT with all the frequency band at the same magnitude. However, it can be observed a higher magnitude in the CWT centered on 300 kHz. It appears that this frequency corresponds to the one of the resonance frequency of the sensor. Thus, the acoustic signal measured by the piezoelectric transducer is not the acoustic wave propagating in the beam, but the transfer function of the sensor. This kind of excitation permits to highlight the footprint of the sensor.

3.1.2 CMUT response

The Figure 5 shows the temporal signal measured with the CMUT membrane of 150 µm of radius through the laser vibrometer. The Morlet continuous wavelet transform of this signal is also presented. Two frequency zones emerge: one centered on 230 kHz, which corresponds to the resonance frequency of the first mode (0,1) (only one nodal circle corresponding to the clamped peripheral edge) of the membrane, and a second one around 800 kHz which corresponds to the frequency of the sixth mode (0,2) of the membrane. Once again, as for the piezoelectric transducer, the sensor cannot detect the actual acoustic wave propagating in the beam. Indeed, with this kind of excitation, only the transfer function of the sensor is measured.

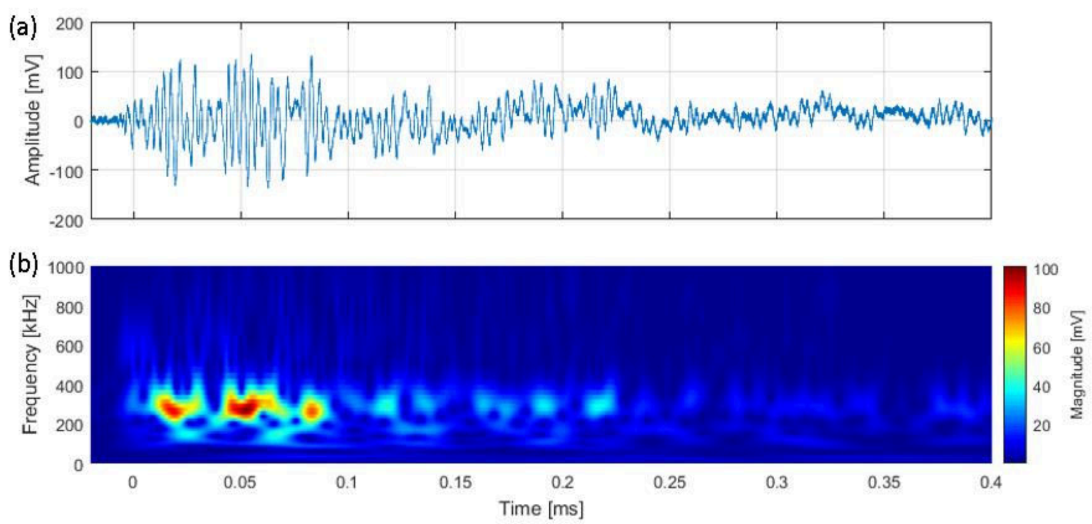

Figure 4. Piezo – pencil lead break, (a) temporal signal, (b) Morlet continuous wavelet transform.

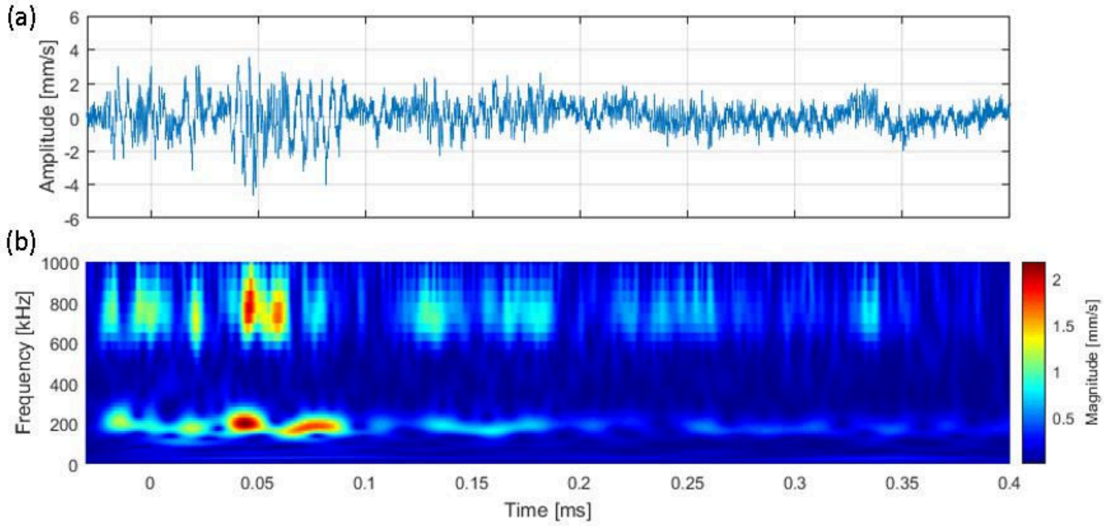

Figure 5. CMUT – pencil lead break, (a) temporal signal, (b) Morlet continuous wavelet transform

3.2 Harmonic excitation

In this part, the behavior of the two sensors is studied in respect to a monofrequency excitation at 500 kHz (Figure 3).

3.1.1 Piezoelectric Micro80 response

The Figure 6 shows the measurement performed with the Micro80 piezoelectric transducer. As the excitation is at 500 kHz, it is expected a CWT centered on this frequency. Nevertheless, the frequency resonance of the sensor around 300 kHz is again involved in addition to the excitation frequency. Thus, it will be difficult to distinguish the different contributions resulting from the damage in the structure on the one hand and the footprint of the sensor itself on the other hand. For a SHM approach, it seems then complicated to obtain accurate information on the damage in the structure with piezoelectric sensors without an advanced deconvolution procedure.

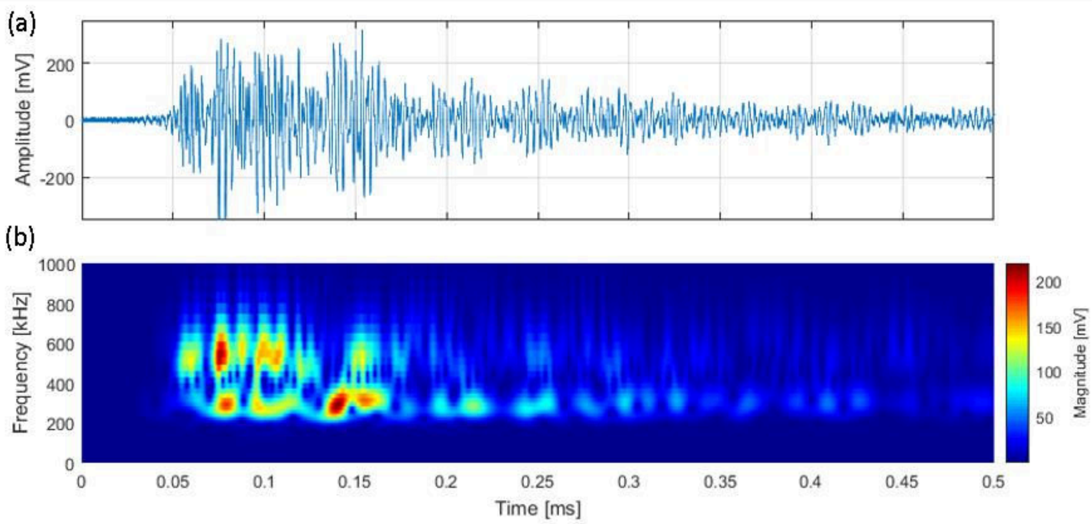

Figure 6. Piezo at 500 kHz, (a) temporal signal, (b) Morlet continuous wavelet transform.

3.1.2 CMUT response

The Figure 7 shows the measurement obtained on a CMUT membrane of 150 µm of radius. This time, only the excitation frequency, at 500 kHz, is clearly involved in the CWT of the temporal signal. The footprint of the CMUT does not corrupt the measured acoustic information. This kind of sensor seems then definitely suitable to assess the features of the acoustic signal propagating in the structure. It has to be mentioned that conclusions are the same with the other membranes (between 50 µm and 350 µm of radius): the CWT is still centered on the excitation frequency, only the magnitude is changing according to the radius of the membrane.

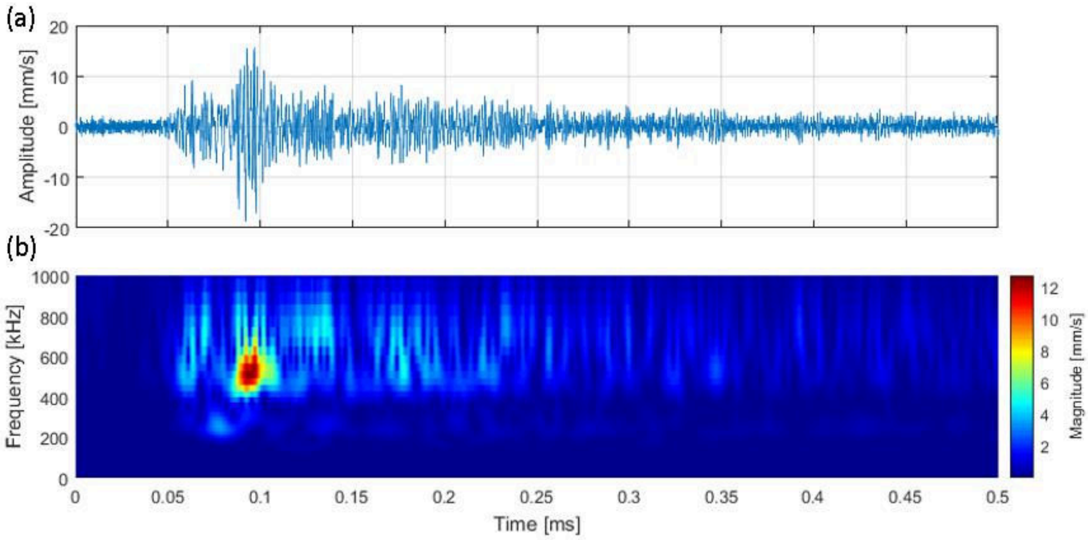

Figure 7. CMUT membrane 150µm, (a) temporal signal, (b) Morlet continuous wavelet transform.

3. Conclusions

Two kinds of excitations, broadband excitation and monofrequency excitation, are used to border the footprint of the piezoelectric and CMUT sensors. The signal post-processing features the limits of each technology according to the excitation type. Concerning the piezoelectric sensor, it has been observed that no matter which excitation sent, the Continuous Wavelet Transform (CWT) of the measured signal is centered on the resonance frequency of the sensor. On the contrary, the CMUT footprint depends on the excitation type involved. For a wideband excitation, the CWT of the CMUT signal is also centered on the resonance frequency of the membrane; but for a monofrequency excitation, the sensor does not corrupt the CWT and so the maximum amplitude of the CWT is obtained at the frequency of the input signal with an amplification depending on the diameter of the membrane. Finally, this work highlights the important potential of the CMUT sensor, which gathers lot of information on a microscopic surface.

Acknowledgements

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