Multifunctional piezopolymer film transducer for structural health monitoring applications

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P. Giannelli, *Student Member, IEEE*, A. Bulletti, and L. Capineri, *Senior Member, IEEE*

***Abstract*—This paper describes the design of a multifunctional transducer for structural health monitoring (SHM) applications that integrates an interdigital piezoelectric transducer (IDT), used for Lamb Wave generation and reception, a circular piezoelectric sensor, used for the detection and localization of low-velocity impacts, and a resistance temperature detector (RTD) in a single device. The three elements were fabricated on the same metallized piezoelectric polyvinylidene fluoride (PVDF) film using a laser etching process. Characterization of the resulting device proved the advantages of having different transducers on the same device, providing information useful to implement advanced SHM algorithms. Testing of the RTD highlighted some criticalities of the metallized PVDF film that prevented accurate temperature measurements due to spurious behavior under strain.**

***Index Terms*—Piezoelectric transducers, piezopolymer film transducers, structural health monitoring, Lamb waves, acoustic source localization, sensor integration.**

I. Introduction

THE structural health monitoring of critical components is a growing field of interest in the aerospace, transportation and automotive industries. Among the many techniques proposed by the scientific community, those based on acoustics/ultrasound have received considerable attention: passive impact detection and localization methods were developed in [1], while damage inspection techniques based on guided Lamb waves are described in [2]–[5].

In a previous work [6], the authors presented a SHM system that adopted arrays of piezopolymer (PVDF) IDTs to perform both Lamb wave inspection and impact localization (i.e. acoustic source localization) on a composite pressure vessel. The experiments performed with said system highlighted a couple of limitations that needed to be addressed to improve the accuracy of impact localization and damage detection. Using IDTs to perform impact localization introduced up to a few cm of positioning error due to their large active area and lack of circular symmetry (the transducers were rectangular, 24mm×40mm in size). When performing damage detection, the structure under test needed to be kept at a fixed temperature to avoid tainting the results of the algorithm [7], [8].

A new transducer was thus developed to address the issues mentioned above, by integrating together with our IDT a smaller circular piezoelectric sensor and a RTD. The additional sensing elements were mostly able to fit inside the unused area of the original design, and the final transducer required a PVDF film only 7.5% wider. The adoption of metallized piezopolymer film together with a versatile patterning technology based on laser ablation allowed the design of electrodes of arbitrary shape that could serve different purposes, such as capacitor plates and resistive paths.

This paper deals mainly with the design and characterization of the novel sensing elements of the proposed transducer. The reader is referred to a previous work by the authors [9] for a detailed description of the IDT part of the transducer.

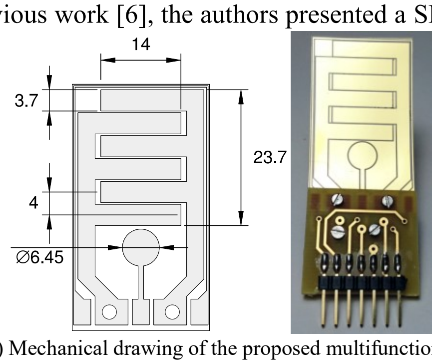

Fig. 1. (Left) Mechanical drawing of the proposed multifunctional transducer (dimensions in mm). The same electrode pattern is etched on both sides of the piezoelectric film; grey areas highlight the active electrodes. (Right) Picture of the manufactured transducer including the clamping board used to connect the electrode pads to the cable.

II. Multifunctional Transducer Design and Characterization

The base material used for our transducer was a 110µm-thick poled PVDF film with a nominal piezoelectric strain constant d_{33}=−30pC/N (thickness mode), metallized with a gold-chromium alloy on both sides (the film is manufactured by Precision Acoustics Ltd., UK). Patterning of the metal coatings was done through a laser ablation process that resulted in etching the same electrodes on both sides with self-alignment (the PVDF film is transparent to the beam).

Fig. 1 shows the complete electrode pattern designed for the proposed multifunctional transducer and a picture of the final device, including the feed electrodes which, clamped between two circuit boards (as shown in the picture), create a pressure contact. The figure distinctly shows the circular element and the IDT electrodes, while the RTD is barely visible, as it is

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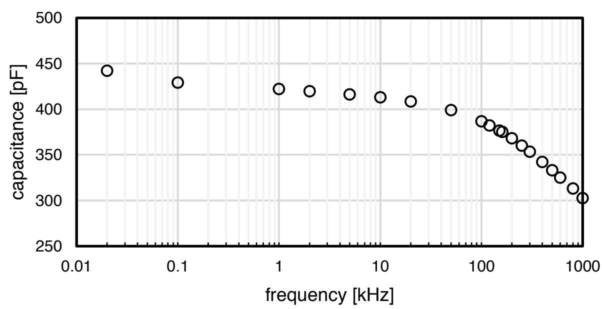

Fig. 2. IDT capacitance vs. frequency measured at 25°C.

constituted by a thin conductor (250µm wide) running along the border of the piezoelectric film.

A. Interdigital Transducer

The IDT design was based on the criteria reported in [9], and had geometrical dimensions similar to those adopted in [6], with the finger pitch of 4mm setting the peak response of the transducer at λ=8mm (see Fig. 1). This transducer is intended to be used in the frequency range 100kHz to 1MHz.

The capacitance of the IDT (free-hanging) was measured over frequency using a RCL meter (Keysight 4284A). The results are shown in Fig. 2. The decrease of capacitance with frequency is a typical characteristic of piezoelectric polymer films.

B. Circular Piezoelectric Sensor

The circular piezopolymer transducer was designed with diameter 6.45mm (1/4") to match the dimension of a commercial transducer manufactured by Acellent Technologies, inc. (SML-SP-1/4-0); this size makes these devices a good approximation of a point-like transducer at the wavelengths of interest for impact detection and localization [10].

The capacitance of this device (free-hanging) was measured with the RCL meter, and the results are shown in Fig. 3

The reception sensitivity of the circular transducer was compared to a piezoceramic device of similar dimension (a P-876.SP1 from Physik Instrumente GmbH). Both devices were used to receive a Lamb wave packet transmitted over an aluminum plate 1.2mm thick in the same experimental setup (coupling to the plate was done with double-sided tape, 200mm away from the source). The output signals, both acquired with the same custom instrumentation amplifier (gain 78dB@250kHz), are shown in Fig. 4. The peak output of the circular PVDF sensor is ~15 times weaker than that of the piezoceramic device.

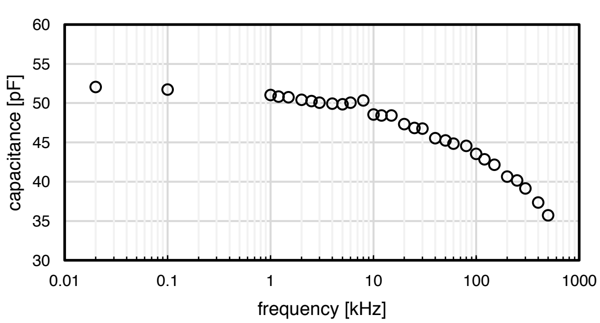

Fig. 3. Circular element capacitance vs. frequency measured at 25°C.

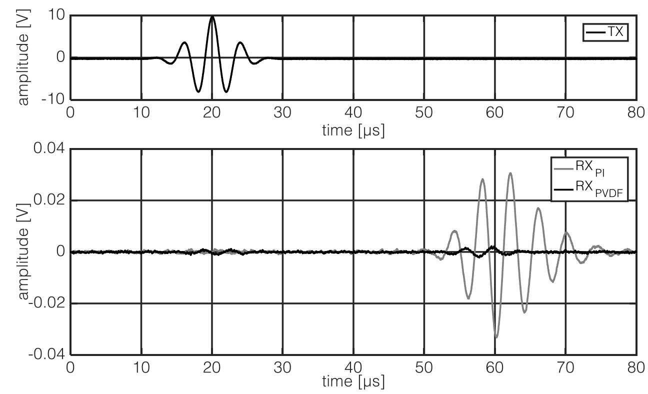

Fig. 4. Sensitivity comparison of the proposed circular element PVDF sensor with a commercial device of similar size (PI P-876.SP1). On top is the transmitted wavelet (Morlet centered at 250kHz), guiding medium was an aluminum plate 1.2mm thick, propagation path length was 200mm. The bottom plot shows the first S0-mode packet received by both transducers. The same amplifier was used in both cases.

Even though the test signal used for this comparison was centered on a frequency higher than the usual bandwidth targeted by these transducers (250kHz), the devices could still be considered reasonably small with respect to the wavelength, thanks to the high phase velocity of the S_0 mode (~5000m/s) at that frequency.

C. Resistive Temperature Device

The RTD was obtained by designing a conductor sufficiently thin and long to present a significant resistance at room temperature (around the hundreds of Ω). Since the characteristics of the metal coating of the Piezopolymer film were not known and, as will be shown later, have poor repeatability, it was difficult to predict the final resistance of the RTD at the design stage.

Our RTD, with a length of 93mm and a constant width of 250µm, yielded a resistance R_0=350Ω at 25°C. The resistance change with temperature was measured in an oven between 25°C and 60°C using a benchtop multimeter (Keysight 34410A). Fig. 5 shows the experimental results compared to the nominal response of a PT100 RTD.

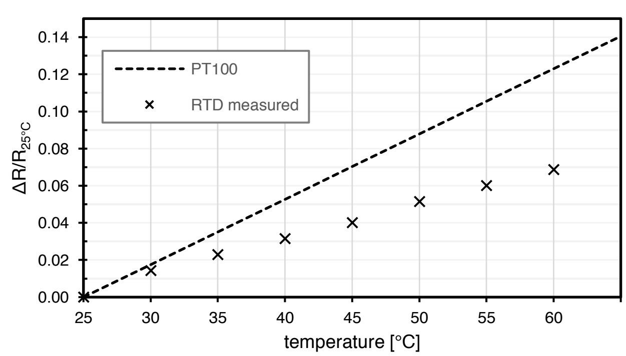

Fig. 5. Relative resistance change measured between 25°C and 60°C. The characteristic plot of a standard PT100 is shown for comparison.

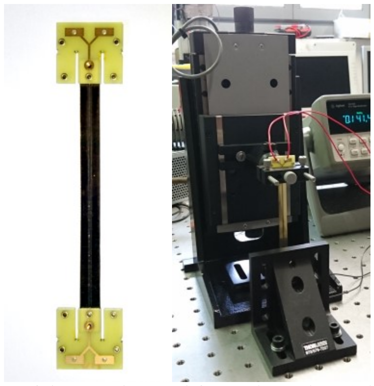

Fig. 6. (Left) One of the samples used for strain testing. (Right) Fixture used to manually strain the PVDF strips.

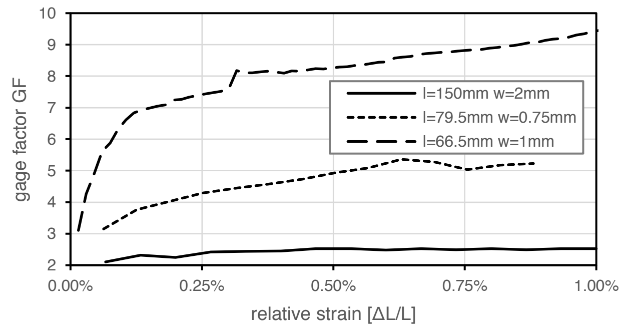

Fig. 7. Plot of GF w.r.t. relative strain of the sample. The legend lists length and width of the electrical conductor subject to strain. All tests were performed between 22°C and 23°C.

Further experiments were performed to assess the effect of transducer strain on the resistance change of the RTD. The relevance of this investigation lies in the existence of multiple physical effects that could result in straining the transducer during its normal operation. For instance, some variable amount of stress will be exerted by the structure to which the transducer is coupled during normal operation (either due to thermal expansion or other mechanical phenomena). For what concerns specifically the results shown in Fig. 5, the transducer was not coupled to a structure during the experiment, allowing it to thermally expand (the linear thermal expansion coefficient of PVDF is around $130\times10^{-6}K^{-1}$). Knowing the strain-induced resistance change of the sensor would allow the correction of the temperature measurements in the cases were such strain can be measured or estimated.

Several thin strips were cut from the same PVDF sheet and placed in a micro-positioner fixture to measure the gage factor (GF) of their metal coating at constant temperature. Fig. 6 illustrates the experimental setup, along with one of the test samples.

It was expected that the various samples would yield a similar GF when subject to the same relative strain, regardless of their actual dimension; the results shown in Fig. 7, however, did not confirm this hypothesis. The GFs belonging to different samples showed a remarkably wide value range, suggesting that the metal coating of the PVDF film was considerably uneven in its physical properties. This behavior was somewhat in line with the film manufacturing process, which used sputtering to metal-coat the polymer. These characteristics of the metallization are not a primary concern of the piezoelectric film manufacturers at present.

III. Conclusion

An extended version of piezopolymer IDT has been designed to include a circular element and an RTD on the same piezoelectric PVDF film, simply by etching the appropriate electrode pattern on the metal coating.

A prototype has been fabricated and tested with mixed results: while the circular element has shown the expected level of performance, the RTD has proven to be severely hindered by the inhomogeneous properties of the metal coating.

The results suggest that, while the idea of patterning additional sensors on the PVDF coating has merit, there are some technological problems that need to be addressed to ensure that the metal presents repeatable physical characteristics appropriate for building resistive devices.

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