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Printed PZT Transducers Network for the Structural Health Monitoring of Foreign Object Damage Composite Panel

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Abstract. The work presented here focuses on the structural health monitoring (SHM) of a foreign object damage (FOD) composite panel equipped with an innovative printed piezoelectric transducer network. The 3D woven composite FOD panel measures approximately 800 mm x 320 mm, is curved with a cross-sectional thickness varying from approximately 2 mm to 12 mm, and a stainless-steel leading edge is bonded at one of its sides. The core idea explored here is to rely on an innovative screen-printing technology to print a full piezoelectric transducer allowing to successfully achieve SHM on such a complex composite structure. This work is being carried out within the European project MORPHO – H2020. After printing a 25 elements PZT network, a four points bending fatigue experimental campaign using the PZT network along with other sensor technologies (embedded optical fibres with FBG sensors and acoustic emission sensors) is carried out. This unique experimental campaign allows to generate data and will help to develop diagnostic and prognostic methodologies for remaining life estimation and SHM of the FOD panel. It is demonstrated here through impedance measurements that the printing process associated with the printed PZT transducers is highly repeatable thus validating its use at a larger industrial scale. Furthermore, the printed piezoelectric transducers are shown to be able to detect foreign object impact and sense Lamb waves signals. This innovative printing technology for PZT transducers network is thus extremely promising. It is furthermore highly advantageous to use the printed transducers for SHM instead of regular ceramic ones as this technology is non-intrusive, add negligible weight, can be printed during the manufacturing process, and arrays of transducers ensure easy availability of another transducer in case of failure of one.

Keywords: Printed piezoelectric sensors, smart composite structures, guided waves,

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screen printing technology, MORPHO H2020

Introduction

The aviation industry is at the forefront of developing and deploying high strength yet light carbon fibre reinforced (CFRP) composite materials in its endeavours of sustainability and eco-efficiency. With this increasing emphasis on reducing environmental footprint, the demand of non-destructive evaluation and structural health monitoring (SHM) based on a variety of sensor data is also increasing rapidly.

Impact damages, such as bird impact on an engine fan blade, are one of the leading causes of damage initiation in structures. Since more than two decades, electromechanical impedance based techniques are being developed to estimate damages, for example impact, material degradation, crack, etc., in a number of aerospace, civil, and mechanical structures using piezoelectric sensors [1]. However, this technique is efficient in estimating only local damages close to the sensor and therefore requires a vast sensor network. A large number of techniques based on high frequency Lamb waves measurements using piezoelectric transducers have also been studied [2, 3, 4]. All these methods rely on the data collected from the number of externally bonded sensors located all over the structure under study.

One of the challenges in this regard is the development of smart structures and systems equipped with various sensors with minimal alteration to the structural behaviour to the host structures [5]. Consequently, the sensors should be small in size and as low in weight as possible in order to avoid local stiffness alteration. With the advancement in research of additive manufacturing, functional materials, micro and nanotechnology and other related fields, the development of a variety of sensors is also advancing rapidly.

The innovative printing technologies involving functional materials are promoting the development and integration of customized sensor for various applications. The use of this technology allows direct printing of sensors on planar, non-planar, metallic as well as composites surfaces [6, 7]. Screen printing is a potential technology that can achieve good results in terms of accuracy, reliability, and be cost effectively incorporated in the manufacturing stages of a structure. In this work, we discuss the fabrication process and demonstrate the working of novel screen printed piezoelectric sensors on a 3D woven composite panel. The composite panel is a foreign object damage substructure of an aircraft engine fan blade. The electromechanical impedances of the printed sensors are first studied, followed by their response to impact with an aim to estimate damage location. The ability of the printed sensors in sensing guided waves is also discussed in this work.

1. **Fabrication of Printed Piezoelectric Sensors**

The 3D woven composite FOD panel measures approximately 800 mm x 320 mm, is curved with a cross-sectional thickness varying from approximately 2 mm to 12 mm, and a stainless-steel leading edge is bonded at one of its sides. The piezoelectric sensors are fabricated using the state of the art screen printing technology in 3 layers comprising of a top electrode, a central sensing piezoelectric layer, and a bottom electrode. Both the electrodes are printed using a silver conductive paste, 1901-SB by ESL Europe. The piezoelectric layers were printed using a lacquer from the ALGRA Group. All the pastes used in this process consist of a binder system, elemental or pre-alloyed powders, and some additives. Five arrays with 5 sensors each are printed on the FOD panel, one each at pre-determined locations close to the left leading edge (LLE), left trailing edge (LTE), centre (C), right leading edge (RLE), and right trailing edge (RTE) of the FOD panel, as shown in Fig. 1. The sensors in each of these arrays are identified as LLE, LTE, C, RLE, or RTE depending on their locations followed by numbers 1 to 5 with 1 corresponding to the leftmost sensor in an array and 5 corresponding to the rightmost sensor henceforth in this work. Each sensor has the diameter of 15 mm and the pitch between sensors in an array is 25 mm.

After printing, the structures are subjected to electric field of 400 V for half an hour for alignment of the dipoles in the piezoelectric layer. Finally the connecting wires are connected to the printed electrodes using conductive paste.

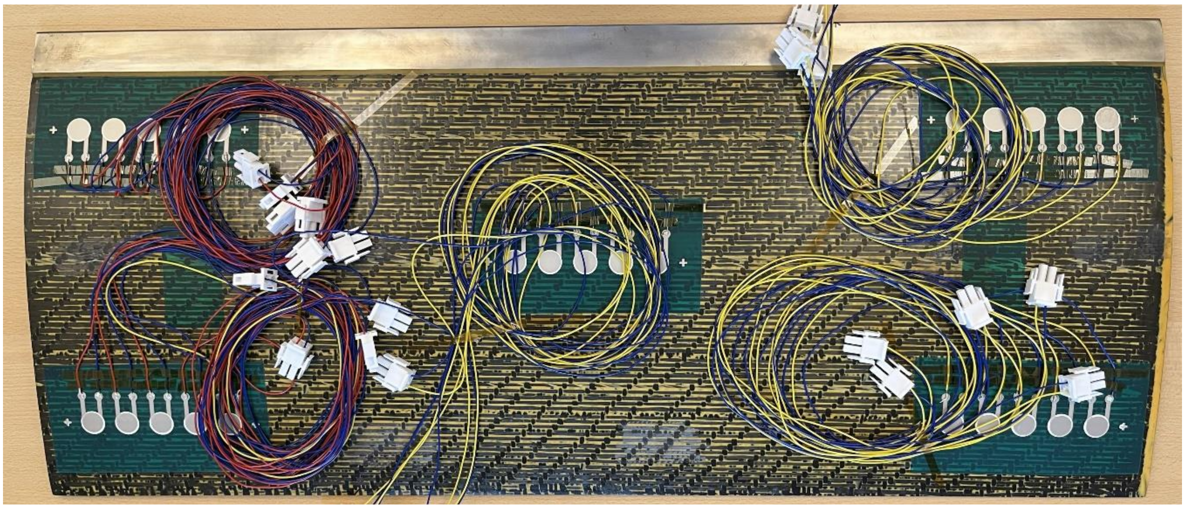


Fig. 1. Fully sensorized FOD panel with five printed sensors arrays plus connecting wires for data acquisition

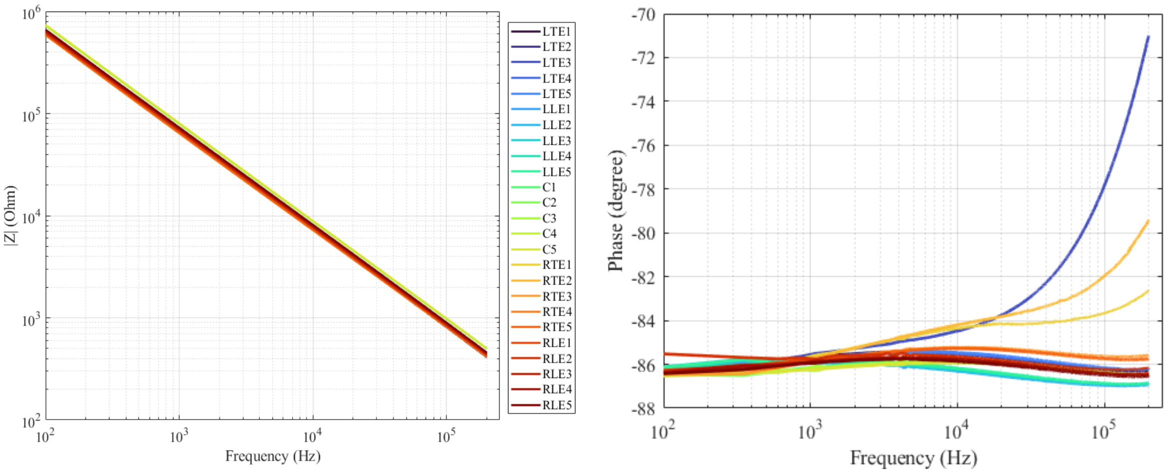
2. Experiments, Observations, and Discussions

Three studies are performed here with the aim to develop methodologies to ensure that the printed PZT are working well and the for damage monitoring purposes. Firstly, electromechanical characterization of the printed sensors is carried out by measuring their impedances over a range of frequencies in order to ensure that the printed PZT are behaving electrically as expected. Secondly, an impact test is performed on the FOD panel using a drop impactor setup and the printed sensors are used to measure the response. Finally, the ability of the printed sensors to sense guided waves generated using ceramic piezoelectric disc transducers is studied.

2.1 Electromechanical Characterization of the Printed Piezoelectric Sensors

The impedances of the 25 sensors on the FOD panel are measured for frequencies ranging from 100 Hz to 200 kHz. The overall trend of the impedances of all the sensors is shown in Fig. 2. It is seen that the standard deviation of impedance values of all the printed elements is less than 10 percent.

The electromechanical behaviour of the printed sensors is highly dependent on the fabrication process of the sensors, which in turn depends on the viscosity of the pastes, precision of printing, polarization voltage, roughness of the printing surface among other factors. The capacitance values for the sensors printed in this study are around 1.87 nF. Overall, the results indicate that the printing process has a good repeatability. Consequently, with further improvements like ensuring smoothness of the surface, controlling the thickness of printing precisely, it is possible to implement the printing process on a large scale during the manufacturing process.



(a) Impedance (b) Phase

Fig. 2. Electromechanical impedance and phase behaviour of all the printed sensors on the FOD panel

In future, damage will be introduced in the panel and the altered impedances of the printed PZT lying on the damaged panel will be compared with that of the healthy case in order to provide a damage indicator allowing for damage monitoring [8].

2.2 Response of the Printed Piezoelectric Sensors to Impact

Impact loading on an engine fan blade typically occurs due a bird strike, and rapid energy transfer takes place which results in generation of typical dynamic response due to the piezoelectric effect. With the intention of measuring these typical impact signatures using the printed sensors, the drop test is carried out. In this second study, the FOD panel is subjected to impact loading of approximately 50 J. A drop impactor setup is used to perform the experiment and the response generated in the FOD panel is measured by all the sensors.

In order to validate the nature of the responses measured by the novel printed sensors and compare the responses, a standard ceramic piezoelectric disc transducer is also bonded to the FOD panel. This standard sensor along with the printed sensors are used to measure the impact response and it is observed that the responses are comparable as shown in Fig 3. The time of arrival of the signals at the standard sensor and printed sensors are in sync and arrive as per the distance between impact location and the sensor locations. Unlike the standard sensor, the faster decay of impact response measured by the printed sensors makes it easier to distinguish between the various secondary responses seen later in time.

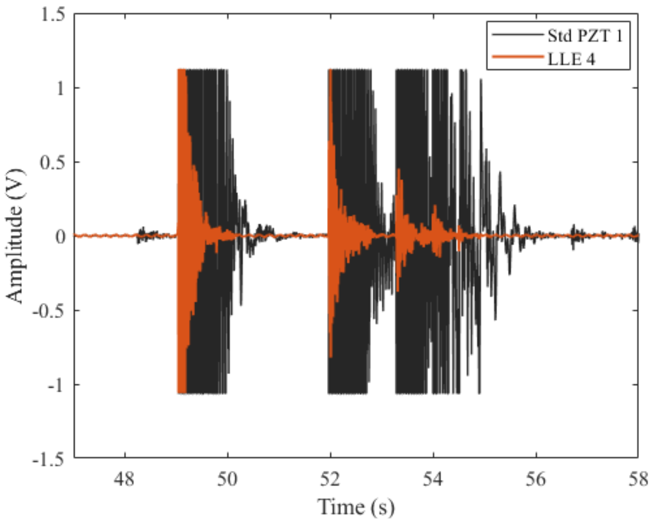


Fig. 3. A comparison between the response to impact measured by a standard ceramic PZT and a printed PZTs

The response measured by a printed sensors 4, 2, 5, 3, and 1 in each of the printed sensor arrays, LLE, LTE, C, RLE, and RTE, respectively, is shown in Fig. 4. Measured responses are saturated around 1 V in order to measure as precisely as possible what occurs at the early beginning of the impact response. The first peak observed around 48.5 seconds corresponds to the primary impact, and all the following peaks observed from approximately 52 seconds are due to the elastic nature of the FOD panel. This shows that all the printed sensors are able to measure the primary as well as secondary impacts efficiently. The small differences seen in the responses in Fig. 3 are due to the differences in location of the sensors. In future, an algorithm will be developed to estimate the location of impact on the panel based on the times of arrival of the responses along the sensors.

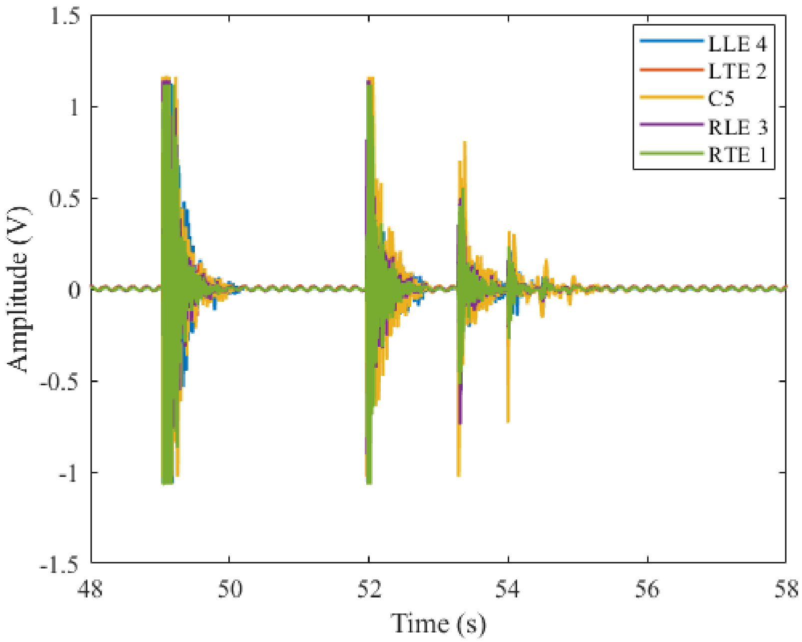
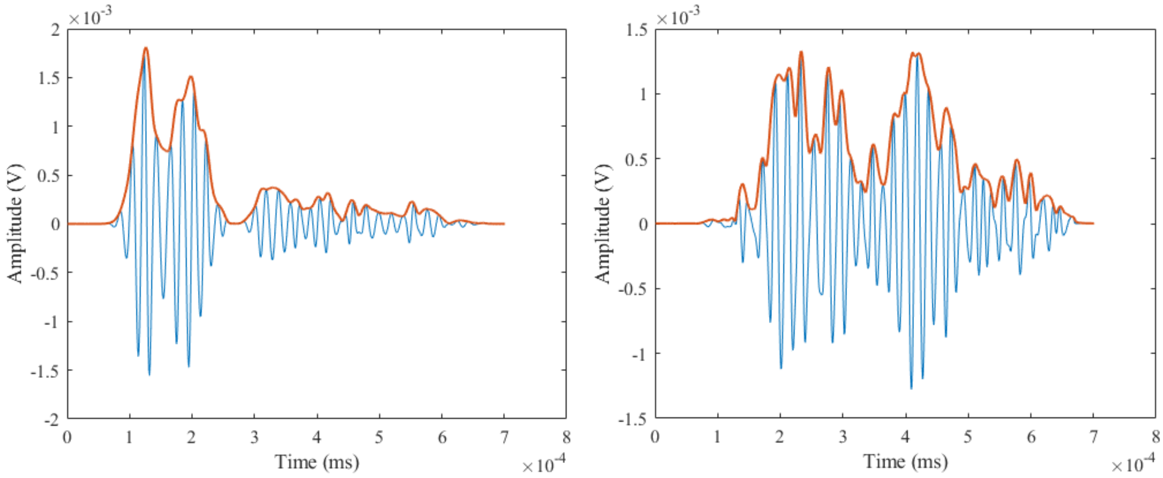


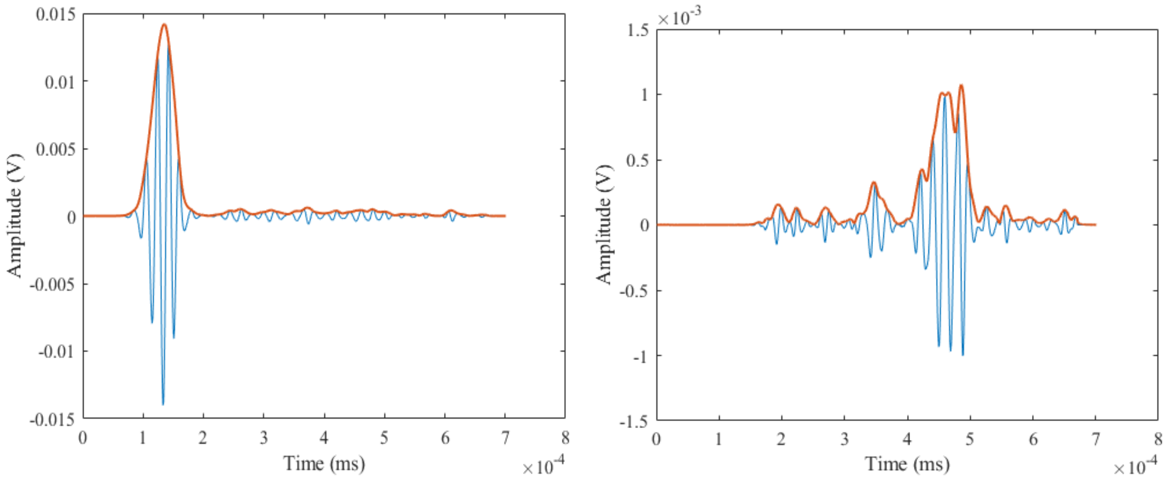
Fig. 4. Saturated responses measured by one of the printed sensors in each of the 5 arrays on the FOD panel when the panel is subjected to a drop impact

2.3 Guided Waves Sensing by the Printed Sensors

After studying the behaviour of the printed sensors in detecting broad spectrum impact response, we study the guided wave sensing abilities of the printed sensors next. The standard ceramic transducer bonded to the panel for impact studies is also being used in this study to generate 5 cycled tone burst excitations with central frequencies of 50, 100, 150, 200, and 250 kHz. The wave response generated in the FOD panel is then measured using the printed sensors at a sampling rate of 1 MHz. The raw signals are filtered using Symlet 8 wavelet filter based around the central frequency of excitation and the crosstalk is removed from the signals. The denoised signals received by some of the printed sensors are shown in Fig. 5 below.



(a) Sensor C3 (b) Sensor LTE 5



(c) Sensor LLE 1 (d) Sensor RLE 3

Fig. 5. Responses measured at some printed sensors generated by 50 kHz excitation

The variability seen in the amplitudes of responses measured by each of the sensors in the FOD panel can be attributed to the variation in the fabrication process at micro scale, variation in the smoothness of the printing surface, variation in the thickness of the print layers, variation in alignment of dipoles during the polarisation process. This should be further characterized.

The measured signals are quite complex and contain multiple reflections. To study the signals further, wave packets corresponding to A0 and S0 modes are identified and the velocities of propagation of these modes are calculated from the time of arrival of the relevant wave packets. The theoretical dispersion curves are obtained using the material properties of the 3D woven composite used to manufacture the FOD panel. While calculating the theoretical dispersion curves [9], the orthotropic nature of the FOD panel was considered. However, due to the large radius of curvature of the panel, the effect of curvature on wave propagation behaviour is ignored in the study presently [10]. A comparison between the theoretical and experimental velocities of the A0 wave mode show a very good match as per Fig. 6. It can also be observed that the printed sensors are able to measure the S0 wave mode at certain frequencies but mainly the A0 mode.

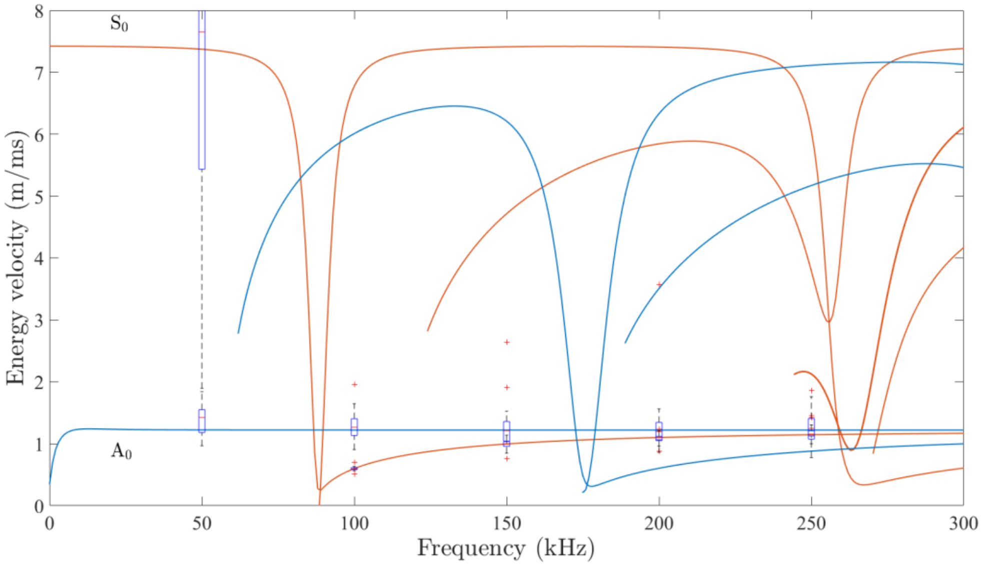


Fig. 6. A comparison between the theoretically calculated and experimentally measured velocities by the printed sensors

The guided waves signals will be studied further and used as baseline (healthy) reference signals. Damage will be progressively introduced in the panel and the printed sensors network will be used to measure guided waves at range of excitation frequencies. The signals measured for damaged cases will be similarly analysed and damage indicators will be estimated.

4. Conclusions

Printed piezoelectric sensors can possibly have a wide scale use in aviation and other related domains for structural health monitoring purposes. These sensors can be printed during the manufacturing process before the part does in service and reduce the downtime during maintenance. The printed sensors can be used to detect and monitor structural deformation, impact damage, or fatigue in aircraft, helping to ensure the safety and reliability of the aircraft. In this work, the sensors are fabricated using screen printing technology in 3 layers of bottom electrode, piezoelectric sensing layer, and the top electrode. All the sensors printed using this technology show similar electromechanical characteristics. The printed sensors are also capable of sensing impact on the 3D woven composite FOD panel as well as measure various guided wave signals. Overall, these printed piezoelectric sensors can be used for various purposes of SHM in aerospace structures as well as other structures like bridges, pipelines, wind turbines, etc.

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