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# Integration and Characterisation of Piezoelectric Macro-Fibre Composite on Carbon Fibre Composite for Vibration Energy Harvesting

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# Integration and Characterisation of Piezoelectric Macro-Fibre Composite on Carbon Fibre Composite for Vibration Energy Harvesting

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**Abstract.** Carbon fibre composite is a strong and a lightweight structural material with applications in automotive, aerospace, medical and industrial applications. The integration of piezoelectric transducer films onto the composite stack can add vibration energy harvesting capabilities to enable net-zero-power autonomous sensing for an otherwise purely mechanical structure. A PZT macro-fibre composite is co-cured with a carbon/epoxy pre-preg in order to manufacture the multi-functional composite plate. Without noticeably increasing profile, adding weight or compromising mechanical integrity, the resultant mechanical plate can recover power from vibrational excitations. With a volume of $13.5\,\mathrm{cm}^3$, a peak average power of $9.25\,\mathrm{mW}$ was recorded at $2.66\,\mathrm{ms}^{-2}$. The normalised power density of $97\,\mu\mathrm{W\,cm}^{-3}\,\mathrm{m}^{-2}\,\mathrm{s}^{4}$ is comparable to some of the state-of-the-art PZT generators reported in the literature.

## 1. Introduction

Fibre composite is desirable as as a lightweight and strong structural material. Apart from its mechanical advantages, in recent years, there is also a growing interest to realise multi-functional composite in order to infuse smart electronic capabilities onto the otherwise purely mechanical material. The seamless integration of piezoelectric macro-fibre composite (MFC) onto carbon fibre enables the addition of energy generation and sensing functionalities to an otherwise purely mechanical structure, without the need for extra wire tethering or altering the structural profile. MFC is manufactured from spun PZT fibres and it has demonstrated promising power performance as an energy harvester [1]. MFC differs from bulk PZT [2] and MEMS piezoelectric transducers [3] as it offers structural flexibility without sacrificing charge constant and electromechanical coupling. This work builds upon previous work on integrated MFC with carbon fibre reinforced polymer [4] in order embed energy harvesting capability onto the mechanical structure. A co-curing process is developed and employed in the present work to minimise any potential impact to the mechanical properties of the composite plate.

## 2. Design and fabrication

A schematic of the fabrication and co-curing integration process is shown in figure 1. The MFC transducer is laid out on the top layer of a stack of the carbon fibre/epoxy pre-preg plys (cross woven carbon fibre pre-impregnated with epoxy resin). Electrical pads on the MFC were protected by a simple protective mask to re-expose the pads after the curing process. Conductive silver epoxy and wire bonds were used to route out the electrical connections post fabrication.

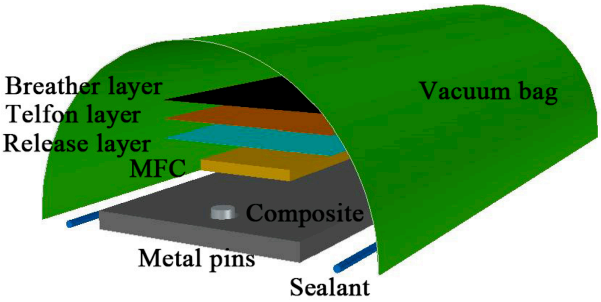

**Figure 1.** Design schematic of the piezoelectric macro-fibre composite (MFC) integration process onto the carbon fibre composite.

The composite stack is cured in an oven as illustrated in figure 2, while being held in place within a vacuum bag. Low temperature pre-preg (125 °C) was chosen to remain well below the Curie temperature of the piezoelectric transducer as well as to be compatible with the survivability of most electronic components. A small circular metal pin is used to pre-define a mounting hole on the carbon fibre plate during the curing process. This prevents the need to drill the plate post fabrication, which is known to introduce local cracks. Figure 3 shows the integrated prototype mounted on a shaker.

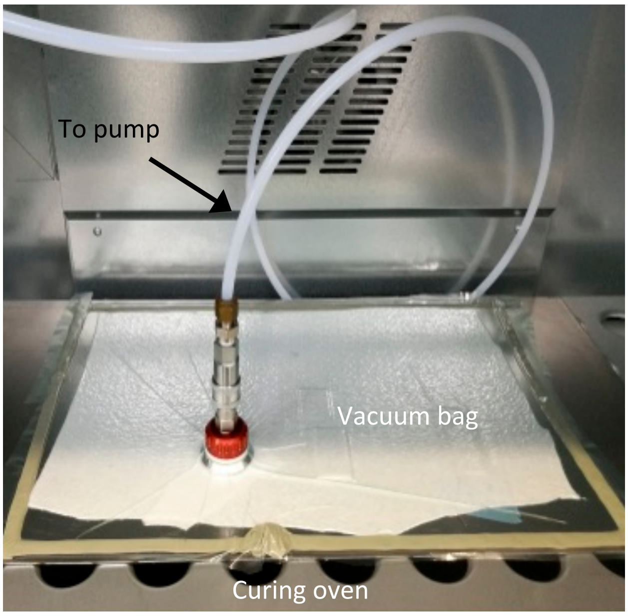

**Figure 2.** MFC laid out as top ply on carbon fibre/epoxy pre-preg, placed in a vacuum bag, cured in an oven.

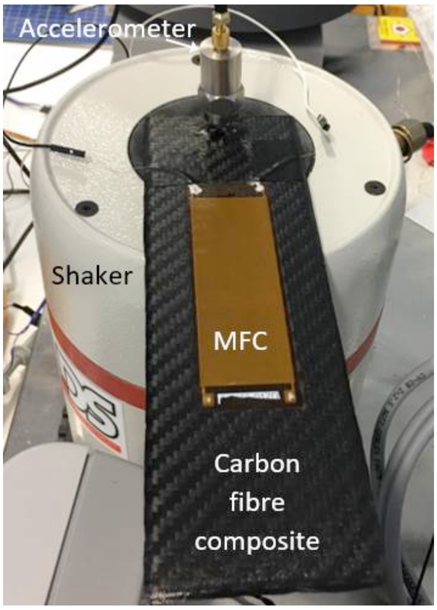

**Figure 3.** Photograph of the integrated MFC on carbon fibre mounted on a mechanical shaker.

## 3. Results

The integrated MFC-on-carbon composite plate was characterised using the test setup shown in figure 4. The shaker is controlled by a function generator via a power amplifier, while the transducer voltage output across a load resistance is measured on a digital oscilloscope. Resistance matching found an optimal load at 20 kΩ for the first resonant mode.

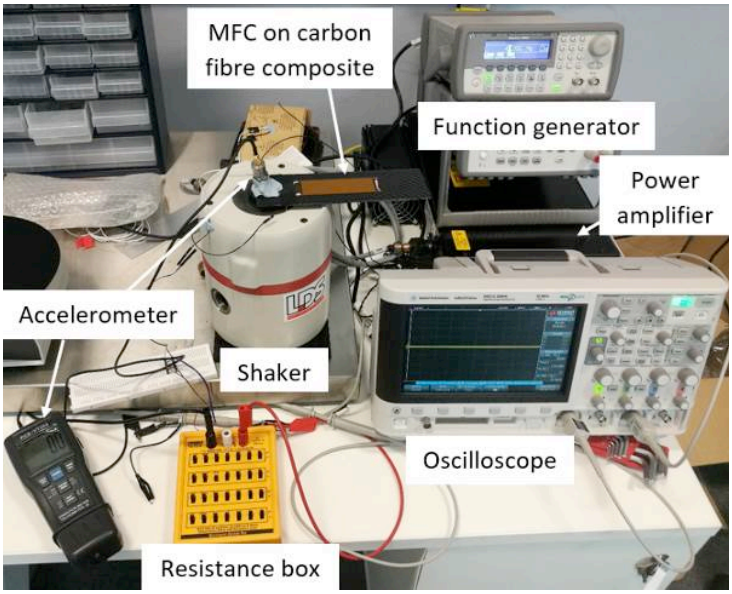

**Figure 4.** Experimental apparatus for the vibration characterisation of the prototype harvester.

Figure 5 presents the frequency domain characteristics of the prototype plate mounted as a cantilever. The fundamental mode resonance frequency is at 46 Hz for this particular case. A weakly nonlinear spring hardening effect can be observed from the harvester, even at low acceleration levels. This could be a result of residual stress between the MFC and carbon fibre layers left behind after the co-curing process due to the varying thermal expansion coefficients.

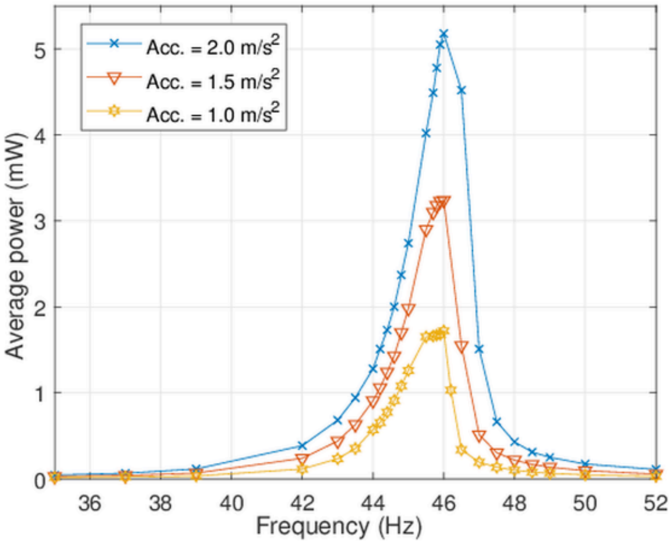

**Figure 5.** Frequency domain characteristics measured across a load resistance of 20 kΩ.

Figures 6 and 7 show the voltage and power responses of the prototype when subjected to sinusoidal excitation at resonance and 2 kHz band-limited white noise excitation respectively. It can be noted that the RMS voltage output is typically in the order of a few 1's volts, even for broadband noise excitation. This is ideal for overcoming the minimum diode or transistor voltage thresholds to activate conditioning and power management circuits.

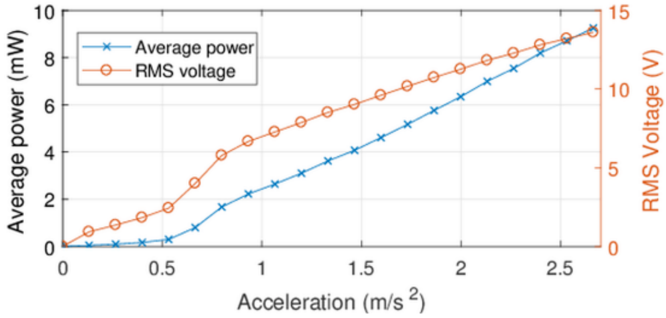

**Figure 6.** Input acceleration versus average resonant power output plot when subjected to sinusoidal excitation with a load of 20 kΩ.

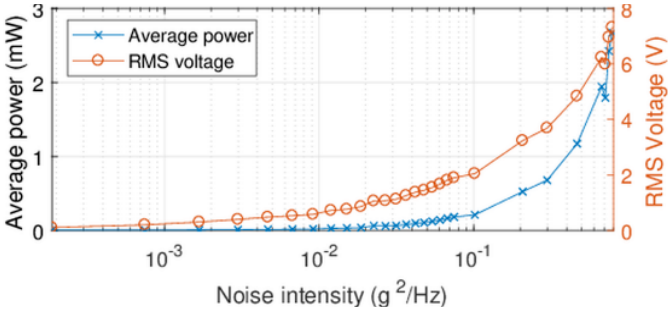

**Figure 7.** Input acceleration versus average power output plot when subjected to 2 kHz band-limited noise excitation with a load of 20 kΩ.

The highest average power recorded was 9.25 mW at 2.66 $\mathrm{ms}^{-2}$ at 46 Hz. Higher acceleration scan was not done due to experimental constraints. Given a total volume of 13.5 $\mathrm{cm}^{3}$, the power density normalised against acceleration squared is 97 $\mu\mathrm{W\,cm}^{-3}\,\mathrm{m}^{-2}\,\mathrm{s}^{4}$, which compares favourably against some of the state-of-the-art in the literature, such as a thinned bulk PZT harvester at 105 $\mu\mathrm{W\,cm}^{-3}\,\mathrm{m}^{-2}\,\mathrm{s}^{4}$ [2].

## Conclusion

This paper presented a MFC and carbon/epoxy pre-preg co-cured integrated smart composite capable of harvesting ambient vibrational energy. The resultant VEH enabled carbon fibre plate recorded a normalised power density that compares favourably to some of the state-of-the-art cantilever harvesters reported in the literature. The relatively high-power output from the thin profile harvester offers a feasible on-composite power solution for microelectronics and sensors that can be similarly integrated onto the composite stack. Applications can be found within the aerospace and automotive sectors, where traditionally purely mechanical composite structures can be transformed into self-powered and self-sensing multi-functional smart composites.

## Acknowledgement

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## References

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