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# Energy harvesting for a self-powered compact Structural Health Monitoring system based on Acoustic Emission

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## Abstract

The use of composite materials in aerospace structures has been recently increasing on the basis that they could make structures lighter whilst maintaining the same level of safety; concerns and uncertainties on damage behaviour of such materials, especially on their tolerance to impacts, have forced designers to increase safety factors to a point that the use of advanced lightweight composite materials is not adding as much benefit as initially envisioned.

The introduction of Structural Health Monitoring (SHM) systems could improve this situation, by informing the operator immediately about the presence and severity of damage, and thus reducing the safety factors currently in place to allow the structure to remain safe until the next inspection, i.e. allow a certain amount of damage growth within safe boundaries and within a maintenance window.

Structural Health Monitoring systems based on Acoustic Emission (AE) are traditionally high-power. However, a bespoke low-power wireless device based on AE is currently being *developed through the Innovate UK project "Sentient"*. This work deals with the *development of a tuneable device to harvest vibration power from the aircraft's natural* vibrations to enable a fully autonomous system to be realised.

A set of Finite Elements models have been developed to assess the performance of different energy harvester configurations. These models have been validated experimentally using a shaker to excite different harvester layouts based on Macro-Fiber Composite patches. The paper shows that it is possible to tune such devices through simplified FE models, and that each device can harvest power in the 1-10 mW range at typical acceleration levels.

## 1 INTRODUCTION

Composite materials are being increasingly employed in aerospace structures due to their appealingly higher stiffness to weight and strength to weight ratios. Designers and manufacturers, however, have to take into account complex damage mechanisms and material characteristics that make such materials difficult to inspect, especially when dealing with impact damage which can be invisible from the outside of the structure (Barely Visible Impact Damage, BVID). These concerns have forced increases in safety factors to a point that the benefit of advanced lightweight composite materials is not fully exploited.

The systematic use of Structural Health Monitoring (SHM) could help improve this, by providing operators and maintenance providers with a tool that informs them about damage location and severity [1, 2]. Such a tool would be useful in the development of maintenance strategies and facilitate the decision making process following the identification of damage by providing data enabling the assessment of whether continued flight would be within the safety envelope.

Structural Health Monitoring systems based on Acoustic Emission (AE) are traditionally high-power and as such unsuitable for autonomous operation powered by energy harvested from the surrounding environment [3, 4]. To address this, a bespoke low-power wireless device based on AE currently being developed through the Innovate UK project “Sentient”.

Different types of compact vibration harvesters have been designed [5, 6]. This work will focus on the use of Macro Fibre Composite (MFC) transducers [7], which have the dual use of actuators and generators. In this case, the transducers will be used purely as generators.

## 2 MATERIALS AND METHODS

To determine the level of power which could potentially be harvested from a typical aircraft application, MFC (Smart Material Corp.) with d31 polarization and a 28mm x 14mm active area, were bonded to two bespoke stainless steel laser cut sheet metal units (Figure 1). Units were designed to fit the sensor developed whilst incorporating cantilever type harvesters which could be tuned to maximise energy harvested.

Figure 1: Energy Harvesting Units: tuned (left) and heavy (right)

The units were fitted to a shaker via an aluminium adapter through M4 bolts, visible in the setup in Figure 2. An accelerometer was fitted to the fixture in order to calibrate vertical acceleration levels. The harvesters were then tested based on the following parameters taken from typical flight scenarios:

- Frequency range: 20Hz to 1000 Hz
- Acceleration values: 0.5g, 1g, 2g
- Harvester configurations: T1, H1

Peak-to-peak voltage measurements were taken at various frequencies, densifying frequency increments around resonances. Separate measurements were made for the MFC resistance with a LC bridge to account for the variable resistance of the MFC as a function of the frequency.

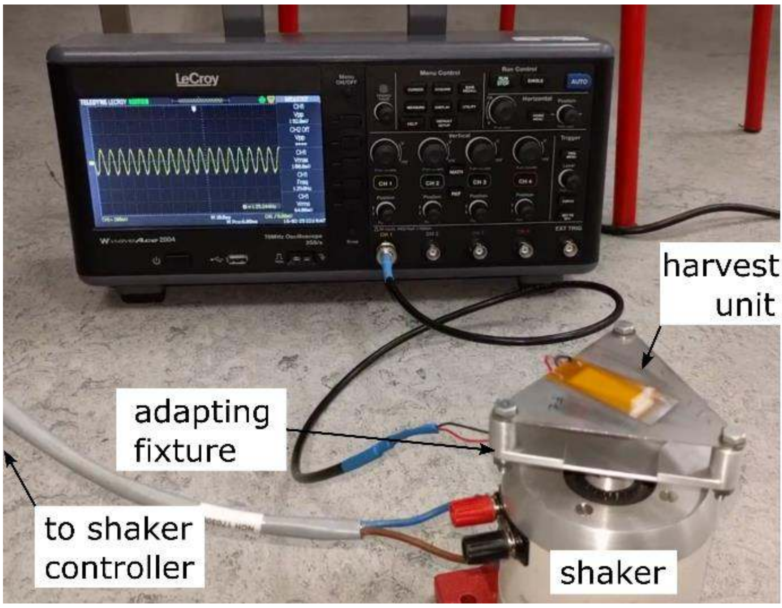
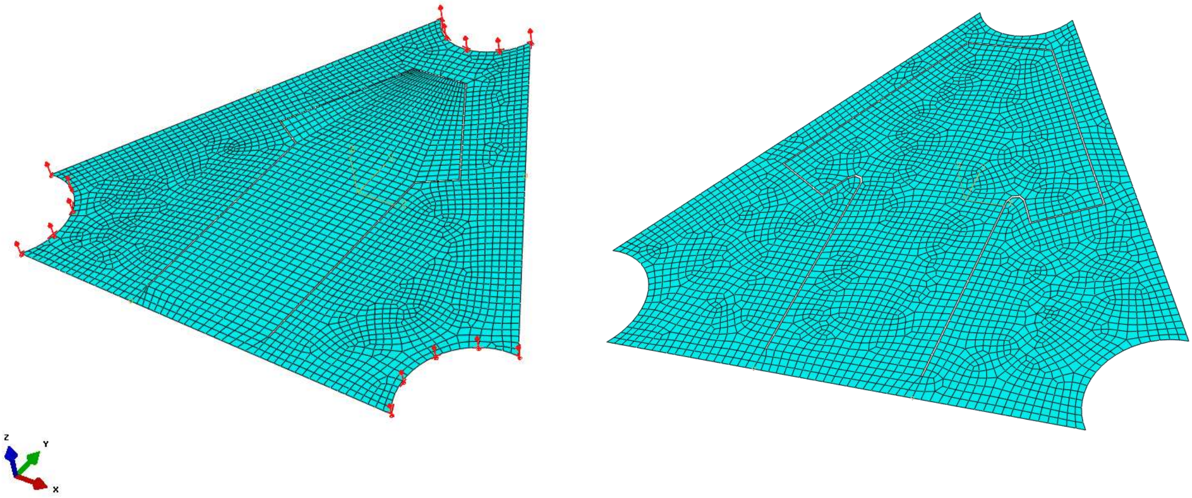


Figure 2: experimental setup

In parallel, Finite Elements models of the two harvesters were generated and analysed using Abaqus/Standard. Models consisted of 3247 S4R linear shell elements (Figure 3). Care was taken with selecting the element's minimum size [8] to ensure the element's resonant frequency was far from the 1kHz upper region of interest. A vertical unit acceleration was applied to the model at the boundaries corresponding to the bolted areas in order to simulate the conditions in the experiment, modelling the supports as infinitely rigid. A steady state dynamics model was run, preceded by a simpler eigenfrequency/ eigenmode extraction.



(a) (b)

Figure 3: FE mesh of tuned harvester (a) and heavy harvester (b)

A separate model of the same harvester, this time including the MFC harvester, modelled using an additional shell structure was included to investigate the effects of the increased stiffness and mass. The model is shown in Figure 4. Nodes on the MFC model were tied to the substrate by constraining all degrees of freedom between the two parts (assuming perfect bonding with no sliding). The properties used in the model are listed in Table 1.

Table 1: material properties used in FE model

| | **Elastic Properties** | | | | **Density / kg×10$^3$×mm$^{-3}$** |
|---|---|---|---|---|---|
| | E / N mm$^{-2}$ | | | ν | |
| **Steel** | 210000 | | | 0.33 | $7.8\times10^{-9}$ |
| | $E_1$ | $E_2$ | $G_{12}=G_{13}=G_{23}$ | $\nu_{12}$ | |
| **MFC** | 30000 | 16000 | 5500 | 0.31 | $5.44\times10^{-9}$ |

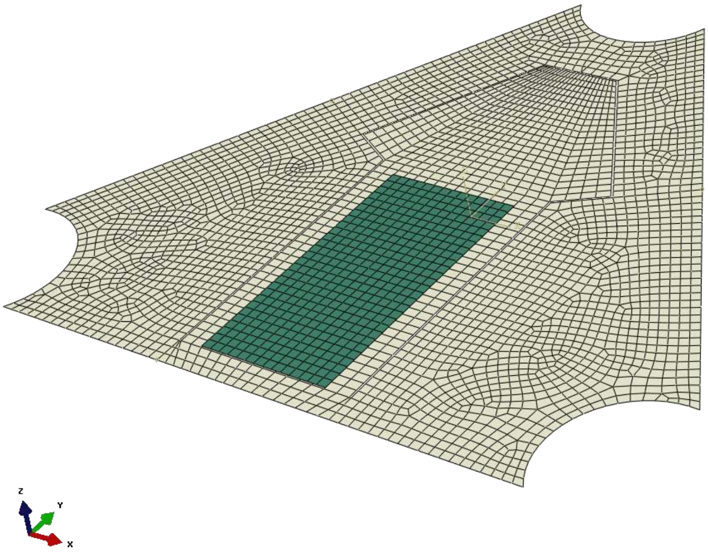


Figure 4: FE mesh of substrate and MFC generator

# 3 RESULTS

## 3.1 Experimental measurements

Output power charts for both harvesters are shown in Figure 5 and Figure 6. The power output as a function of the shaker frequency is shown at 0.5, 1 and 2g.

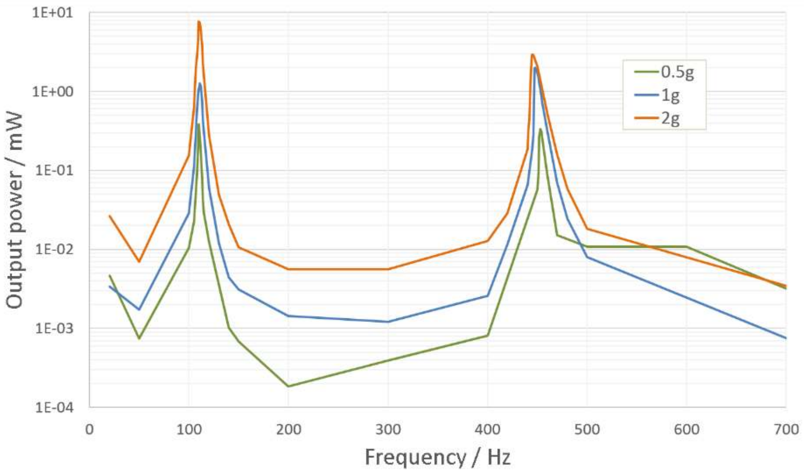


Figure 5: power output for the T1 harvester

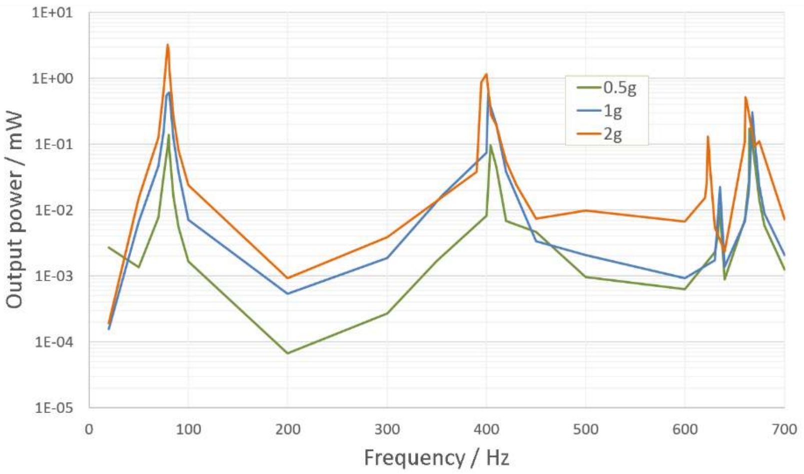
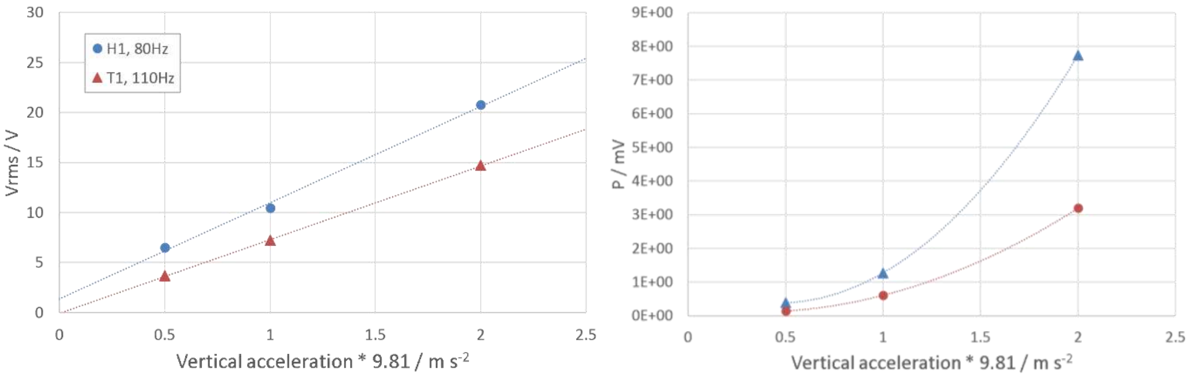


Figure 6: power output for the H1 harvester

Figure 7 compares the RMS voltage (a) and the power output (b) at the first resonant peak, at the different g levels investigated and for both harvesters.



(a) (b)

Figure 7: Voltage and power outputs from generators

## 3.2 Finite Elements models

Under the assumption that the MFC output is proportional to the strain that the generator sees, the sum of longitudinal strain was extracted from the elements that represented the MFC active area. Table 2 lists the first two resonant frequencies as extracted from the steady state dynamic model. The differences between models including and excluding the MFC stiffness was negligible in the T1 model, and the harvester was therefore not included in the H1 model.

Table 2: FE / model resonant frequencies (dynamic model) comparison

| | **$f_1$ / Hz** | | | **$f_2$ / Hz** | | |
|---|---|---|---|---|---|---|
| | FE model | | | FE model | | |
| | Base | MFC | Experimental | Base | MFC | Experimental |
| T1 | 103 | 102 | 110 | 445 | 435 | 450 |
| H1 | 82 | - | 80 | 394 | - | 395 |

The normalized sum of longitudinal strain from the numerical model is compared with the experimental results in Figure 8 and Figure 9.

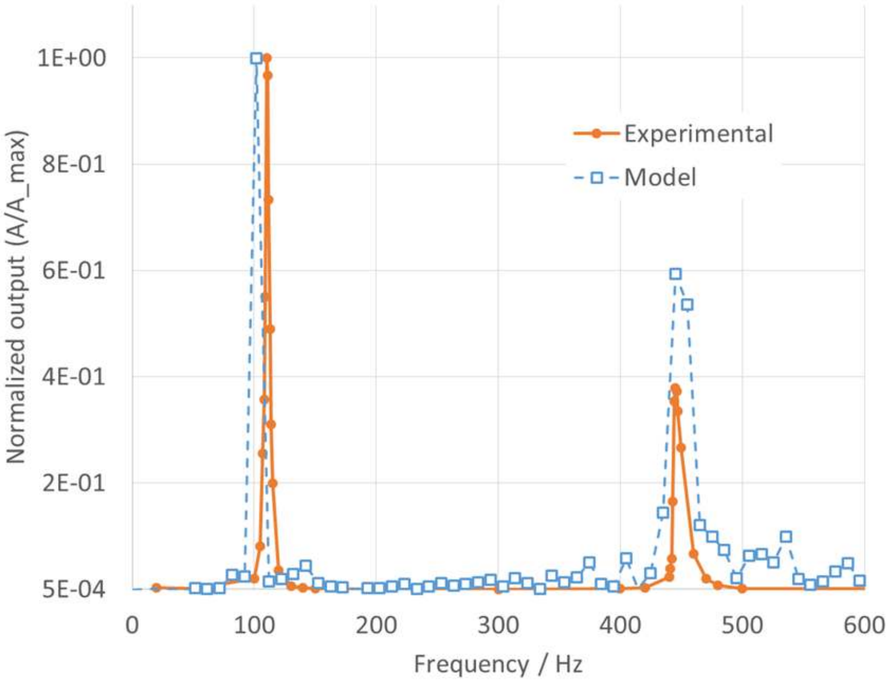


Figure 8: experimental / numerical comparison, harvester T1

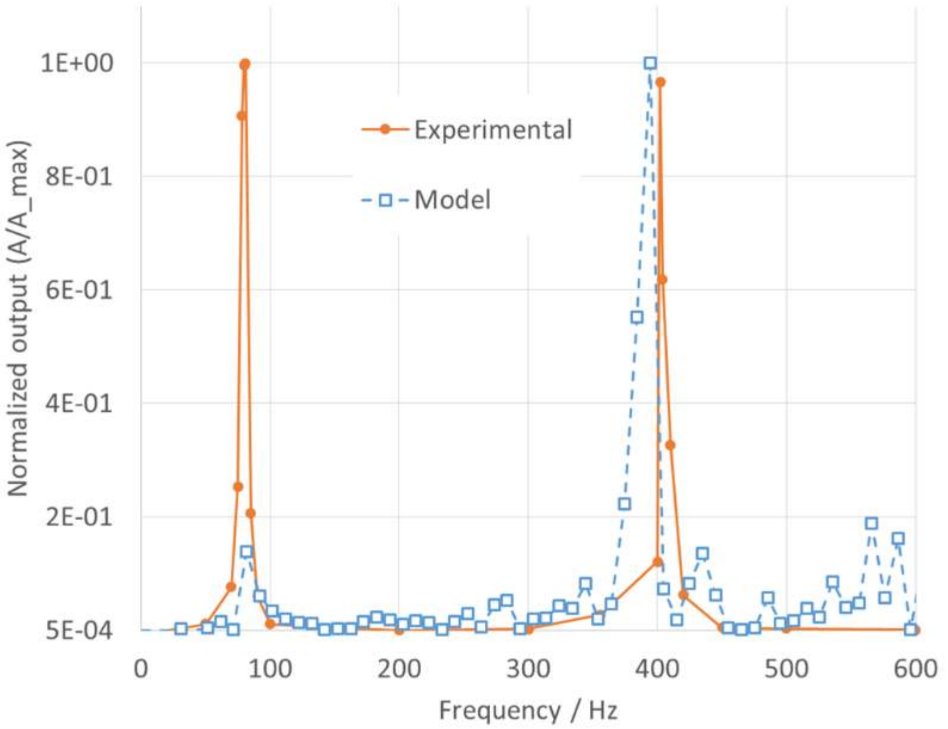


Figure 9: experimental / numerical comparison, harvester H1

## 4 DISCUSSION

The experimental test showed a similar order of magnitude for the power output of both harvesters. Moreover, the tests showed a linear dependence between the RMS voltage output and the acceleration level. As a consequence of this, the power output increases parabolically.

The Finite Element models provide a reliable prediction of the resonant frequencies. The addition of the MFC stiffness and mass to the model had negligible effect; this is believed to be due to two opposing factors, with the increased weight decreasing the resonant frequency, while the increased stiffness increases it. These two effects appear to outweigh each other in reality, providing a negligible net effect.

A good match between the power profile and the total strain seen in the MFC region in the model was demonstrated. The discrepancies seen in the relative peak amplitudes for the two numerical models are expected to be caused by non-linearities and damping effects, which are more pronounced in the heavier harvester.

## 5 CONCLUSIONS

The experimental tests on bespoke energy harvesting units for low-power, aeronautical targeted Structural Health Monitoring showed the feasibility of using Macro-Fiber Composite generators to provide power of order of magnitude of 1-10 mW, making them a potential energy source for a low powered structural health monitoring system based an acoustic emission. The tests demonstrated the feasibility to tune the resonant frequencies based on the application's region of interest by cutting a cantilever beam with an appropriate shape. Finite Element models showed the feasibility of designing such harvesting units and tuning the frequencies in a way that closely matched the experiment. Further work will be necessary to adequately link the model's strain output to the generators output, in order to optimize the shape and number of harvesters required for a specific application. Other harvester materials and layouts will also be tested.

## ACKNOWLEDGEMENTS

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