

Vibration Energy Harvesting of Multifunctional Carbon Fibre Composite Laminate Structures

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Abstract

A sustainable power supply for a wide range of applications, such as powering sensors for structural health monitoring and wireless sensor nodes for data transmission and communication used in unmanned air vehicles, automobiles, renewable energy sectors, and smart city technologies, is targeted. This paper presents an experimental and numerical study that describes an innovative technique to harvest energy resulted from environmental vibrations. A piezoelectric energy harvester was integrated onto a carbon fibre reinforced polymer (CFRP) laminate structure using the co-curing method. The integrated composite with the energy harvester was lightweight, flexible and provided robust and reliable energy outcomes, which can be used to power different low-powered wireless sensing nodes. A normalised power density of $97 \mu\text{W cm}^{-3} \text{m}^{-2} \text{s}^4$ was obtained from resonance frequency of 46 Hz sinusoidal waves at amplitude of 0.2 g; while the representative environmental vibration waves in various applications (aerospace, automotive, machine and bridge infrastructure) were experimentally and numerically investigated to find out the energy that can be harvested by such a multifunctional composite structure. The results showed the energy harvested at different vibration input from various industrial sectors could be sufficient to power an autonomous structural health monitoring system

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and wireless communications by the designed composite structure.

Keywords: Vibration energy harvesting, macro fibre composite, multifunctional composite, aerospace, automotive, infrastructure, compressor

1. Introduction

There has been a growing interest to develop multifunctional composite materials, where the actuators, sensors, controllers, and power generators can be embodied in a new smart composite structure[1, 2, 3, 4]. The composite with capability of energy harvesting technologies has arisen a significant interest in various application, especially in wireless structural health monitoring technologies [5, 6]. Various standalone vibration energy harvesters are reported, including electromagnetic vibration energy harvesters [7, 8], electrostatic vibration energy harvesters [9, 10], piezoelectric vibration energy harvesters [11, 12, 13, 14], and recently developed triboelectric nano-generator for vibration energy harvesting [15, 16, 17]. However, the application of different energy harvesting systems depend on the specific requirement, i.e. environmental conditions and physical constraints. For instance, the efficiency of an electromagnetic vibration energy harvester drops when it is scaled-down since the number of coil turns decrease; this is a series shortcoming since in many applications there is a limited space that can be used to install a harvester [18]. Electrostatic generators might be ideal for micro-applications since the gap required between capacitor plates should be small. Thus, the power outputs of electrostatic vibration energy harvesting is lower in magnitude [19].

Piezoelectric vibration energy harvesters can offer great benefits to different engineering applications due to the characteristics of mechanical and electrical energy conversion mechanism[20]. The optimal power outputs can be reflected by the load/displacement applied at a specific industrial scenario [21]. In table 1, a comparison of various energy harvesting systems is shown in terms of the power per unit volume. It can be seen the piezoelectric vibration energy har-

vesting is capable to achieve high energy density and therefore the piezoelectric harvester was selected in this work [22, 23, 24, 25]. Considering the application for aerospace or automotive where streamlined structure was primary, the macro-fibre composite (MFC) has been able to offer structural flexibility without sacrificing charge constant and electromechanical coupling [26]. The high efficiency and almost ignorable thickness are thought to be the most ideal for integration with aircraft wing, vehicle structural body or wind turbine blade etc. The MFC was hence applied in this work to integration with CFRP.

Table 1: Comparing energy densities between four major energy harvesting mechanisms [27].

	Electromagnetic	Electrostatic	Piezoelectric	Triboelectric nano-generator
Energy density (mJ cm^{-3})	24.8	4	35.4	55
Assumption	0.25 T magnetic field	$3 \times 10^7 \text{ V m}^{-1}$ electric field	PZT 5H material	Liquid electrode [28]

Energy harvesting has been studied extensively [29, 30], however, most work was published uses a typical input of sinusoidal vibration waves and few publications look at the actual representative environment data. In particular, the multifunctional composite materials combined with energy harvesting capability were rarely studied considering the various applications, such as aerospace, automotive, energy, and infrastructure applications. A recommended guide referring to the actual input data of above sectors should accelerate the application of energy harvesting with composite structures. Therefore, this work will be the catalyst to further develop the energy harvesting in the aerospace, automotive, energy, and infrastructure applications. Representative environment vibration data can validate and estimate the practically achievable power outputs for various selected applications. Therefore, the developed multifunctional composite can harvest sufficient energy to power an autonomous structural health monitoring and communication system for a real-time updating and directing purpose.

2. Methodology

50 2.1. Energy Harvester Integration

Pre-preg specimens used 2×2 twill weave carbon fibres with aerial weight 275 g m^{-2} (SHD Composite Materials, UK). This was cut into sheets ($200 \times 60 \times 1.63\text{mm}$) and hand laid onto an aluminium plate covered by PTFE to prevent sticking. The MFC transducer M85280-P2 (Smart Materials, Germany) with
55 dimensions of ($85 \times 28 \times 0.3\text{mm}$) was placed onto the pre-preg stack, a PTFE tape was used to protect MFC electrodes during the cure. A small circular metal pin was used to pre-define a mounting hole on the CFRP laminate panel, this mounting hole was used to install the CFRP laminate on the electrodynamic shaker. The whole set-up was enveloped in a vacuum bag and placed in an
60 oven to cure at $125 \text{ }^\circ\text{C}$ for 120 min under vacuum pressure $\approx 95 \text{ kPa}$. Figure 1 shows the experimental set-up, it was reported in the literature [31, 32] that the optimum piezoelectric area is $\approx 30\%$ to 40% of a cantilever beam length near the clamped end.

Once the curing cycle has finished, the CFRP laminate was taken out of
65 the oven, the PTFE tape was removed, it was found that a high soldering temperature causes damage to the MFC electrodes, therefore, conductive Silver Epoxy adhesive was used to make electrical contacts between electrical wires and the MFC electrodes prior to excitation. The MFC M8528-P2 operates in d_{31} mode, their operational lifetime is $\geq 10^9$ cycles when operating at 1 kV_{p-p} .
70 Typical maximum voltage for energy harvesting application is expected to be $\approx 10^3 \text{ V}$.

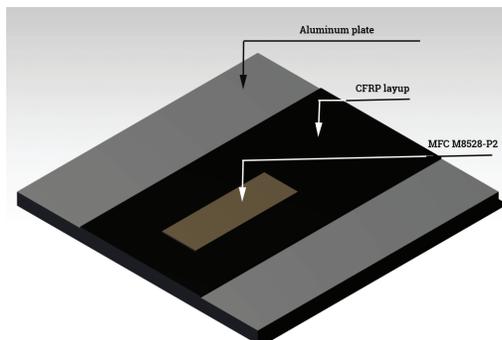


Figure 1: Schematic shows the integration process of the MFC M8528-P2 onto a CFRP laminate.

2.2. Excitation Method

The MFC M8528-P2 was excited using real-life environment vibrations with an optimum load of 20 k Ω . These vibration data were collected from different applications that were CGJ aircraft, BMW 5 series, compressor, and a suspension bridge. The frequency ranges from few hertz up to 2 kHz, while the resonance frequency of the composite laminate at the optimum load was 46 Hz. Waveform Editor (Agilent Technologies) was used to define and programme arbitrary waveforms on a function generator (33210A , Agilent Technologies), which in turn controlled an electrodynamic shaker (LDS 406, Brüel & Kjaer) via a power amplifier (LDS PA100E, Brüel & Kjaer). The voltage output from the MFC M8528-P2 transducer was connected to a variable resistance box in parallel and measured by a digital oscilloscope (DSO-X-2004A, Agilent Technologies). A commercial MEMS accelerometer (ADXL 337Z, Analog Devices) was installed on the electrodynamic shaker table to replicate the actual vibration traces on the electrodynamic shake; the prototype devices and the test set up is shown in Figure 2.

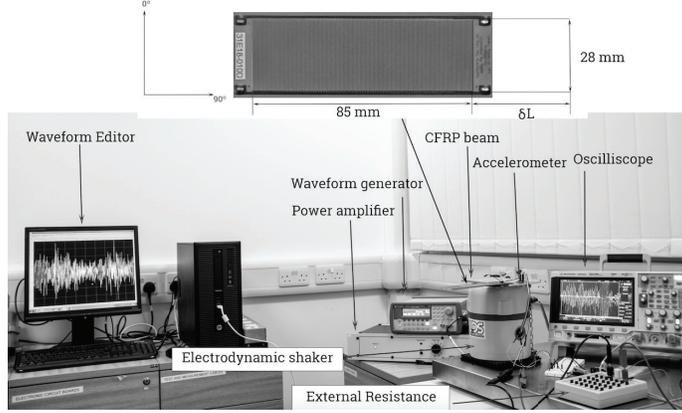


Figure 2: Experimental apparatus for the vibration characterisation of the prototype harvester.

3. Theory and Simulation

3.1. Analytical Model

The governing equation of motion for a cantilever beam can be described by a classic beam theory, with inclusion of a viscous air damping term. The addition of a piezoelectric layer (MFC M8528-P2), a further strain rate damping term representing the electrical damping of the transducer can be included [6]. Therefore, the forced vibration equation of a piezoelectric cantilever beam can be described by equation 1 [33].

$$EI\left(\frac{\partial^4 w(x,t)}{\partial x^4}\right) + c_s I \frac{\partial^5 w(x,t)}{\partial^4 x \cdot \partial t} + c_a \frac{\partial w(x,t)}{\partial t} + m \frac{\partial^2 w(x,t)}{\partial t^2} = F(x,t) \quad (1)$$

where, E is Young's modulus of the composite laminate in the x -direction as shown in Table 2, I is area moment of inertia, $w(x,t)$ is deflection in transverse x -direction, t is time domain, m is the effective mass of the beam, c_s is strain rate damping coefficient and c_a is viscous air damping coefficient. $F(x,t)$ is the excitation force, for a free vibration $F(x,t) = 0$. The deflection in x -direction $w(x,t)$ is given in 2

$$w(x,t) = w_b(x,t) + w_{rel}(x,t) \quad (2)$$

With $w_{rel}(x, t)$ as the transverse displacement relative to the clamped end of the beam and $w_b(x, t)$ is the base displacement. Substituting 2 in 1 and applying cantilever beam boundary conditions, the solution of the beam equation can be represented by a convergent series of eigenfunction as shown in equation 3.

$$w_{rel}(x, t) = \sum_{r=1}^{\infty} \phi_r(x) \eta_r(t) \quad (3)$$

Where, $\phi_r(x)$ and $\eta_r(t)$ are the mass normalised eigenfunction and the modal coordinate of a uniform clamped-free beam for the r-th mode, respectively. The natural frequency of a continuous cantilever beam can be given equation 4.

$$f = A \sqrt{\frac{EI}{\mu L^4}} \quad (4)$$

Where A is a constant, μ is mass per unit length of the beam. The strain at a certain place on the beam at a distance x from the neutral axis is presented by equation 5.

$$\epsilon(x, t) = -x(t) \frac{\partial^2 w}{\partial x^2} \quad (5)$$

Furthermore, stress can be given by $\sigma(x, t) = E\epsilon(x, t)$. For a piezoelectric transducer with charge constant d_{31} , width b and length l , the short circuit electrical charge Q_{sc} generated from the transducer can be given by equation 6.

$$Q_{sc}(x, t) = d_{31} \sigma(x, t) bl \quad (6)$$

Taking the total charge generated across an average stress $\sigma(t)$, the output power $P(t)$ of the piezoelectric transducer across an impedance load (Z) can then be expressed by equation 7.

$$P(t) = [\omega(t) d_{31} \sigma(t) bl]^2 \frac{Z_{load} Z_i^2}{Z_i^2 + Z_{load}^2} \quad (7)$$

90 Where $\omega(t)$ is the excitation frequency.

3.2. Finite Element Analysis

A 3D FEA model is developed and previously published as shown in figure 3, for detailed information see [33]. The CFRP beam was made from eight plies

of RC200T woven fabric CFRP; the CFRP beam was configured to a cantilever
 95 structure. Solid Mechanics, Electrostatics and Electrical Circuit physics mod-
 ules within COMSOL Multiphysics were used to simulate the mechanical and
 piezoelectric response of the device. The beam was defined as an orthotropic
 material as part of the Solid Mechanics physics, with material properties pre-
 sented in Table2, the mechanical properties of MFC is presented in Table 3 and
 100 Table4, for more details about electrical properties and FE model details can
 be found in [33].

Table 2: Mechanical properties of CFRP laminate

E_x (Gpa)	E_y (Gpa)	E_z (Gpa)	G_{xy} (Gpa)	G_{yz} (Gpa)	G_{xz} (Gpa)	ν_{xy}	ν_{yz}	ν_{xz}
59.45	69.3	3.9	62.9	1.5	62.35	0.3	0.4	0.3

Table 3: Mechanical properties of MFC [26]

E_1 (Gpa)	E_2 (Gpa)	G_{12} (Gpa)	ν_{12}	ν_{21}	ρ ($\text{kg} \cdot \text{m}^{-3}$)
30.34	15.86	5.52	0.31	0.16	5400

Table 4: Piezoelectric and dielectric properties [26]

d_{31} (pC/N)	d_{33} (pC/N)	C (nF/cm^2)	ϵ_p (nF/m)	ϵ_r
-170	400	7.8	0.15	1695

Eigenfrequency analysis revealed natural frequency at 47.2 Hz (1st bending
 mode), with the first few higher resonant modes estimated at: 147.1 Hz (1st lat-
 eral mode), 275.4 Hz (2nd bending mode), 362.3 Hz (1st torsional mode), 772.0 Hz
 105 (3rd bending mode), 1095.2 Hz (2nd torsional mode), 1498.9 Hz (4th bending mode)
 and 1935.0 Hz (3rd torsional mode). Body load was used to introduce base
 point acceleration for Frequency Domain and Time Dependent Modal analyses.
 Damping ratio of 0.02 was used as a starting assumption, and fitted according
 to experimentally measured quality factor.

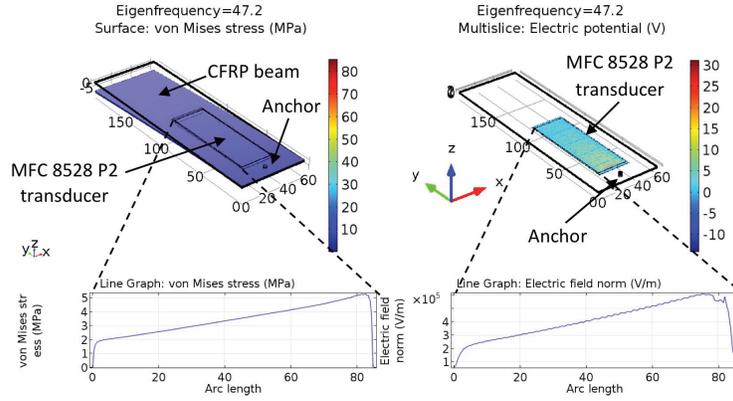


Figure 3: FE model of the MFC-on-composite vibration energy harvester. The natural frequency is at 47.2 Hz. The figures on the left shows the stress induced while the figures on the right illustrates the generated voltage. This is the region near the clamped end of the beam where stress induced electric charge is most profitable.

110 4. Results and Discussions

4.1. Sinusoidal Vibration Waves

The average power responses at the different acceleration input was compared in Figure 4. The energy harvested was remarkably increased with the higher acceleration introduced. It could be also found the peak of energy that can be harvested always occurred at a consistent frequency value of 46 Hz, which is barely related to the acceleration applied. Figure 5 showed that RMS voltage outputs were typically in the order of a few 1's volts, even for a broadband noise excitation. This is ideal for overcoming the minimum diode or transistor voltage thresholds to activate conditioning and power management circuits. The highest average power recorded was 9.25 mW at vibration level of 2.66 m s^{-2} under frequency of 46 Hz, in Figure 5. Higher acceleration scan was not done due to experimental constraints. Given a total volume of 13.5 cm^3 , the power density normalised against acceleration squared is $97 \text{ } \mu\text{W cm}^{-3} \text{ m}^{-2} \text{ s}^4$, which compares favourably against some of the state-of-the-art in the literature, such as a thinned bulk PZT harvester at $105 \text{ } \mu\text{W cm}^{-3} \text{ m}^{-2} \text{ s}^4$ [34]. Similar work was undertaken by other researchers, as presented in Table 5. However, lower

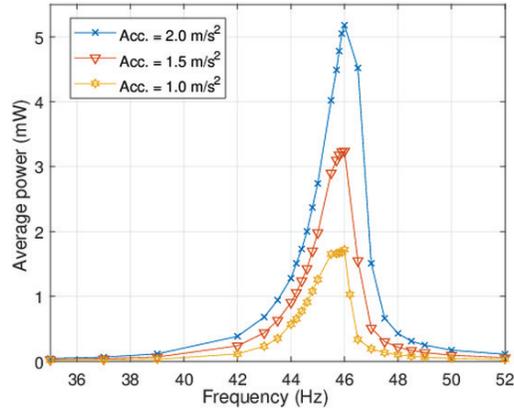


Figure 4: Changes in power outcomes at sinusoidal frequencies of 33 Hz to 52 Hz at various accelerations with a resistive load of 20 k Ω .

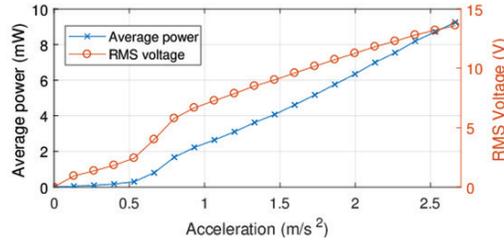


Figure 5: Average power outputs at resonant frequency of 46 Hz with a resistive load of 20 k Ω .

power densities were obtained as shown in the table. The high power density
 obtained in this work was attributed to many factors, such as in a previous
 study finds that integrating MFC M8482-P2 harvester with CFRP laminate
 using co-curing method helps to avoid any additional dissipation of energy as
 130 well as allows the harvester to yield a direct image of strain/displacement within
 CFRP laminate beam [35]. The second factor was the optimised position of the
 harvester on the cantilever structure, a previous study suggests that to opti-
 mize energy output the harvester should be placed 30% - 40% away from the
 135 clamped end [31]. In addition, the MFC co-cured composite offers the benefit
 of flexibility to be compatible with streamlined structure and the resin from
 carbon fibre prepreg forms the protection outside the MFC to resist externally

environmental and operational impact during application.

Table 5: Comparison of power density for various piezoelectric energy harvesters from sinusoidal waves.

Frequency(Hz)	Amplitude (g)	Power density (mWcm ⁻³)	Reference
100	7.2	82	[36]
120.1	0.4	0.0932	[37]
5	0.21	2.255	[38]

4.2. Aerospace Vibration Waves

140 The vibration data used in this study was collected from CGJ aircraft, where the vibration was dominated by an internal mechanical sources. However, due to the vibration of the body (external source) and the aero-engine (internal source) while in-flight, the vibration data was typically broadband and high frequency in nature (≈ 2 kHz) with some periodic frequency signatures embedded [39].
 145 The amplitudes of these vibration waves can potentially attain severals 10's of g. Figure 6a shows a typical example of the broadband vibration (x-axis runs along the aircraft) in-flight. The Fast Fourier Transform (FFT) analysis revealed that there was not a dominant frequency peak and it was a band-limited noise vibration, as shown in Figure 6b.

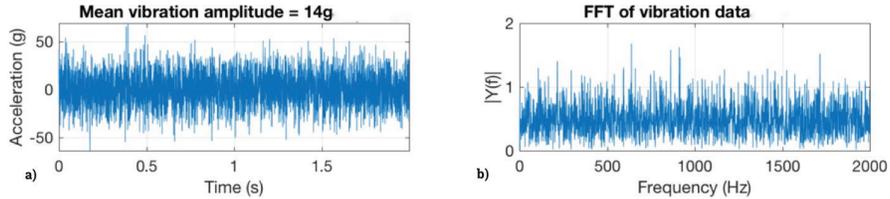


Figure 6: CGJ vibration trace of x-axis[39] in a) time series data and b) FFT analysis. The mean vibration amplitude was 14 g.

150 The average vibration amplitude was around 14 g, while the maximum peak to peak values exceeded 100 g. It was not possible to replicate the full amplitude range of this trace using the available laboratory electrodynamic shaker system,

as described in Section 2.2. Experimental measurements were therefore taken up to 1.8 g average amplitude (over 10 g peak to peak). Using measured results,
 155 a power fit was performed to estimate the power outcomes of input vibration trace up to the full amplitude range was applied (figure 7). During the elevation

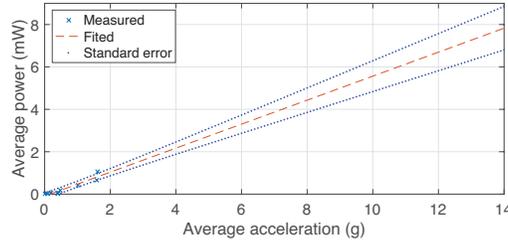


Figure 7: Experimentally measured power response for CGJ aircraft along x-axis vibration trace.

flight data on the other hand, continuously varying periodic frequency signatures started to emerge amongst the broadband vibration. This was contributed in part by the aero-engine. Figure 8 illustrates an example of such a vibration
 160 trace at y-axis and z-axis for CGJ type aircrafts, y-axis ran across while z-axis ran up through the aircraft . The average amplitude varies between 5 g to over 7 g across various axes. Figure 9 presents the experimentally measured average power outputs when the prototype device was subjected to the elevation flight data of CGJ type aircraft. Experimental measurements were taken up to 2.8 g
 165 and numerical fit was applied to over 7 g. Three axes data were separately ran on an electrodynamic shaker and power outcomes measured in turn. In real applications, all three axes vibrations would be simultaneously experienced by the harvester. However, the experimental apparatus adopted in this study can only characterise one axis at a time. The maximum in-flight power density obtained
 170 was 0.077 mW cm^{-3} at vibration amplitude of 1.6 g and 0.577 mW cm^{-3} at vibration amplitude of 14g. At a given acceleration that amount of energy was low when it was compared with commercial harvesters, such as APA400M-MD (CEDRAT technologies,France) and PVEH (MicroStrain,USA) that can harvest up to 1.42 mW cm^{-3} and 0.46 mW cm^{-3} when excited at resonance frequency

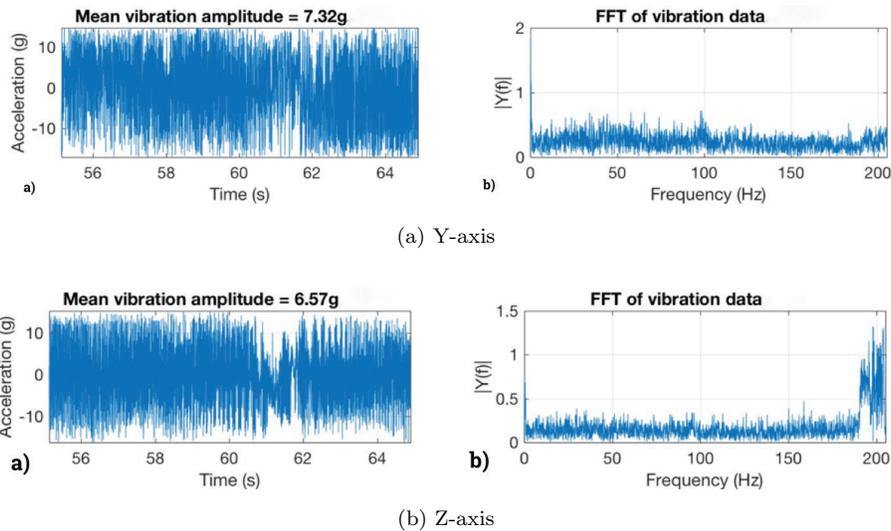


Figure 8: CGJ vibration trace y-axis and z-axis [39] in a) time series data and b) FFT analysis. The vibration amplitudes were 7.32 g and 6.57 g in y-axis and z-axis respectively.

175 of 100 Hz and 1000 Hz (at vibration amplitude 1.5 g) respectively. The current vibration energy harvester has advantages over APA400M-MD and PVEH that it was low profile, highly flexible, and smaller in size 13.5 cm^3 where APA400M-MD and PVEH are 35.2 cm^3 and 64 cm^3 respectively.

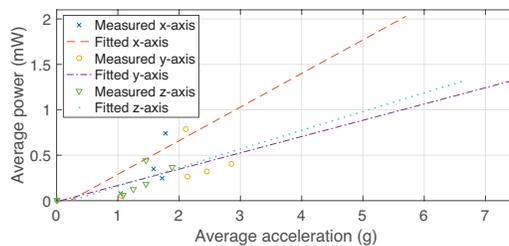


Figure 9: Experimentally measured and fitted power response for y-axis and z-axis CGJ aircraft vibration trace.

4.3. Automotive Vibration Waves

180 The automotive industry has an immense interest in energy harvesting to self-power wireless sensor systems for control and safety purposes as well as V2X

concept and therefore avoid the weight and assembly difficulties resulted from cable/wire connections. Moreover, it is also promising to help assess the safety of battery by efficient self-powered monitoring systems. Although high amount
185 of energy can be recovered from suspension or brake systems in most of road cars, the current study is interested in harvesting power from low frequency and acceleration sources for powering sensors and wireless nodes. Figure 10 presents vibration data measured from under the bonnet of a road car near its engine, the axes were set as following: x-axis ran along the car, y-axis ran across the car,
190 and z-axis ran up through the car. The road car used in this study was a BMW 525D SE 2011 model. X-axis vibration (mean amplitude 0.68 g) contained a clear frequency peak at around 33 Hz corresponding to the engine's 2000 RPM, followed by two harmonics at twice and thrice the frequency. As the RPM of the engine varied when the accelerator was engaged, these frequency peaks
195 also varied. Z-axis vibration (mean amplitude 1.05 g) was more broadband, with a flat active frequency range covering up to the first 200 Hz, suggesting a combination of various structural responses and their harmonics. Y-axis was a combination of the two frequency characteristics with a mean amplitude of 0.86 g. It was noticed that the vibration data in the three axes depended on
200 many factors such as, the roughness of the roads, the health condition of the car and the acceleration.

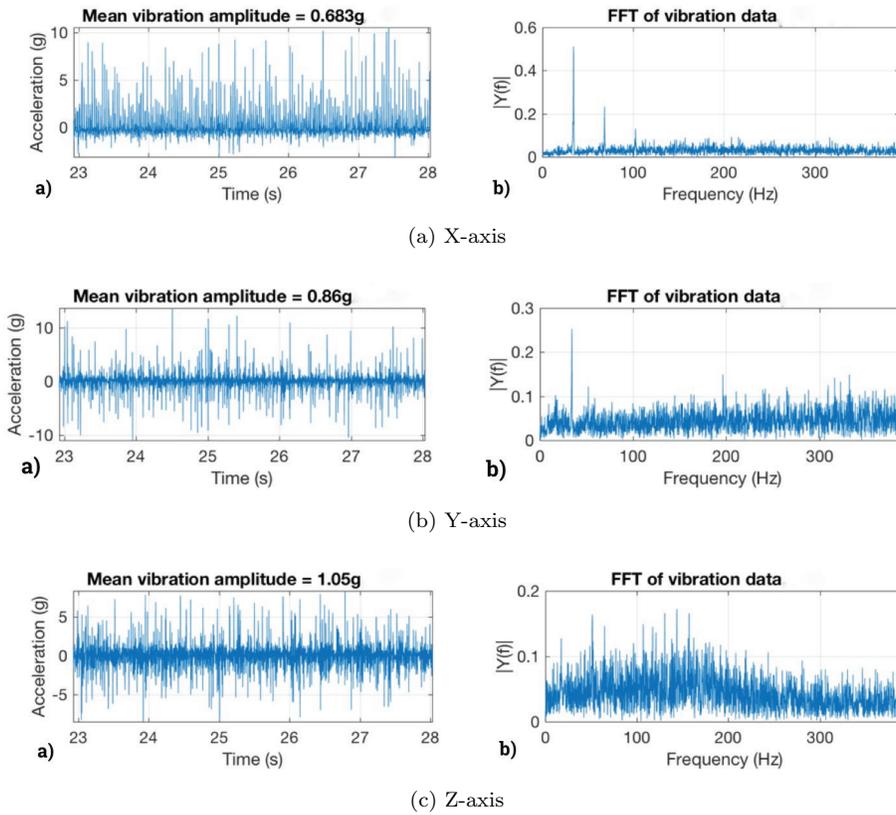


Figure 10: Representative environment vibration of a road car near the engine beneath the bonnet, measured using GCDC vibration logger X16-4 [40]. a) Time domain vibration data, b) FFT analysis.

Figure 11 summarises the average power output measured in the lab, when subjected to representative data testing of various axes. It can be seen that the x and y axes vibration induced the highest power response. The response was off-resonant with some level of resonant trigger from the wide active frequency region covered by z-axis vibration. in Figure 11 the measurements were taken up to 0.65 g within the lab and the rest of the amplitude range up to 1.0 g was numerically fitted as per the existing data.

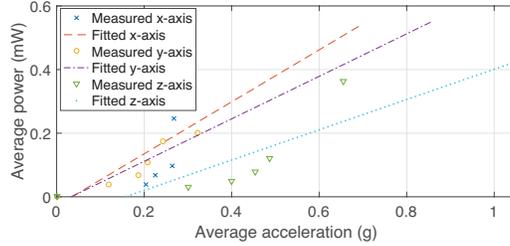


Figure 11: Experimentally measured power response of the energy harvester at varying input accelerations of the automotive vibration data.

It should be noted that the current harvester prototype natural frequency
 210 at 46 Hz does not match with the first frequency peak (33 Hz) of the x-axis
 automotive representative vibration data, as shown in Figure 10. Therefore, the
 power response was primarily non-resonant for this unmatched case. The power
 output can theoretically be substantially improved when the dimensions were
 designed specifically for the target frequency application. Nonetheless, even for
 215 the current experimentally measured output with the mismatched harvester, the
 road car representative data still managed to generate about 0.37 mW average
 power at an average acceleration amplitude of 0.25 g. For an ideally resonance
 frequency matched design, with the same transducer and device size, using a
 finite element model to solve Equation 7, the power output was numerically
 220 estimated to be able to attain 3.5 mW across a load resistance of 20 k Ω [33]. At
 this average power output, there was already sufficient power budget to sustain
 most low power autonomous wireless sensors $\approx 0.8 - 3$ mW[41].

4.4. Machine Vibration Waves

The increased usage of composite materials in machinery encouraged to in-
 225 vestigate the amount of power that could be harvested. For most machine and
 engine applications there is a distinct frequency signature associated with the
 RPM of the motor. By targeting this frequency, harvested energy can power
 condition monitoring sensors. The use of integrated MFC on CFRP material
 can enable these smart functionalities within the housing of the machines. For

230 constant RPM motors, this target frequency does not change. However, for variable RPM motors, the system needs to be designed and optimised to cover the most profitable range of frequencies. Figure 12 shows an example of measured vibration from a 1600 RPM compressor engine. The vibration profile can also contain a number of harmonics and higher order vibration modes.

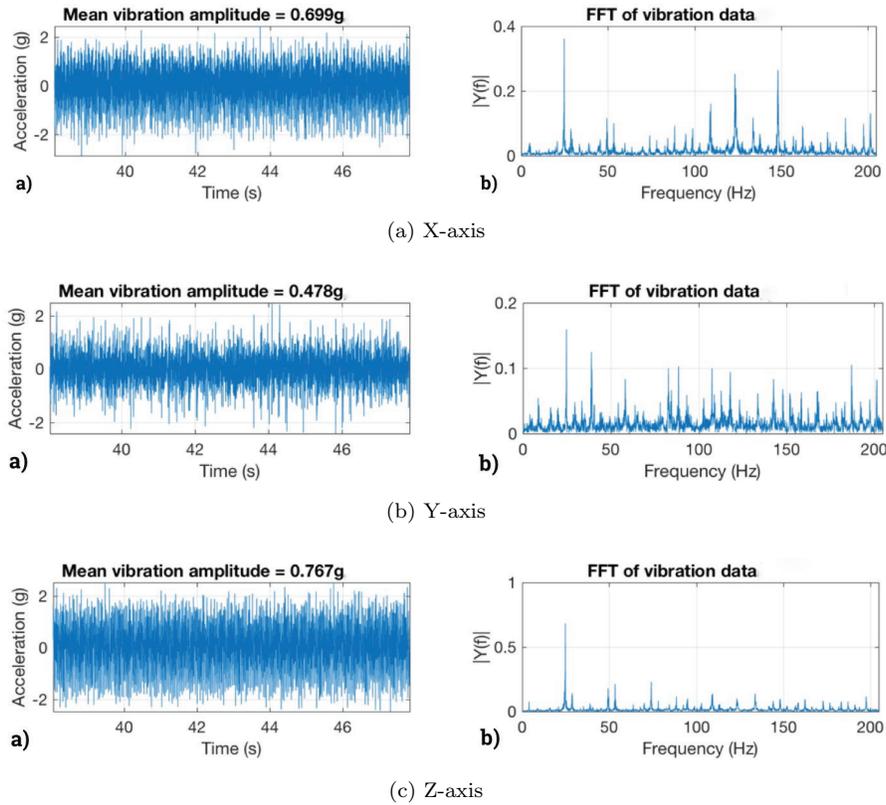


Figure 12: Representative environment vibration of a compressor motor, measured using GCDC vibration logger X16-4 [40]. a) Time domain vibration data, and b) FFT analysis.

235 Similarly with automotive scenario, the harvester natural frequency (46 Hz) also does not match the first frequency peak of the representative data (26.7 Hz), as shown in Figure 12a. Figure 13 illustrates the non-resonant power achievable from all three axes, the mis-matched cases when excited by the representative vibration profile. The highest power outcome was only 77 μ W from z-axis.

240 Y-axis yielded the lowest power outcome due to low acceleration as shown in
 Figure 12b. However, for a perfectly frequency tuned scenario, given the the
 quality factor of around 23, the average power output after resonant amplifica-
 tion was estimated to approximately attain ≈ 1.8 mW. This amount of energy
 was higher than the amount of energy obtained by Henry et al. [42], where
 245 amount of energy obtained from using MFC bonded onto an aluminium shim
 was extremely low and not sufficient to charge a nickel metal hydride battery.
 The researcher used automobile compressor vibration data at a random fre-
 quency in the range between 0 - 500 Hz. However, in the present study the use
 of cantilevered CFRP beam helped to increase the deformation due to vibration.
 250 This is in turn led to higher energy accumulation.

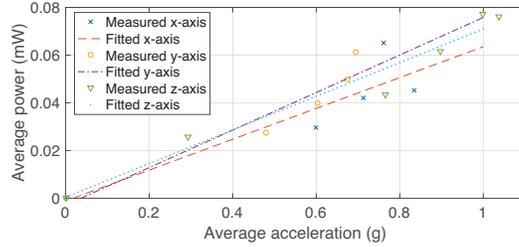


Figure 13: Experimentally measured power response across $20\text{ k}\Omega$ of a resistive load for varying input acceleration of the compressor motor vibration data.

4.5. Bridge Vibration Waves

There has been increasing interests to adopt piezoelectric materials in in-
 frastructures, such as roadway and bridges [43, 44]. Composite material with
 the proposed integrated energy harvesting functionality can also be used in in-
 255 frastructural applications, such as the body of key support structures within
 bridges, tunnels and rail applications. In addition to their lightweight, CFRP
 laminates have shown a high compatibility with the MFC energy harvester, the
 energy harvested in turn may be used to power and sustain embedded sensors
 for health monitoring of a structure or other applications. Different transducer
 260 configurations were adopted on roadways, such as cymbal piezoelectric trans-
 ducer [45], the energy harvested was 1.2 mW at frequency of 20 Hz per one

vehicle passage. Other researchers used the energy generated via piezoelectric materials to power LED signs [46, 44]. In this study, vibration data collected from cross girder of the Forth Road suspension bridge (Scotland, UK) [40] was used to harvest energy by MFC M8528-P2/CFRP laminate harvester. Figure 14 shows overhead time-dependent traffic introduces vibration that triggers structural vibration of the cross girder and other localised structural response. A first resonant peak occurred at around 15 Hz, along with higher frequency peaks in excess of 100 Hz. Apart from being broadband, the main challenge in harvesting this vibrational source was the time-varying nature of the vibration. This makes sustained resonant build up particularly difficult to achieve.

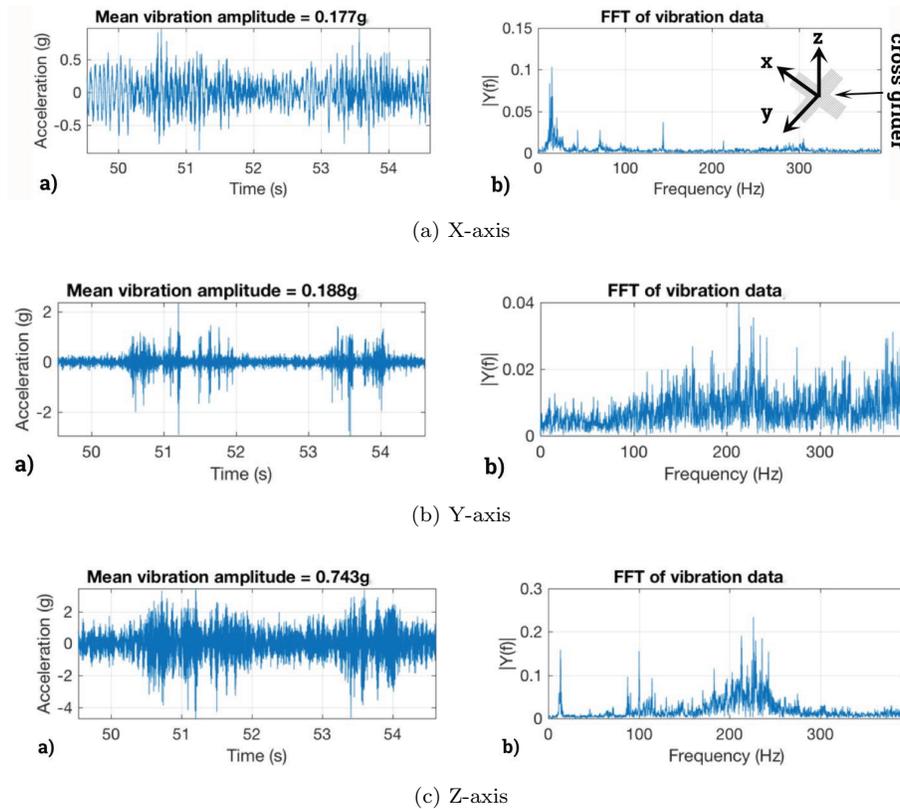


Figure 14: Representative environment vibration for three axes of cross girder on the Forth Road Bridge (suspension bridge), measured using GCDC vibration logger X16-4 [40]. a) Time domain vibration data, b) FFT analysis.

It can be noted from Figure 14 that the bridge vibration in three directions (x-axis, y-axis, and z-axis) were low frequencies and small amplitudes, however power of the order of 0.19 mW was harvested from vibration in y-axis, as show in Figure 15. The response of the structure was off-resonance with occasional resonant triggered due to the frequency varying broadband spectrum. Despite the frequency mis-match between harvester’s 46 Hz natural frequency and the first frequency peak of the representative infrastructural data at 15 Hz, an average power of 0.17 mW was measured at an average acceleration amplitude of 0.32 g. For a matched frequency harvester design, the average power was estimated to attain 1.0 mW. The harvested energy was 17.7% higher than the energy harvested from bridges due to traffic-induced vibrations as reported in [47], where a cantilevered traffic-induced energy harvester was excited at resonance of 14.5 Hz and vibration amplitude of 0.03 m s^{-2} .

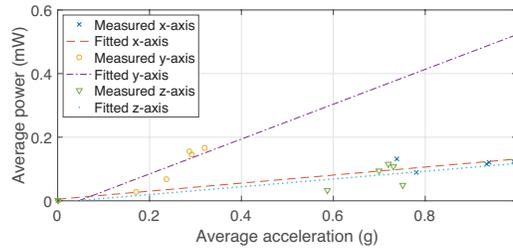


Figure 15: Experimentally measured power response measured across $20 \text{ k}\Omega$ load resistance for varying input acceleration of the suspension bridge vibration data.

5. Conclusions

The result of an extensive experimental and numerical study conducted on carbon fibre composite laminates and macro-fibre composites are presented and discussed thoroughly. Hence, this paper will be helpful resource and reference with real world vibration data for multifunctional composites with energy harvesting capability. The energy harvesting of sinusoidal, aerospace, automotive, machinery, and infrastructure vibration waves is investigated. Figures 7, 9, 11,

13, and 15 indicate that relatively high-power outcomes from the thin profile and flexible harvester offers a feasible on-composite laminate power solution for microelectronics and sensors that can be similarly integrated onto the composite stack.

295 For sinusoidal vibration waves at resonance of 46 Hz and vibration amplitude of 0.27 g , power of 0.6 mWcm^{-3} is obtained. Power output obtain from environmental vibration waves was lower in magnitude than sinusoidal vibration waves. Environmental CGJ aircraft vibration waves yield power in the range between 0.077 mWcm^{-3} to 0.577 mWcm^{-3} at vibration amplitude of 1.6 g and
300 14 g respectively. Power harvested from environmental automotive (BMW 5 series) , compressor, and a suspension bridge vibration waves are much lower than CGJ aircraft. Power outputs are 0.027 mWcm^{-3} at frequency of 33 Hz and vibration amplitude of 0.25 g, $5.7 \mu\text{Wcm}^{-3}$ at frequency of 26.7 Hz and vibration amplitude of 1 g, and 0.012 mWcm^{-3} at frequency of 15 Hz and vibration
305 amplitude of 0.32 g respectively. It is noted that the power outcomes can be substantially increased when the harvester is tuned to operate at the resonance frequencies.

Acknowledgements

This research was supported by Innovate UK (Project Reference 104030).

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