VIBRATIONAL ENERGY HARVESTING OF MULTIFUNCTIONAL COMPOSITE BLADE FOR OFFSHORE WIND TURBINE

T. Wen[1], Y. Shi[1], J. Tao[2], L. Pan[2] and Y. Jia[3]

[1,3] Department of Mechanical Engineering, University of Chester, Pool Lane, Chester, UK
Mechanical Engineering and Design, Aston University, Birmingham, UK
[1] t.wen@chester.ac.uk
[2] Department of Material Science and Technology, Nanjing University of Aeronautics and Astronautics, No. 169 Sheng Tai West Road, Jiang Ning District, Nanjing, Jiangsu Province, China

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ABSTRACT

Glass fibre composite, as a high strength and lightweight structural material, is widely applied to the wind turbine blades. Without affecting its mechanical properties, the vibration energy harvesting capability to power attached wireless sensor networks (WSNs) technology can be realized by integrating PZT macro- fibre composite onto the structure. Based on the multifunction composite concept, a PZT macro-fibre composite co-cured within the surface of glass/epoxy pre-preg is manufactured. The resultant mechanical plate combined with actual vibration data from wind field can implement power generation. The experiment average output voltage of 4.10 V, which relates to power of 0.84 mW, was estimated. The FEA simulation average output voltage is about 4.46 V, which the error is less than 10% compared with experiment.

1 INTRODUCTION

The Fibre composites are extensively applied in various industries due to its lightweight and excellent mechanical advantages. Simultaneously, there is also a growing requirement to realise multi-functional composite in order to add structural health self-monitoring capabilities onto otherwise mechanical material based on its application environment. The WSNs applied on wind turbine blades can offer in situ early detection of the damages within the glass fibre composite blades. However, the power supply for WSNs has become a challenge under this setting, as transitional wire transmission way is inadvisable with extra part altering the structural profile [1]. The integration of Piezoelectric macro-fibre composite (MFC) onto wind turbine blades implements on-site energy generation and perfectly solves the transmission problem. The MFC is fabricated by embedding piezofibers in an epoxy matrix and coated with Kapton skin [2]. This research work set upon previous work of integrated MFC on carbon fibre composite for energy harvesting application onto mechanical structure [3]. The same method while applied on glass fibre composite is processed in present work. A pre-cured MFC on glass fibre plate with minimize potential effects to its mechanical properties is manufactured.

2 EXPERIMENTAL DESIGN

2.1 Vibration data processing

The wind turbine vibration data used in this work is measured at 6 m from the root of a 42 m long wind turbine with an X16-4 rechargeable data logger by Titan company in China. This data logger can collect acceleration data in three directions, where z orientation is the normal direction of the turbine blades. Also, the bending torque caused on z axis, as the leading factor affecting the energy harvested, is the main research part of this experiment work. The practical acceleration data on z axis is shown in figure 1.

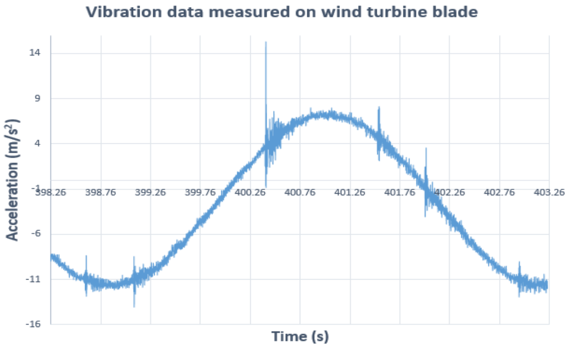


Figure 1: Practical vibration acceleration input on Z orientation.

However, as can be seen, the rough sine wave, due to circular motion of turbine blade, is caused by gravitational acceleration. These acceleration data, which is non-vibration data, is filtered out by polynomial function processing within Matlab. The filtered vibration data is shown in figure 2.

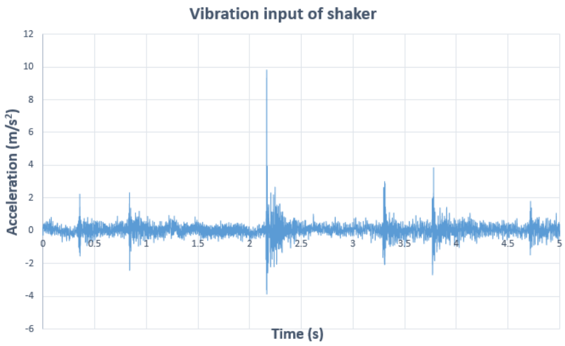


Figure 2: Vibration acceleration filtered out gravity affect.

2.2 Experiment setup

The experimental setup to characterize the harvester is shown in figure 3. The vibration data normalized for waveform editor is used as input acceleration to excite the vibration shaker through function generator and its output amplitude is amplified by power amplifier. In order to simulate the original state of the vibration amplitude of wind turbine blade onto glass fibre composite cantilever, the accelerator powered by DC power supplier is fixed on the shaker, where its amplitude value shown on oscilloscope can verify the experiment accuracy. Meanwhile, the MFC procured on the cantilever transfers the mechanical energy to electrical energy, which is also presented as output voltage on oscilloscope.

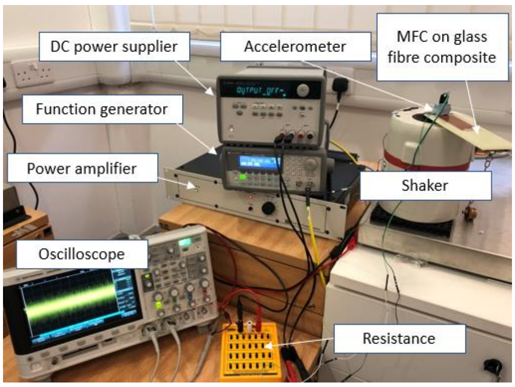
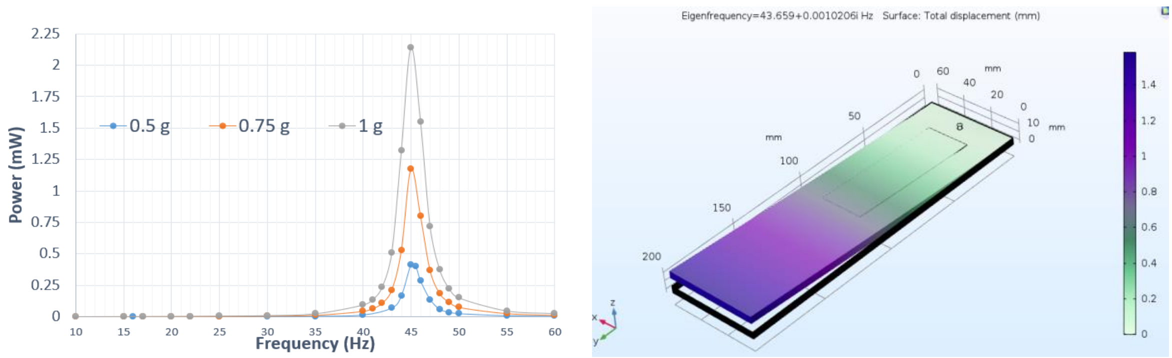


Figure 3: Experimental setup to characterize the harvester.

3 PRELIMINARY TEST AND EXPERIMENTAL

3.1 Preliminary test result and data processing

To detect the resonant frequency where highest power would be generated in the same vibration condition, the frequency domain response under sine waveform of different amplitudes were tested. Figure 4(a) presented that over 2mW power can be generated at 1g around 45 Hz. In addition, with the intention of verifying the accuracy of the resonant frequency tested, a three dimensional (3D) finite element model was performed by the commercial software COMSOL to simulate the modal result, which is 43.659 Hz, as shown in figure 4(b). Compared with the experiment result tested, the error is less than 2.9%.



(a) (b)

Figure 1: (a) Frequency domain response measured across 20 kΩ, (b) Simulation modal result on COMSOL model.

3.2 FEA simulation and blade tip vibration prediction

As the vibration data is collected from root segment, the preliminary test based on root condition has been made in order to have a potential awareness in mind about its value of energy harvesting, also can be considered as a criterion to compare the subsequent test result of energy harvesting from tip segment. According to the basic information provided by TITAN company, a 4 mm thick glass fibre cantilever was fabricated with integrated MFC and applied to the experimental setup to measure the efficiency of energy harvesting, as shown in figure 5 below.

Figure 5: 4 mm glass fibre cantilever integrated with MFC.

Consequently, the RMS (root mean square) voltage output recorded from oscilloscope is about 260 mV across a load resistance of 20 kΩ, which relates to 3.38 μW, due to the vibration amplitude at the root segment is too small to generate effective electrical power.

However, this power level is expected to be higher towards the tip of the blade where acceleration is larger. Therefore, a wind turbine FEA model, as shown in figure 6, is set up to predict the vibration result of blade tip with actual activation subjected to the root of the blade model.

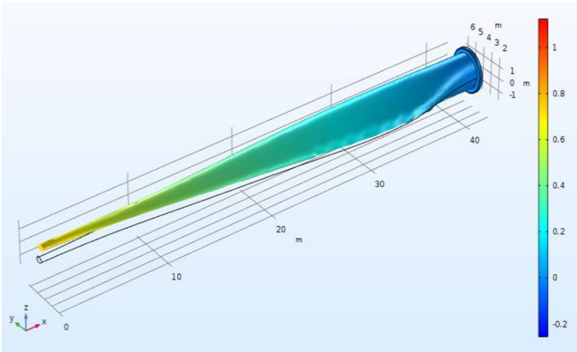


Figure 6: Turbine blade displacement result of FEA model.

According to the FEA simulation result, a point of the blade tip geometry was selected and defined to plot its acceleration and displacement result, which can properly reflect its predicted vibration circumstance, as shown in figure 7. It can be noted that the acceleration floating curve between positive and negative region of the figure is uniform, which is reasonable. Also, the displacement changing of blade at tip area shows a tendency as elastic round-trip motion, in addition, the maximum deflection of the blade tip within the selected time period is under 1.2 m, which is still reasonable compared to the length of the wind turbine blade.

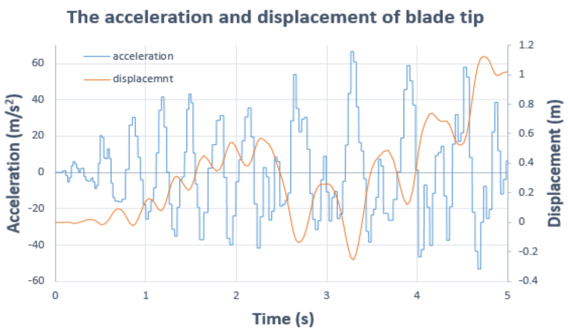


Figure 7: FEA result of wind turbine blade tip.

4 ANALYSIS AND FINAL RESULT

Based on the above vibration data, the energy harvesting result of blade tip, where thickness is 0.8 mm, has been simulated under the same set up of boundary conditions and input loads, as shown in figure 8 below. According to the results, the RMS voltage output calculated from these data is about 4.46 V across a load resistance of 20 kΩ, which relates to 0.99 mW.

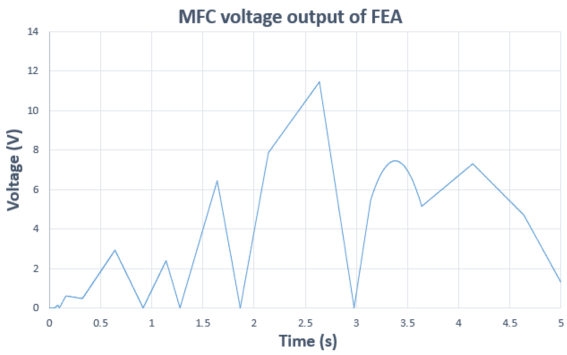


Figure 8: FEA voltage output.

To validate the FE model result, an experimental test is processed by employing the experimental setup mentioned previously with the same circumstances applied to the FE model. However, the obtained blade vibration output result, as can been seen in figure 6, is not a smooth continuous curve, which does not conform the practical circumstance. In addition, its proximate step vibration input is impossible for shaker to realise during the experimental test. Therefore, a processing with filter function was applied to the output vibration acceleration result simulated in order to smooth the vibration of the shaker, and the optimized data is shown in the figure 9.

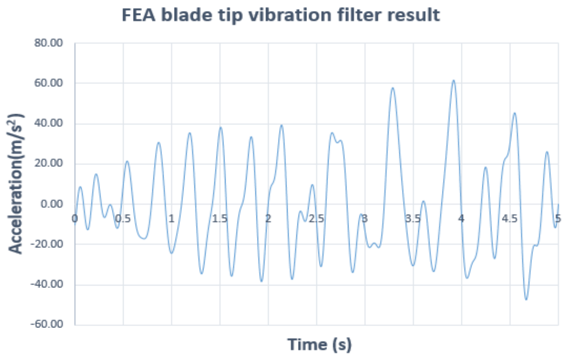


Figure 9: The filtered blade tip vibration output result.

Hence, this optimized vibration result is normalized and then imported to the waveform edit on computer, which is connected to function generator as signal source. In order to intuitively show the effect of amplitude on energy output, incremental excitation is adopted to excite the glass fibre composite plate, where RMS voltage output generated can be measured and displayed on oscilloscope. However, due to the limitation of the shaker, the maximum peak-to-peak acceleration that shaker can approach is about 10 g, while the peak-to-peak acceleration of predicted vibration data is about 12 g.

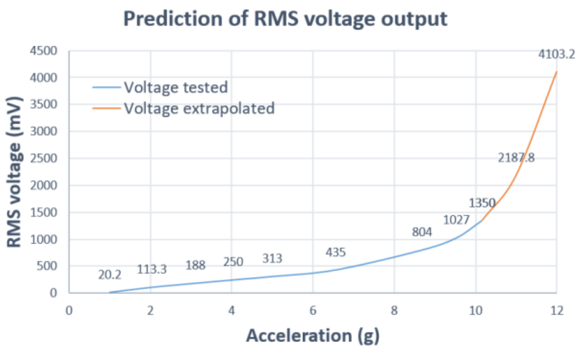


Figure 10: RMS experiment extrapolation result.

Figure 10 illustrates the prediction processing of RMS voltage output, with experimental tested RMS voltage output data under 10 g acceleration, as the blue curve shown in figure, where an extrapolation function is adopted to predict the RMS voltage output result around maximum peak-to-peak acceleration, as the orange curve shown in figure above. The highest RMS voltage extrapolated at 12 g is about 4.103 V, whose error is less than 10% compared to the FEA simulation result. Also, figure 11 shows the prediction of power output result as converting the voltage output result.

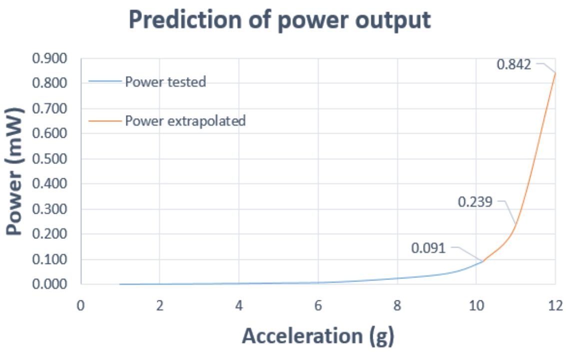


Figure 11: RMS experiment extrapolation result.

5. CONCLUSIONS

This paper presented a glass/epoxy pre-preg cantilever integrated with a MFC, contributing to a capacity of vibration energy harvesting within the structure. This technology of collecting energy in situ makes it possible for mechanical structure realizing functionalities where it could not be applied in the past due to the application circumstance. The resultant electrical output from the piezoelectric transducer were simulated and was validated by the experimental result with same conditions. The experimental measurement deviated from the FE model simulation by less than 10% in terms of the average voltage output. Consequently, the proposed concept that WSNs applied on wind turbine blades offering in situ early detection of the damages within the glass fibre composite blades has made a valuable progress. Also, this technology can enable the parametric research for further topological design so as to realise real-time computational analysis for achieving the purpose of detection and optimization.

ACKNOWLEDGEMENTS

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REFERENCES

[1] A. Gaglione, D. Rodenas-Herraiz and Y. Jia, S. Nawaz, E. Arroyo, C. Mascolo, K. Soga, et al, Energy neutral operation of vibration energy-harvesting sensor networks for bridge application, *EWSN*, 1-12. (http://dl.acm.org/citation.cfm?id=3234847).

[2] H. A. Sodano, *Finite element analysis of composite laminates Mocro-fiber composites for sensing, actuation and power generation*, 2003.

[3] Y. Jia, X.Y. Wei, L. Xu, C.S. Wang, P.Y Lian, S. Xue, A. Al-Saadi and Y. Shi, Multiphysics vibration FE model of piezoelectric macro fibre composite on carbon fibre composite structures, *Composites Part B: Engineering*, **161**, 2019, pp. 376-385 (doi: https://www.sciencedirect.com/science/article/pii/S1359836818341234).