SANDWICH STRUCTURES WITH GRADED CORE TOPOLOGIES FOR PIEZOELECTRIC ENERGY HARVESTING

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ABSTRACT

This paper developed a smart sandwich structure with functional grading design on the re-entrant honeycomb core. Functional grading schemes of linear and bilinear cell ligament angle variation have been proposed. The sandwiches with the grading-designed cores were 3D printed, and piezoelectric P(VDF-TrFE) transducers were inserted between the sandwich facesheet panels and the cores. The smart sandwiches were tested in terms of their piezoelectric energy harvesting performance. It has been found that the sandwich with the optimised grading scheme could exhibit a maximum 158.7 nW power at its resonant frequency and under 0.71 g RMS sinusoidal excitation. The power generated by the sandwich with optimised core grading scheme was almost 60% higher than the sandwich with non-graded re-entrant honeycomb core.

1 INTRODUCTION

The sandwich structures with cellular cores are one of the most prevalent engineering structures due to the feature of light-weight and excellent energy absorption performance[1,2]. Sandwich structures consist of a cellular core in the middle and two facesheet panels on both sides covering the core. The cellular core topology design has been a hot topic. A large number of core topologies have been proposed by the academics to improve the energy absorption and vibrational damping properties[1–8].

Among all cellular topologies, auxetic cellular structures received attention in applications such as sports, automotive and military. Auxetic feature means negative Poisson's ratio. Sandwiches with auxetic features have already been investigated to be beneficial in terms of crashing force efficiency, bending response and energy absorption [9,10]. Particularly, the application of auxetic concept on piezoelectric energy harvesting began to receive interest in 2017 [11]. Sandwich structures with auxetic re-entrant honeycomb cores have been proven to exhibit better power generation performance compared to the sandwich with non-auxetic conventional honeycomb [12].

Topological cores with functional grading design have also been richly studied in terms of the static and dynamic mechanical performance of the sandwiches. The grading parameters being commonly studied were normally the relative density and cell ligament angles [13–15]. Specifically, the effect of auxetic grading design on the dynamic features of the sandwich structures, such as natural frequencies, has been investigated [14]. Inspired by this work, in the present paper, sandwiches with a number of graded re-entrant honeycomb cores were combined with piezoelectric element. The effect of functional grading on the energy harvesting performance was experimentally and numerically assessed.

2 DESIGN, MODELLING AND EXPERIMENT

It has been identified from the previous work [12], that the re-entrant honeycomb topology design helped to improve the power generation efficiency of the sandwich structure. The improvement was due to auxetic feature of the re-entrant honeycomb and low stiffness of the re-entrant honeycomb cell. This work introduced the concept of functional grading, and three grading designs on the cellular topologies were proposed.

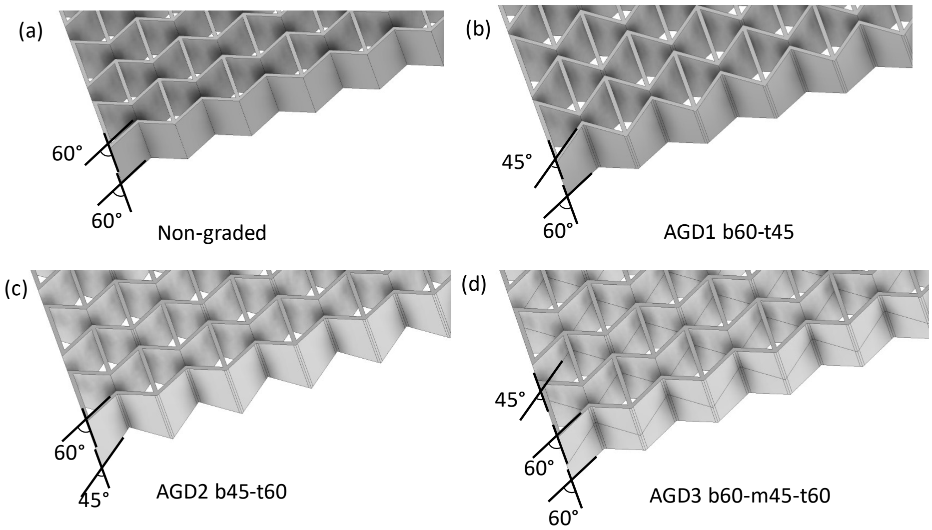

Figure 1 Cores of graded topologies design (a) Non-graded (b) AGD1 b60-t45 (c) AGD2 b45-t60 (d) AGD3 b60-m45-t60

The first design, illustrated by Fig.1 (b) had the cell wall angle of 60˚ at the bottom of the core. The angle varied linearly to 45˚ at the top. The second design was similar to the first one, but it was reversed in terms of the mid-plane of the cellular core (Fig. 1(c)). In the third design, the cell ligament angles at both sides of the cores were both 60˚, and they varied bilinearly to 45˚ in the mid-plane (Fig. 1(d)). The benchmarked non-graded design was denoted in Fig. 1(a), with a constant cell ligament angle of 60˚ throughout the thickness direction[12]. The three grading designs will be dubbed as AGD1, AGD2 and AGD3 in this work, respectively.

The sandwich prototypes were 3D printed using Acrylonitrile Butadiene Styrene (ABS). To fabricate the piezoelectric transducer, silver ink was first of all, inkjet printed onto the Kapton substrate to form the bottom electrode. Next, the P(VDF-TrFE) solution was spin-coated on the electrode to form a 10 μm thick piezoelectric layer. The silver top electrode was sputtered onto the P(VDF-TrFE) film. The piezoelectric transducer was polarized by a home-built polarization setup at electrical field of 50 V/μm. The P(VDF-TrFE) transducer was inserted between the top facesheets and the cellular cores with designed cellular topologies, and top facesheets were heat pressed to be bonded to the rest of the smart sandwiches via film adhesive.

To assess the energy harvesting performance, sandwiches with cores of different graded core topologies were mounted onto a dynamic shaker with a 3D printed fixture. A functional generator was used to generate sinusoidal signal of different frequencies. The signal was amplified by a power amplifier and sent to the shaker to provide sinusoidal excitation. An accelerometer was mounted on the fixture to monitor the input acceleration. At open-circuit condition, a frequency sweep was applied to find the 1st bending mode resonant frequencies of sandwiches with different core topologies. Meantime, the RMS voltage output at resonance was recorded. At the 1st bending mode resonant frequencies, resistance sweep was performed in order to obtain the maximum power, and the optimum resistance at which the maximum power was obtained. For sandwiches with each topological core, 0.35 g, 0.53g and 0.71 g RMS sinusoidal excitation was applied, in order to study the power output variation with increase of acceleration magnitude.

To simulate the energy harvesting performance, piezoelectric device in COMSOL Multiphysics was employed. The piezoelectric device Multiphysics consists of a 'solid mechanics' physics where all the boundary conditions and loading were built up, and an 'electrostatic' physics to monitor the electrical output. In 'solid mechanics', a fixed constraint was applied to the pinhole on the fixture, and the base excitation with magnitude same as the experiment was exerted as a body load. In the 'electrostatics', one side of the piezoelectric patch was assigned to 'ground' and the other side 'floating potential'. In this case, the open-circuit voltage output could be monitored. The settings were schematically represented in Fig. 2. In terms of the study steps, an 'eigenfrequency' study was performed first to obtain the 1st bending mode natural frequencies of sandwiches with cores of all the designed cellular topologies. After obtaining the information of natural frequency, a 'frequency domain, modal' study was implemented to calculate the voltage amplitude under harmonic excitation. The damping ratio of the 1st bending mode was measured in the experiments and given into the modal solver. The critical material properties used in the model were listed in Table 1.

Mechanical properties of ABS[16]	
Young's modulus (GPa)	2.2
Poisson's ratio(1)	0.3
Density(kg/m^3)	1150
Mechanical, dielectric and piezoelectric properties of P(VDF-TrFE)[17]	
Compliance matrix S_{11} ($x10^{-10}$ 1/Pa)	3.28
Piezoelectric coefficient d_{31}(pC/N)	13
Dielectric constant (1)	14
Density (kg/m^3)	1879

Table 1 Material properties of ABS and P(VDF-TrFE) in the finite element model

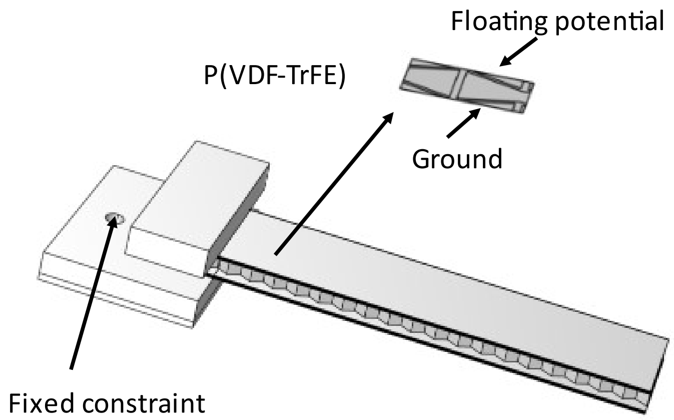

Figure 2 Boundary conditions of the finite element model

3 RESULTS AND DISCUSSION

The open-circuit voltage outcome from experimental measurement and simulation was plotted in Fig. 3, with critical result listed in Table 2. It was observed from Table 2 that the result deviation of experiment to the simulation was smaller than 15%. The deviation might be due to the tolerance caused during the manufacture process and the piezoelectric properties of P(VDF-TrFE). In the finite element modelling, the piezoelectric patch/top facesheet interface, and the piezoelectric patch/core interface were assumed to be perfect bonding. However, practically, there might be potential gaps at the facesheet/core interface which would influence the stress transfer efficiency.

It could be observed from Table 2 that the numerical prediction inclined to overestimate the 1st bending mode resonant frequencies of the sandwich structures. Except for the material property mismatch between the real prototypes and the models, another potential cause might be the deterioration of structure stiffness by the integration of piezoelectric elements.

According to Fig. 3 and Table 2, apparently sandwiches of AGD1 and AGD2 had a higher RMS voltage output compared to sandwiches with other two types of core topologies. Compared to the sandwich with non-graded re-entrant honeycomb core, sandwiches with AGD1 and AGD2 design had an overall lower stiffness. This contributed to a higher deformation under the same loading, and therefore a higher voltage output could be obtained. In addition to the stiffness, sandwiches with AGD1 and AGD2 design were also beneficial in terms of their lower 1st bending mode damping ratio. The sandwich with AGD3 design had similar core stiffness to sandwiches with AGD1 and AGD2 designs. But the higher damping ratio resulted in an inferior voltage output, compared to sandwiches with other two kinds of graded core designs.

To obtain the maximum power output for sandwiches of each core design, the resistance sweep was performed, at 0.71 g RMS sinusoidal excitation, and at the resonant frequencies of each type of the sandwich structure. The result of the resistance sweep was given in Fig. 4. The sandwich with AGD1 design exhibited the highest power output, which was 158.7 nW, obtained at 3 MΩ. The power density in this case was 314.4 W/(m^3.g^2). Power output of 139.5 nW was obtained by sandwich of AGD2 core cellular design, which was similar to the case of sandwich with AGD1 core design. Only 43.5 nW power output could be generated by sandwich with AGD3 design, which was even lower than sandwich without grading core topology. This might be due to the deterioration of adhesion of piezoelectric element with the core during the vibrational process.

To exhibit the power enhancement with the increase of acceleration magnitude, for sandwiches with each core cellular topology design, power output at 0.35 g, 0.53 g and 0.71 g RMS sinusoidal excitation was captured. The result was given in Fig. 5. The power output was obtained at the resonant frequencies of the sandwich structures, and at their optimum external resistance. In the case of sandwich with AGD1 core cellular topology, only 37.4 nW power could be obtained at 0.35 g RMS acceleration, and the power output rose to 158.7 nW when the RMS acceleration magnitude increased up to 0.71 g.

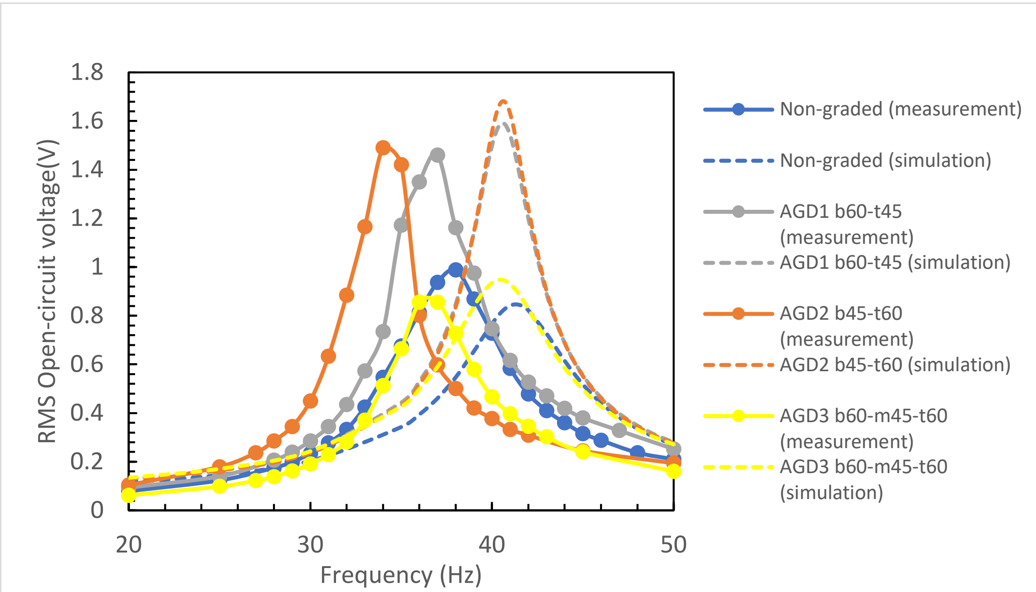

Figure 3 Experimental and numerical open-circuit voltage output of different graded core topologies design

Design	Resonant frequency, experiment (Hz)	Resonant frequency, simulation (Hz)	RMS voltage, experiment(V)	RMS voltage, simulation(V)	1st mode damping ratio
Non-graded	38	41.3	0.99	0.85(-14.14%)	0.068
AGD1	37	40.5	1.46	1.59(+8.90%)	0.04
AGD2	34	40.6	1.49	1.68(+18.75%)	0.037
AGD3	37	40.5	0.86	0.94(+9.30%)	0.068

Table 2 Resonant frequencies and RMS open-circuit voltage outcome of sandwiches with different cellular topologies

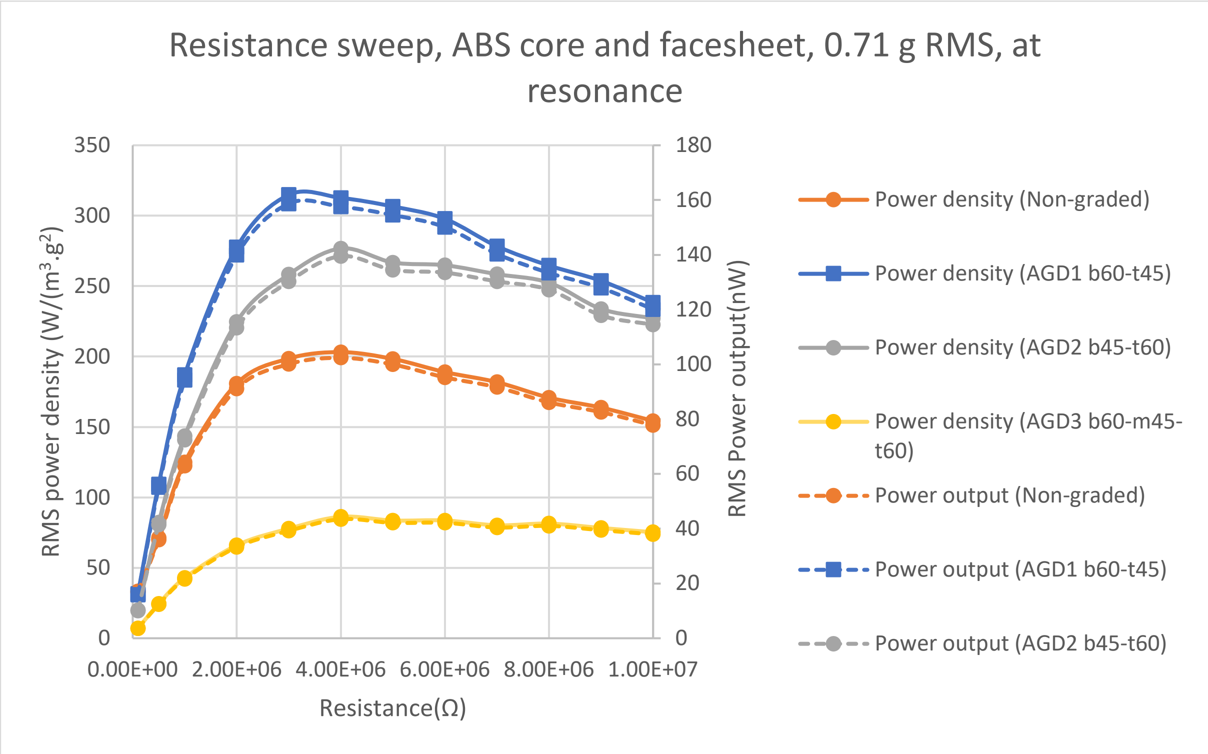

Figure 4 Resistance sweep of sandwiches with different cellular topologies, at 0.71 g RMS acceleration and at resonant frequencies

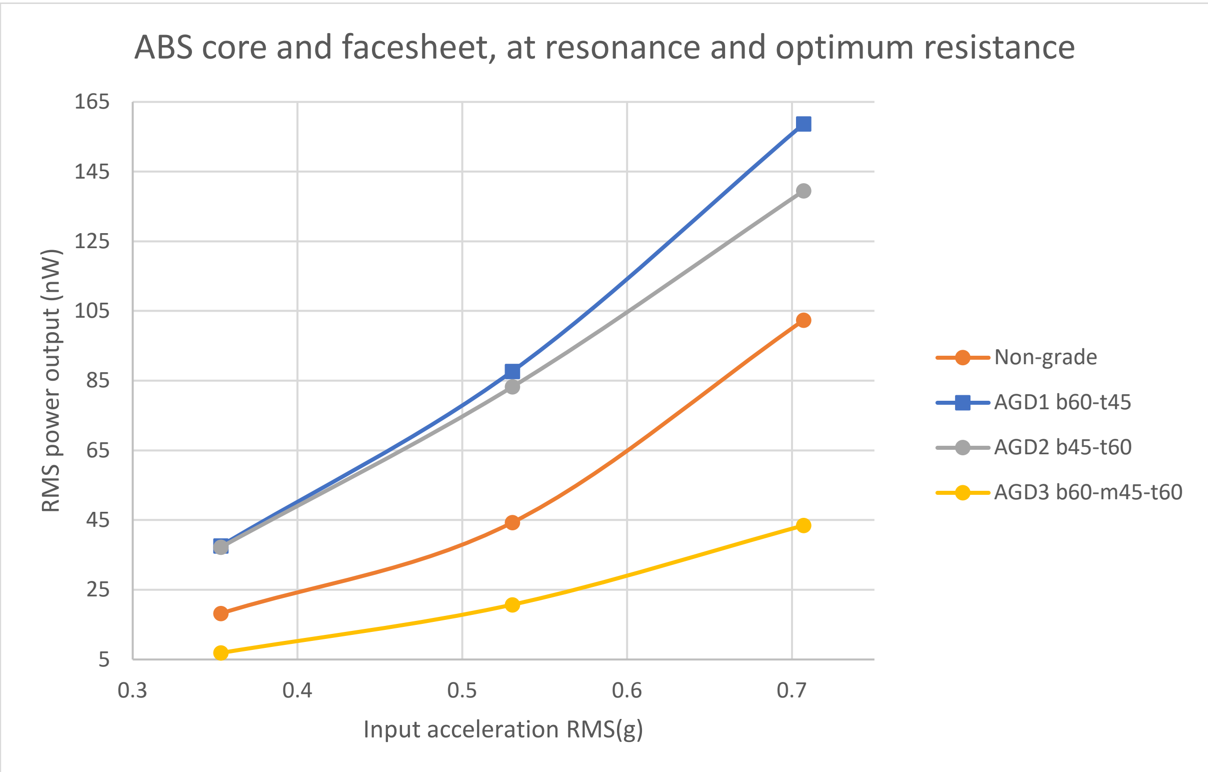

Figure 5 Power output variation with input acceleration magnitude, for sandwiches with different core topologies

4 CONCLUSIONS

The present work studied the effect of grading design of sandwich cellular core topology on the piezoelectric energy harvesting performance. Sandwich structures with re-entrant honeycomb cores of non-graded, linearly grading AGD1 and AGD2, and bilinearly grading AGD3 were designed, manufactured, and tested under sinusoidal vibration to evaluate the energy harvesting performance. Finite element analysis was employed to calculate the open-circuit voltage output of sandwiches with cores of all designs to validate the outcome from the experiment.

It has been found that sandwich with cellular core of AGD1 design exhibited the best energy harvesting performance. At 0.71g RMS acceleration, the sandwich could generate as high as 158.7 nW power at 1st bending mode resonant frequency and at optimum resistance. In contrast, the energy harvesting performance of sandwiches with cores of non-graded design and AGD3 design were inferior, probably because of the high core stiffness and the high 1st bending mode damping ratio.

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