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# Study of Honeycomb Layering in Multi-plane Configuration for Vibrational Energy Harvesting

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***Abstract*—Vibration Energy harvesting converts renewable energy, ambient kinetic energy mostly generated from unwanted mechanical parts vibration or human motion into electrical energy. The honeycomb beam has shown promising results with better vibrational dynamics compared to other shapes or geometry. Dynamical deflection is one of the main factors for effective vibration energy harvesting which depends on the stiffness of the structure. This research aimed to investigate the frequency response of honeycomb beam in single layer and double layers configurations with different thicknesses and out-of-plane orientation layout. Multi-plane configuration allows the manipulation of the vibrational amplitude to weight ratio for better adaptability to suit different applications. Simulation and experiment were conducted to investigate and compare the dynamical amplitude and natural frequency. The double layers honeycomb beams have higher natural frequencies as compared to single layer for the same thickness. The vibrational amplitude decreases with thickness for the same layering configuration due to stiffness. Double layer orientation could potentially provide higher amplitude-to-weight ratio, therefore power as compared to single layer with weight manipulation in its configuration.**

***Keywords*—beam, unit cell, thickness, 3D print, weight ratio**

## I. INTRODUCTION

Energy harvesting is a process of transforming energy into a small level of power [1]. Kinetic energy, also known as ambient energy, is the source of energy harvesting attainable from the unwanted vibration of a vehicle, natural vibration of a bridge, and human motion. The unwanted vibration will be released to the surroundings as wasted potential energy, vibrational energy harvesting able to convert this energy into electrical energy through different techniques [2]. With the drive to promote sustainability, research and effort have been done to develop energy harvesters to replace battery usage. The kinetic energy harvester still requires more research and development as the power-to-weight ratio in most of the energy harvesters research are lower than a battery and only can function as power source support to lengthen the lifespan of a battery [3]. Different geometries of single layer beams were studied, and honeycomb has shown promising performance that can enhance the vibration [4]. There is high interest on its conversion to energy harvesting. The limitation of vibrational energy harvesting is power generated performance highly rely on the resonance of the harvester which is random in real life environment [5]. Different approaches had been done such as changing material and optimization of design to broaden the frequency bandwidth which produce effective power output. With the advancement of technology, there is a need for dimensionally small-scale energy harvesting mechanisms in the near future to provide sustainable power supply to devices. The uncertain environmental frequency will require a more robust vibration system to attain resonance frequency. Therefore, physical flexibility is important as the harvester core component allows natural frequency manipulation to attain high power to weight ratio for efficient energy generation. Multi-plane and layer orientation have yet to be studied which has potential for different parameter manipulation such as weight and stiffness for the same overall size. This paper will investigate the frequency response and dynamical vibration of 3D printed honeycomb infill beams of different layering configurations and thicknesses on a vibrational energy harvester.

## II. LITERATURE REVIEW

The advancement of 3D printing technology has brought interest in fabrication of piezoelectric energy harvester [6]. The development of additive manufacturing has reduced the power-to-weight ratio gap in energy harvesters due to its flexibility in manipulating the specification, manufacturing method and material usage of the harvester [3]. Replacement of conventional longitudinal core of harvester with different geometry such as conventional honeycomb, re-entrant honeycomb and chiral structure as unit cell has been done due to its light

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weight to reduce the natural frequency of harvester. Conventional honeycomb is chosen for the ease of layering in out-of-plane configuration for double layer. Conventional Honeycomb is a structure with unform cell size compressed in direction perpendicular to its cell size [7]. Cellular sandwiches are highly applied in engineering due to its high mechanical strength and lightweight, honeycomb structures are mostly used as core due to its excellent vibration damping, energy and acoustic absorption [4]. Manufacturing of honeycomb will be more efficient with 3D printing technology. 3D printing on energy harvesting enables modification of the PEH regardless of the manufacturing method. Some successful cases in which PEH can replace batteries to power some micro-scale devices show promising replacement batteries of autonomous sensors and microsystems in nano-Watt to micro-Watt range [8]. PEH is still under development and yet to be practical to power devices with larger scales than micro-Watt. Another limitation of PEH is the power output performance of a harvester is subjected to the resonant frequency and study has been working on adopting new materials to overcome that dependency [5]. Therefore, 3D printing allows a wide potential contribution in the study of different materials and specifications.

There are three main techniques in vibrational energy harvesting which are electrostatic, electromagnetic, and piezoelectric [5]. Piezoelectric vibrational energy harvesting gives prominent energy harvesting due to its high electromechanical coupling compared to electrostatic and electromagnetic [9]. The frequency of the harvester generating the highest power will be the resonant frequency of the harvester. In Piezoelectric Energy Harvesting (PEH), maximum stress and strain required are generated by the harvester through the deformation of load and energy to ensure the piezoelectric effect to transfer kinetic energy into electrical energy [10]. Research was done on different 3D printing materials of cantilever bimorph beam and findings showed that brass contributed the highest frequency response and Thermoplastic Polyurethane (TPU) gave worst frequency response. Polylactic Acid (PLA) is still commonly used in many applications due to low cost, ease of print and biodegradability [11]. In the meanwhile, soft core sandwiched material proved to lower the resonant frequency and increased the generated voltage [12]. Adjusting the amplifying frequency can suit different environmental vibration resources for energy harvesting. There was research working on enhancing the sandwich based PEH. Investigation of optimising the core topologies with conventional honeycomb, re-entrant honeycomb, and chiral structure was conducted. At resonant frequency of 37 Hz, the re-entrant honeycomb, conventional honeycomb, and chiral structure sandwich generated 24.4 μW, 14.4 μW, and 12 μW of power respectively [4]. Re-entrant honeycomb geometry has the highest magnitude of square of sum of transverse and longitudinal stress which is proportional to the maximum power generated.

## III. HONEYCOMB CELL DESIGN AND PROTOTYPING

Fig. 1 shows the unit cell of honeycomb for the harvester which is a “horizontally extended” regular hexagon. The upper and lower horizontal width is 10 mm, and the maximum width is 15.94 mm. The height of the unit cell is 10 mm based on the geometry studied by Chen *et al.* [4]. The inner angle of two adjacent edges is 120° and the thickness of the unit cell is 5 mm. Fig. 2 shows the Computational Aided Drawing (CAD) modelling of a honeycomb beam in single layer configuration.

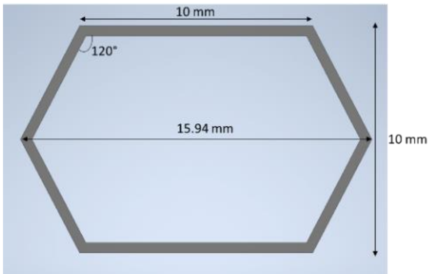

Fig. 1. Unit cell of honeycomb.

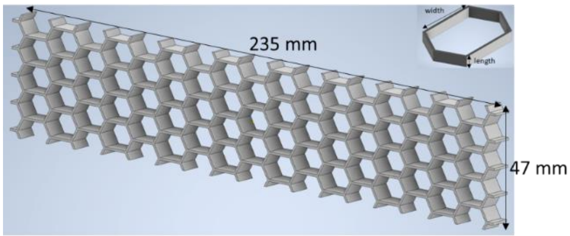

Fig. 2. CAD modelling of proposed honeycomb beam in single layer configuration.

This research also intends to study the impact from out-of-plane layering orientation of the honeycomb structure. Fig. 3 illustrated the CAD modelling of a honeycomb beam in double layers configuration. The top honeycomb cell layer is shifted out-of-plane from the bottom unit cell by half of the upper width size. Fig. 4 shows the Polylactic Acid (PLA) 3D printed honeycomb beam with Fused Deposition Modelling.

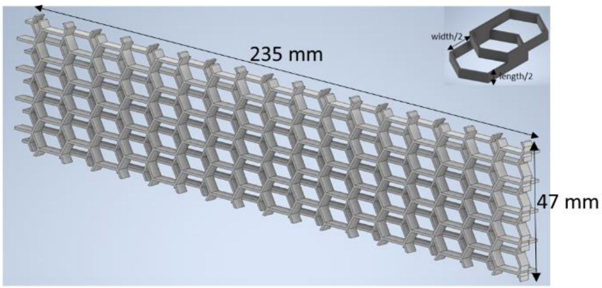

Fig. 3. CAD modelling of proposed honeycomb beam in double layers configuration.

Fig. 4. PLA 3D printed honeycomb beam.

## IV. PERFORMANCE VERIFICATION

The honeycomb CAD model will be simulated in ANSYS 2023 R2 to obtain dynamical amplitude. The simulation will start with modal analysis followed by random vibration. Fixed-end boundary condition is applied to simulate the clamped end, and an acceleration load is set as vibrational source. Structural analysis has been conducted to study the longitudinal and lateral stress when acted by the acceleration load. A consistent 0.1 g acceleration was applied throughout the analysis. The amplitude was obtained in the response Power Spectral Density (PSD) tool.

### *A. Simulation*

#### *1) Modal analysis*

The first three mode shapes will be obtained as the natural frequencies of the honeycomb. During the modal analysis, fixed support was assigned to one end to simulate the clamping of one end of samples in the real experiment. The first natural frequency will be taken as the resonant frequency and the frequency range of shaker input will be decided based on the resonant frequency from simulation.

#### *2) Random vibration*

In random vibration, the Power Spectral Density (PSD) $G$ acceleration tool was selected to simulate the experimental condition of the shaker. The load of acceleration was chosen and assigned to the fixed support boundary condition. Eq. (1) shows the $G$ acceleration value is calculated by squaring the $g$ value which is 0.1 g with its respective frequency. When the frequency increases, the $G$ acceleration value decreases due to the constant value of $g$ and increasing value of frequency, $f$.

$$G = \frac{g^2}{f} \tag{1}$$

By using Eq. (2), the amplitude, $A$ will be converted by the square root of response PSD with its respective frequency from the unit of m²/Hz to m.

$$A = \sqrt{PSDxf} \tag{2}$$

#### *3) Structural analysis*

A load of acceleration applied at the fixed-end was set at acceleration value of 0.1 g, with acceleration load vector of 0.981 m/s² along the z-axis direction to simulate the input vibration from shaker. Normal stress was added in x direction and z direction. The average values of the longitudinal stress in x-axis and transverse stress in z-axis direction were studied in this analysis.

### *B. Experiment*

Fig. 5 illustrated the hardware setup for the experimental verification. The honeycomb sample is clamped on Espec EV-501 analogue vibration shaker for the experiment to study the dynamical amplitude. Two infrared laser sensors (Keyence IL-065) will be placed on top of the honeycomb to study the amplitude of the honeycomb beam. Four 3D printed honeycomb beams with different configurations as listed in Table I are tested in the experiment. Lower and upper frequencies will be set for the shaker, while the sweep speed and base excitation are set at 0.5 oct/min and 0.1 g respectively. The shaker will produce vibration from a fixed lower frequency to an upper frequency. The range of the frequencies are approximately from 5 Hz to 100 Hz depending on the magnitude of the obtained natural frequency. The vibrational displacement is acquired in the National Instrument (NI) LabVIEW 2016 software with infrared sensors with DAQ Is National Instrument USB-6003. Fig. 6 shows the Virtual Instrument (VI) layout of NI LabVIEW 2016 used for data retrieval. The raw data from both infrared sensors will be multiplied by 5 to convert the voltage signal into displacement with the unit of millimeter. The exported data will be smoothened through exponential smoothing in Microsoft Excel.

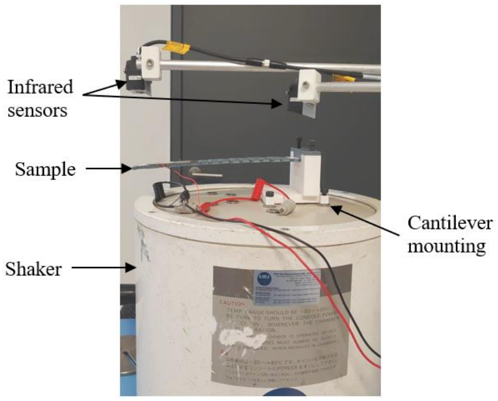

Fig. 5. Setup of the experiment.

TABLE I. NUMBER OF SAMPLES FOR EXPERIMENT

| Thickness/mm | Configuration/layer |
|---|---|
| 8 | Single layer<br>Double layer |
| 16 | Single layer<br>Double layer |

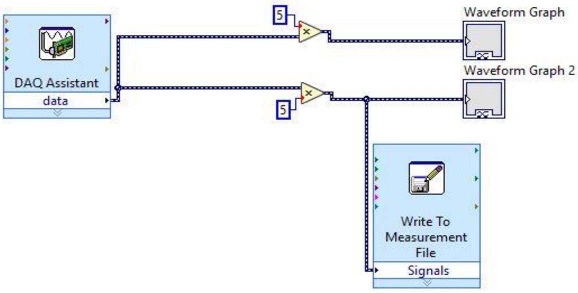

Fig. 6. VI arrangement in NI LabVIEW.

## V. RESULT AND DISCUSSION

### A. *Modal Analysis*

Table II listed only the first natural frequency for the honeycomb beams. The higher mode frequencies will have partial charge cancellation due to the opposite stress sign [13] and therefore neglected. The natural frequency increases with thickness. By comparing the different configurations for the same thickness, the natural frequency of the double layers configuration is slightly higher than single layer configuration due to higher beam density [14]. With different thicknesses, the density will be varied and affect the effective modulus of the honeycomb beam. Study shown that increasing thickness will increase the natural frequency for the same layering configuration [15].

TABLE II. NATURAL FREQUENCIES OF THE HONEYCOMB BEAMS

| Beams | Natural frequency/Hz |
|---|---|
| Single layer-8 mm | 31.813 |
| Single layer-16 mm | 57.169 |
| Double layers-8 mm | 36.692 |
| Double layers-16 mm | 76.181 |

### B. *Dynamical Amplitude*

#### 1) *Different thicknesses*

Fig. 7 shows the simulation and experiment results for dynamical amplitudes of single layer-8 mm and –16 mm honeycomb beams. Since the harvester is excited through harmonic force with a range of frequency, the successive mode shape brings resonance with maximum amplitude [16] which can be observed at the peaks. The slight difference in frequencies were due to the friction from the vibration mechanism. Noise was observed at several small peaks. The difference in dynamical amplitude increases with increasing honeycomb beam thickness due to higher stiffness. With constant base excitation, the dynamical amplitude will decrease with increasing stiffness.

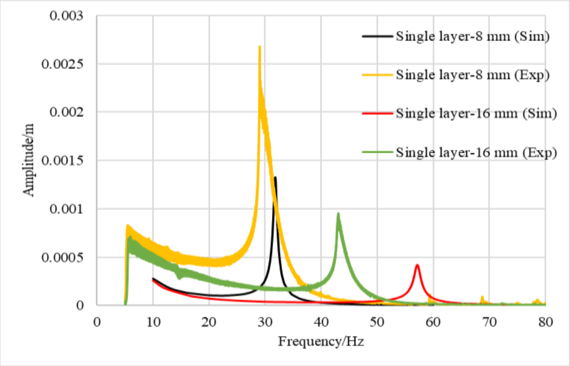

Fig. 7. Simulation and experimental dynamical amplitude for honeycomb beam.

#### 2) *Different layering*

Fig. 8 shows the dynamical amplitude comparison of honeycomb beam for different layering at 8 mm and 16 mm thicknesses, respectively. The results show that double layers configuration has smaller dynamical amplitude but higher frequency as compared to the single layer configuration.

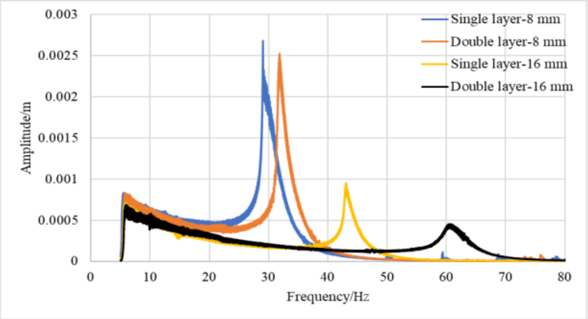

Fig. 8. Dynamical amplitude at different layering for honeycomb beam.

Table III summarises the simulation and experimental natural frequencies and dynamical amplitudes for honeycomb beams with different layering and thicknesses. The obtained natural frequencies are similar to the research done by Chen [4]. In general, the natural frequency increases while amplitude decreases with thickness of the beam. In the meanwhile, the amplitude decreases with increasing thickness and number of layers. It is observed that the amplitude is higher compared to the core polycarbonate plastic with 1 mm thickness without tip mass studied by Li [12]. Table IV shows the percentage error in simulation and experimental of natural frequency and amplitude to weight ratio. The errors are due to possible friction and damping from the mechanical hardware. The amplitude difference increases with increasing thickness and layering configuration due to the lower amplitude at higher thickness causing the environmental noise becoming more significant to the experimental results. The infrared sensor captured a difference of ±0.02 mm which is significant to the experimental data.

TABLE III. SUMMARY OF NATURAL FREQUENCY AND DYNAMICAL AMPLITUDE

| Beams | Natural freq. (Sim) / Hz | Natural freq. (Exp) / Hz | Amplitude (Sim) / mm | Amplitude (Exp) / mm |
|---|---|---|---|---|
| Single layer-8 mm | 31.79 | 29.04 | 1.30 | 2.68 |
| Single layer-16 mm | 57.13 | 43.07 | 0.41 | 0.94 |
| Double layers-8 mm | 39.66 | 31.86 | 0.84 | 2.44 |
| Double layers-16 mm | 60.34 | 61.08 | 0.17 | 0.45 |

With the proportionality of amplitude with generated voltage [12], maximizing the vibrational amplitude will directly maximize the voltage/power generated for energy harvesting. Therefore, the base excitation should match the natural frequency to create resonance and maximum amplitude [17]. The amplitude-to-weight ratios were calculated in Table IV to reflect the potential power-to-weight ratio. The single layer-8 mm gives the highest amplitude of 2.68 mm due to lower stiffness however, honeycomb beam with double layer-8 mm had the highest amplitude-to-weight ratio. This indicates a promising factor of weight manipulation to improve the power generation with multi-plane configuration.

TABLE IV. PERCENTAGE ERROR AND AMPLITUDE TO WEIGHT RATIO

| **Beams** | **Natural frequency percentage error/%** | **Amplitude to weight ratio / mm/g** |
|---|---|---|
| Single layer-8 mm | 8.65 | 0.110 |
| Single layer-16 mm | 24.61 | 0.028 |
| Double layers-8 mm | 19.67 | 0.114 |
| Double layers-16 mm | 1.23 | 0.011 |

## VI. CONCLUSION

The frequency response, vibrational amplitude and amplitude-to-weight ratios for different layering configurations and thickness were studied. Single layer configuration will have higher stiffness as compared to double layers configuration and therefore having better dynamical amplitude. However, multi-plane configuration allows manipulation of the beam weight. Double layer-8 mm honeycomb beam has the highest amplitude-to-weight ratio due to lower weight with amplitude close to its single layer. Environmental factors, mechanical loss, shaker timing error and fabrication tolerance needed to be considered in this research as significant differences were observed when comparing experimental and simulation results. Improvement can be done by designing a groove for a piezoelectric patch for fabrication tolerance. For future research, adjusting the natural frequency to environmental frequency range can be done by changing the thickness of the honeycomb unit cell, adding a load mass to lower the natural frequency, and comparing between different materials to enhance the dynamic amplitude and the power-to-weight ratio.

## CONFLICT OF INTEREST

The authors declare no conflict of interest.

## AUTHOR CONTRIBUTIONS

Tan conducted the research and wrote the draft; Hoo secured the funding, reviewed and revised the paper; Lai advised the research methodology; Foong reviewed and advised the hardware operation. All authors had approved the final version.

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