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***Research paper***

# Vibration Analysis of Fused Deposition Modelling Printed Lattice Structure Bar for Application in Automated Device

**M. S. Azmi[1], R. Ismail[1,2], R. Hasan[1,2*] and M. R. Alkahari[1,2]**

*[1]Faculty of Mechanical Engineering, Universiti Teknikal Malaysia Melaka*
*[2]Centre for Advanced Research on Energy, Universiti Teknikal Malaysia Melaka*
*Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia*
**Corresponding author E-mail: rafidahhasan@utem.edu.my*

**Abstract**

The purpose of this study is to investigate the effect of size of strut radius to the natural frequencies of acrylonitrile-butadiene-styrene (ABS) polymer lattice-structure bar material by using vibration technique. The lattice structured cellular material parts with body-centered-cubic (BCC) topological design are manufactured using fused deposition modeling (FDM) additive manufacturing (AM) technique with aim to reduce the overall weight of automated device. The specimens are tested by using set up consist of fabricated test rig, accelerometer, force sensor, power amplifier, shaker and signal generator/analyzer. The first mode natural frequency obtained from the vibration testing for specimen with 1.0 mm strut radius is 278 Hz while specimen with 1.2 mm strut radius is 441 Hz. The results obtained from vibration testing show that bigger size of strut radius will yield higher natural frequencies and the lattice structure bar is suitable for use as arm body part in automated device. By utilizing FDM AM, industry will be able to benefit in term of saving in fabrication cost as well as energy consumption.

***Keywords***: *fused deposition modeling; lattice structure material; lightweight application; natural frequency; vibration analysis*.

## 1. Introduction

The reduction of material consumption, fabrication cost and energy in vehicles, machines and devices has been a great demand from the industry. In the industry that makes automated devices such as radio controlled (RC) cars and aeroplanes, the current performance of battery powered device is limited due to heavy body parts that caused higher power consumption for movement that will eventually affect the overall operational hours of the device [1]. With this focus, to reduce the overall weight of body parts, structural properties, material selection and manufacturing technique must be continually improved.

### 1.1. Additive Manufacturing

AM is the one of the major material fabrication process besides subtractive and formative manufacturing [2]. Subtractive manufacturing includes computer numerical control (CNC), milling, grinding etc. that is mostly include machining processes while formative manufacturing includes bending, forging and injection molding etc. [2]. Amongst these three, only AM is able to fabricate complex structure as the other two has limitations due to its fabrication principles. AM builds 3D part by adding layer by layer from 3D computer aided design (CAD) file. AM has been used in many fields such as automotive, aerospace, consumer goods, and casting [3].

Among all AM, FDM is one of the simplest machine that is easy to maintain, cheaper to own, and uses lightweight thermoplastic solid material in the form of filament wire, making it most suitable technique to fabricate low cost strong plastic parts for use in automated devices. FDM was first invented in early 1990s and widely used due to its low-cost materials and very low waste compared to other technique [3]. The parts built by the FDM machine also show great potential with high manufacturing flexibility and complex structure design.

### 1.2. Lattice Structure

Cellular structure material has been widely used as core material to improve energy absorption of the material [4]. The most popular cellular structure used is honeycomb structure which proven to have high stiffness and strength to weight ratio [5]. Other common widely used cellular material is foam structure which also offers significant energy absorption performance [4]. Besides honeycomb and foam structure, another structure that shows high potential thus rising interest between researchers is lattice structure. **Fig. 1** shows the physical appearance of honeycomb, foam and lattice structure materials.

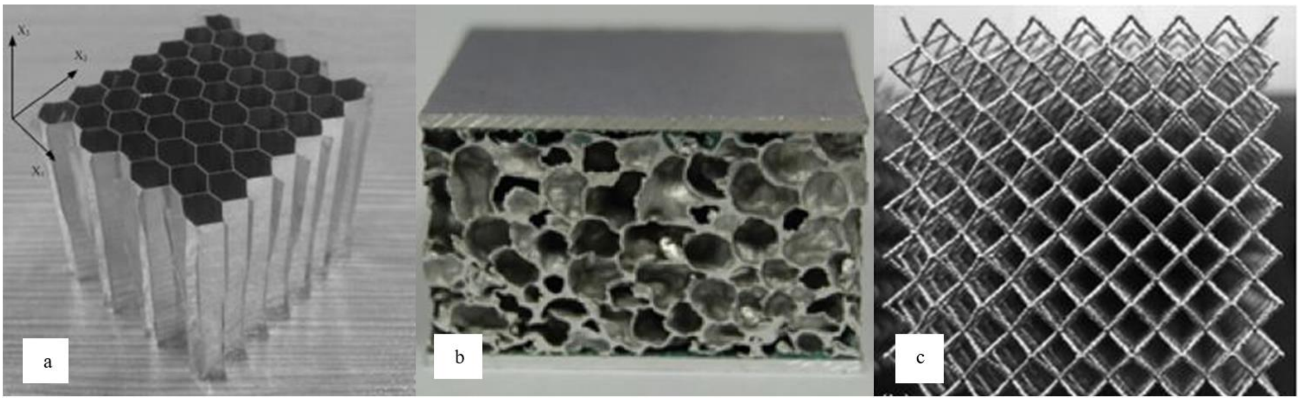


**Fig. 1:** Physical appearance of a) honeycomb [6] b) foam [7] c) lattice structure [8]

Lattice structure is periodic, open cell structure that can be made with many topological design such as octahedral cell, tetrahedral cell, octet-truss cell, body-centered cubic cell, diamond cell and many more [9]. The advantage of open cell structure against closed-cell structure such as foam structure is it can reduce trapped moisture and gas retention [10]. **Fig. 2** shows classification of cellular materials. Lattice structure is also favoured due to its low density that helps in reducing weight and material consumption when compared to bulk material and stochastic foam of the same size and dimension [11].

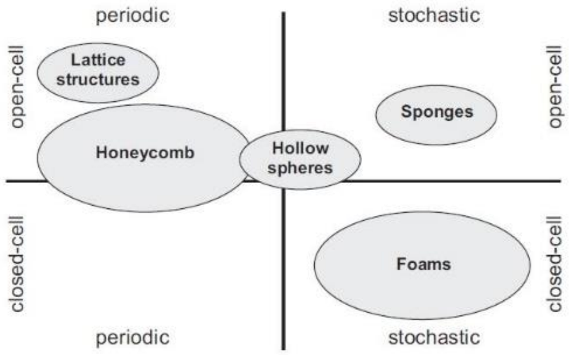


**Fig. 2:** Cellular material classification [12]

### 1.3. Vibration Monitoring

Vibration based monitoring is wider dynamic local non-destructive evaluation (NDE) analysis of a system that can be used to detect changes on a system which indicate damage. from vibration analysis, vibration characteristic such as natural frequencies also can be obtained. The natural frequencies are important vibration characteristic that can be used in order to avoid resonance to happen in vibrating system and also to understand the suitability of material in application. Therefore, the aim of this paper is to investigate the effect of size of strut radius to the natural frequencies of the lattice structure bar made by using FDM AM technique for application as arm body part in automated devices.

## 2. Methodology

### 2.1. Sample Preparation

a

The lattice structure bars are designed using Solidworks CAD softwre with BCC topological design as shown in **Fig. 3**.

**Fig. 3:** Lattice structure design in Solidworks

The BCC lattice structure unit cells are designed with strut to surface angle, θ=35.26° and length, L= 5 mm. The one unit cell of BCC lattice structure is shown in **Fig. 4**. where Ø is the strut diameter in mm. The drawing is then saved as Solidworks part document and converted into .STL file before transferred into CubePro's software for printing.

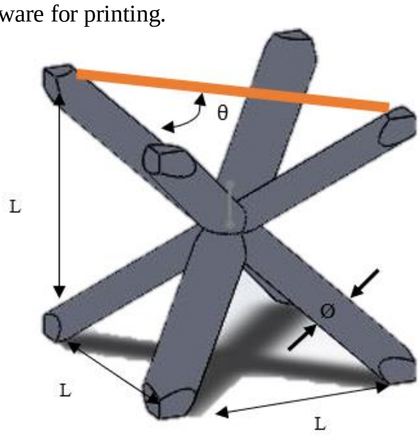


**Fig. 4:** BCC unit cell: L= length, θ= surface angle, Ø= strut diameter

### 2.2. Fabrication of Lattice Structure Bar

Lattice structure bar specimens are designed with size of 160x20x30 mm to match arm part of automated device. The specimens are fabricated using ABS thermoplastic by utilizing CubePro 3D printer by 3D System Inc. with diameter more than 1.0 mm due to machine capability [13]. The specimen printing specifications are as tabulated in **Table 1**.

**Table 1:** Specification of Specimens

| Strut Radius (Mm) | Print Strength | Print Pattern | Layer Thickness (µm) |
|---|---|---|---|
| 1.0 | Solid | Cross | 200 |
| 1.2 | Solid | Cross | 200 |

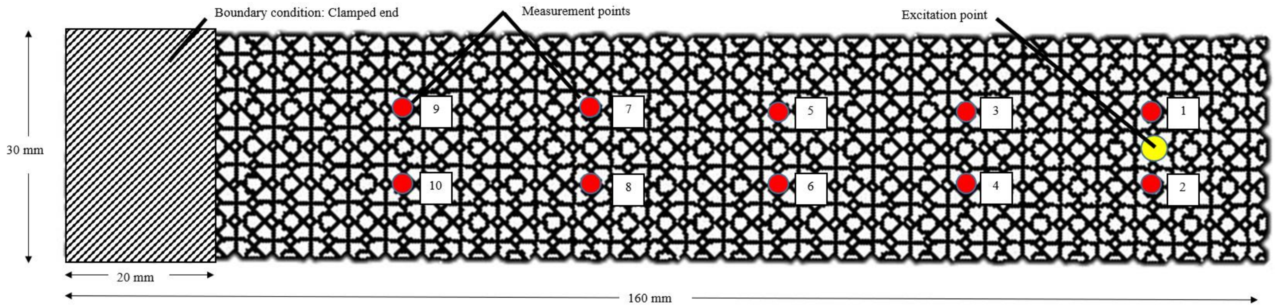

**Fig. 5:** Location of excitation point and measurement points in lattice structure bar (top view)

## 2.3. Experiments

Vibration testing is carried out to two specimens with 1.0 mm and 1.2 mm strut radius to identify the natural frequencies of both specimens. The specimens are subjected to boundary condition with one end of the bar clamped to the test rig. The location of excitation point and measurement points are shown in **Fig. 5**. The experimental set up consist of Dataphysics Quattro as signal generator and analyzer, accelerometer, force sensor, dynamic shaker and signal amplifier. A random approximately 18 N force signal was generated ranging from 0-1000Hz by Dataphysics Quattro and amplified by signal amplifier before inputted into the shaker. The vibration and force signals then measured by accelerometer and force sensor respectively for each measurement points. Data acquired from the test were analyzed by using SignalCalc 240 Dynamic Signal Analyzer. The experimental set up for vibration testing is as shown in **Fig. 6**. Three readings were taken and averaged for each measurement point for each sample to ensure the consistency of the results measured.

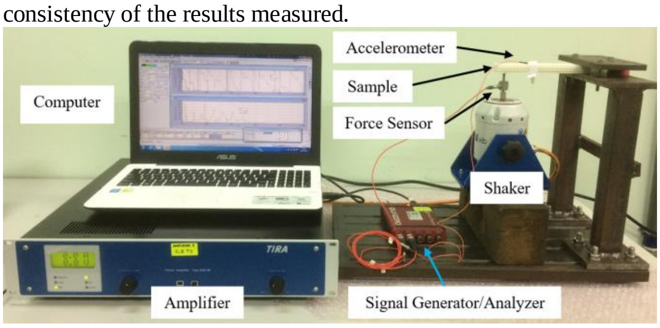

**Fig. 6:** Experimental set up for vibration testing

# 3. Results and Discussion

Data acquired from the experiments are plotted into frequency response function (FRF) graphs by using MATLAB, the FRF graphs from two measurement points for both specimens with 1.0 mm and 1.2 mm strut radius are shown in **Fig. 7** and **Fig. 8** respectively. The average frequency for two measurement points for both specimens from FRF graphs are then tabulated in **Table 2**.

**Table 2:** Experimental Results of Vibration Testing

| | | Average Frequency (Hz) | | | | | |
|---|---|---|---|---|---|---|---|
| Measurement Point | | 5 | | | 6 | | |
| Vibration Mode | | 1st | 2nd | 3rd | 1st | 2nd | 3rd |
| Lattice Structure Bar Strut Radius (mm) | 1.0 | 278 | 409 | 919 | 278 | 413 | 913 |
| | 1.2 | 441 | 611 | 922 | 441 | 613 | 922 |

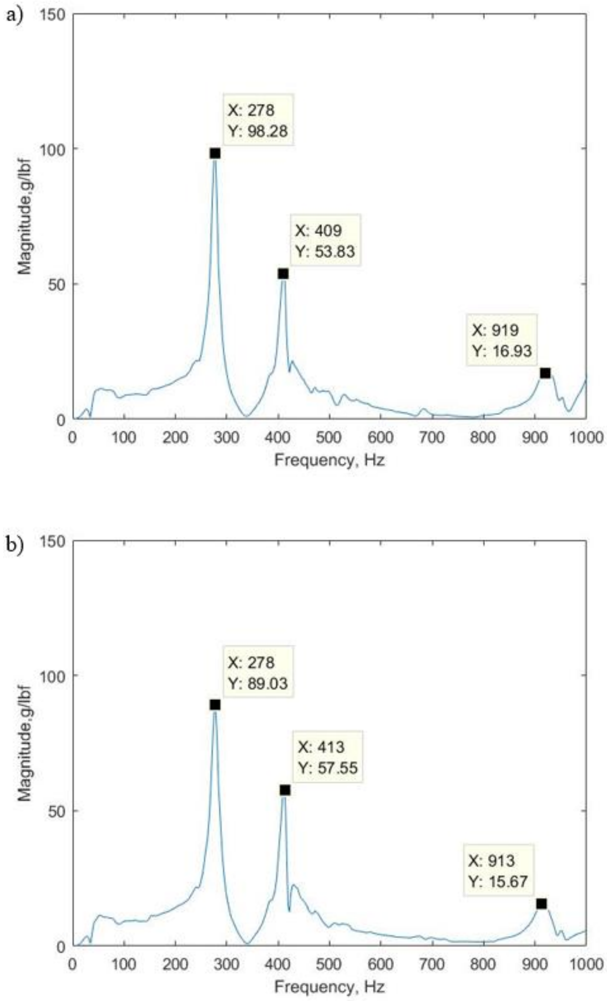

**Fig. 7:** FRF graphs of specimen with 1.0 mm strut radius at measurement point a) 5 b) 6

The lattice structure bar is behaving as cantilever beam when vibrated, therefore the stiffness of the lattice structure bar can be calculated using the following formula:

Stiffness, $k = 3EI/L^3$ (1)

Where, $E$ is the Young's modulus, $I$ is the total area moment of inertia and L is the length of cantilever beam.

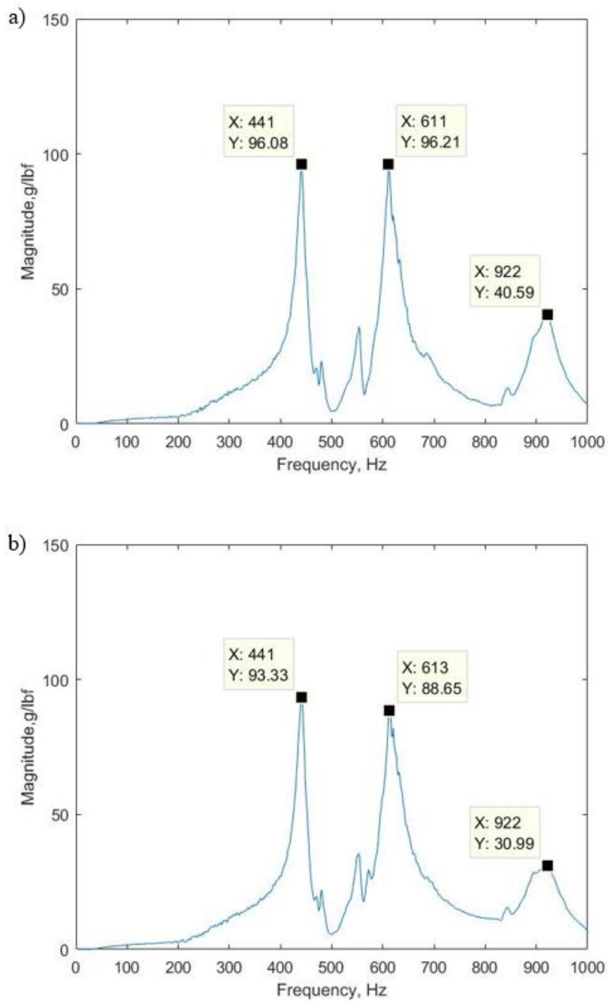


**Fig. 8:** FRF graph of specimen with 1.2 mm strut radius at measurement point a) 5 b) 6

Since the specimens are made with same dimensions using same material, length, L and Young's modulus, *E* of the specimens are the same. However, specimen with 1.2 mm strut radius has higher stiffness, *k* value compared to specimen with 1.0 mm strut radius due to higher value of total area moment of inertia, *I* as cross-sectional area of the specimen with 1.2 mm strut radius is higher than specimen with 1.0 mm strut radius.

Natural frequency, $\omega_n = (k/m)$ ^1/2 (2)

Based on natural frequency formula, natural frequencies increase as stiffness, *k* increases. This explains the higher value of natural frequencies of specimen with 1.2 mm strut radius than specimen with 1.0 mm strut radius. Nevertheless, both specimens exhibit more than 250Hz natural frequency for the first mode of vibration which makes both sample feasible for application in automated device that typically uses less than 15000 rotations per minute (RPM) rotating speed motor as vibration source.

## 4. Conclusions

The natural frequency values for all three modes of vibration of the specimen with 1.2 mm strut radius are higher than specimen with 1.0 mm strut radius due to higher stiffness of the specimen with bigger strut radius, these results show that bigger size of strut radius will yield higher natural frequencies and the lattice structure bar is suitable for use as arm body part in automated device. By utilizing FDM AM to fabricate lattice structure bar, industry that makes automated devices will be able to minimize fabrication cost and save energy. However, further study is needed to fully understand the limitation of lattice structure bar for application in automated device industry.

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