Additively Manufactured Polymeric Surface-Based Lattice Structures for Vibration Attenuation

Imabin Kelvin Ekpelu
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ADDITIVELY MANUFACTURED POLYMERIC SURFACE-BASED LATTICE STRUCTURES FOR VIBRATION ATTENUATION

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering

by

IMABIN KELVIN EKPELU
B.M.E, University of Dayton, 2016

2023
Wright State University
I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Imabin Kelvin Ekpelu ENTITLED Additively Manufactured Polymeric Surface-Based Lattice Structures for Vibration Attenuation BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science in Mechanical Engineering.

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ABSTRACT

Ekpeulu, Imabin Kelvin. M.S.M.E., Department of Mechanical and Materials Engineering, Wright State University, 2023. Additively Manufactured Polymeric Surface-Based Lattice Structures for Vibration Attenuation.

The focus of this study was to select triply periodic minimal surface (TPMS) structures made of 3D-printed polymers. The primary variables in this study were: TPMS shape, lattice volume ratio, and lattice material. Vibration absorption was characterized by damping ratio via transmissibility at the system’s natural frequency. The vibration testing was performed using an electro-dynamic shaker, a known mass, an input/control accelerometer, and an output/response accelerometer. The 3D-printed absorber/lattice was mounted to the shaker baseplate and a mass will be mounted on top of the absorber. One accelerometer will be mounted to the shaker baseplate and the other will be mounted to the top of the mass. A broadband frequency sweep was the test type for the vibration absorption characterization in this study. Additional testing was performed to help further characterize other properties of the lattice structure. Monotonic load testing was performed to calculate the stiffness of the lattice. This information was used to determine a suitable mass to use for vibration testing. The results show a clear separation in the damping performance of PLA vs TPU, with TPU having the better performance.
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Chapter 1  Introduction

1.1 Motivation

Well-applied vibration absorption is an important tool for reducing the negative effects of vibration on components and systems. Absorbers such as packing foam for shipping and handling applications work to deaden the vibration from over-the-road and other transport excitations so as not have it damage the shipped goods. Absorbers like those found in the speakers' feet work to deaden the vibration generated by the use of the speaker to limit transfer through the surface on which the speaker is sitting, potentially resulting in poor overall sound quality for the end user. While the aforementioned examples are well suited for traditional manufacturing methods in the fabrication of the absorber; there may be opportunities in more critical applications to invest in the development of custom absorbers fabricated via additive manufacturing methods. When it comes to the vibration absorption performance of 3D-printed lattice structures, past research has primarily focused on strut-based lattice structures [1], [2]. This study aims to expand research to evaluate vibration absorption performance in surface-based lattices.

With the increased popularity and availability of additive manufacturing and the increased capability of computer-aided design (CAD) software, complex lattice cell structures can more readily be integrated into components. While some work has been done to understand the properties of these structures, there has been little work in evaluating to damping properties of these lattices, specifically surface-based lattices.
Out of many different triply periodic minimal surfaces, Schwarz D (which will be called ‘diamond’ for the remainder of this document), gyroid, and Schwarz P (which will simply be called ‘Schwarz’ for the remainder of this document) were selected in this study for their relative simplicity and potential ease of printing. As the name suggests, TPMS’s repeat themselves in three dimensions. This does not necessarily mean that they are symmetric in three dimensions. Figure 1.1.1 shows examples of this geometry.

Figure 1.1.1 Diamond, gyroid, and Schwarz cells (from left to right) [3]
Chapter 2  Literature Review and Background

2.1 Introduction

The purpose of this chapter is to contextualize the various intersecting concepts that are relevant to this study. Concepts such as lattice structures, additive manufacturing, materials used in additive manufacturing, and the testing of lattice structures will be explored. This chapter will culminate with a discussion of prior works that have been completed to understand the damping performance of 3D printing structures.

2.2 Lattice Structures

In general, lattice structures are patterns that fill a volume or conform to a surface. In engineering design, lattices are cellular materials—sometimes inspired by nature—that consist of struts, surfaces, or plates that fit together following an ordered or stochastic pattern [4], [5]. Strut or beam lattices “consist of a series of rod-like forms” that are arranged by connecting the ends of the rods at different vertexes to create different unit cell configurations [6]. Figure 2.2.1 shows a limited set of different unit cell configurations for strut-based lattices. Surface lattices are generally generated from trigonometric surface equations [6]. Figure 2.2.2 shows a limited set of surface-based unit cell structures and their corresponding equations. Planar-based lattices are “created as a periodic pattern in a 2D plane and then extruded in a single direction to create the 3D structure” [6]. The three types of lattices described thus far are typically periodic, however, this is not a requirement for lattices. There is a class of lattices that are called stochastic, meaning that there is randomness built into their structure. Some foams are stochastic lattices. The four types of lattices described thus far in this section can be
homogenous or heterogeneous. Homogeneous lattice structures have uniform cell properties over the entire lattice. On the other hand, heterogeneous lattice structures can change one or more cell properties (such as wall thickness, density, or cell size) with respect to position in the overall lattice. See Figure 2.2.3 for examples of the lattice types.

![Figure 2.2.1 Example of Strut-based Unit Cells [7]](image)

<table>
<thead>
<tr>
<th>TPMS Type</th>
<th>Image</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schwarz</td>
<td><img src="image" alt="Image" /></td>
<td>(\cos(x) + \cos(y) + \cos(z) = C)</td>
</tr>
<tr>
<td>Gyroid</td>
<td><img src="image" alt="Image" /></td>
<td>(\sin(x) \cos(y) + \sin(y) \cos(z) + \sin(z) \cos(x) = C)</td>
</tr>
<tr>
<td>Diamond</td>
<td><img src="image" alt="Image" /></td>
<td>(\sin(x) \sin(y) \sin(z) + \sin(x) \cos(y) \cos(z) + \cos(x) \sin(y) \cos(z) + \cos(x) \cos(y) \sin(z) = C)</td>
</tr>
<tr>
<td>Neovius</td>
<td><img src="image" alt="Image" /></td>
<td>(3(\cos(x) + \cos(y) + \cos(z) + 4 \cos(x) \cos(y) \cos(z)) = C)</td>
</tr>
</tbody>
</table>

![Figure 2.2.2 Example of Surface-based Unit Cells w/ Their Respective Equations [8], [9]](image)
Except for in certain cases where planar-based lattices are employed, traditional manufacturing methods (subtractive manufacturing and casting) are not well suited for fabricating lattice structures. This is where the advantages of additive manufacturing can be utilized.

### 2.3 Additive Manufacturing

Additive manufacturing sets itself apart from traditional manufacturing because unlike both subtractive manufacturing (milling, lathing, cutting, grinding) and casting, additive manufacturing does not require a starting base structure (i.e., a block or rod of material or a mold). Additive manufacturing can detail internal geometry that would be impossible for even multi-axis computer-controlled traditional machining.

Additive manufacturing can be broken down into seven categories agreed upon by standards bodies: vat photopolymerization, powder bed fusion, binder jetting, sheet lamination, material jetting, directed energy deposition, and material extrusion [10]. As depicted in Figure 2.3.1, vat photopolymerization is an additive manufacturing method that selectively exposes

![Figure 2.2.3 Heterogeneous Strut, TPMS, Planar, and Stochastic Lattices (Left to Right) [4]](image)

Figure 2.2.3 Heterogeneous Strut, TPMS, Planar, and Stochastic Lattices (Left to Right) [4]
the surface layer of a vat of liquid photopolymer resin to light via a laser or projector to cure the resin into the desired solid part. The typical materials are UV-curable photopolymer resins of which have a wide variety of mechanical properties. Figure 2.3.2 depicts powder bed fusion. Powder bed fusion uses a laser or electron beam to selectively consolidate powdered material by melting it with a laser or electron beam. The material typically used for power bed fusion are powdered plastics, powdered metals, and powdered ceramics. Figure 2.3.3 depicts binder jetting. Binder jetting selectively deposits liquid binders onto thin layers of powder material to build up parts. Depending on the material, some parts may need to be sintered as a part of post processing to achieve full part functionality. Similar to powder bed fusion, powdered plastics, powdered metals, and powdered ceramics are typically used for binder jetting. Figure 2.3.4 depicts sheet lamination. Sheet lamination uses adhesives, ultrasonic welding, or brazing to selectively join thin sheets of the same material together. “Unneeded regions are cut out layer by layer and removed after the object is built” [10]. Paper, plastic sheets, and metal foils are typically used in sheet lamination. Figure 2.3.5 depicts material jetting. Material jetting uses droplets of material that “are deposited layer-by-layer to make parts” [10]. “Common varieties include jetting a photocurable resin and curing it with UV light, as well as jetting thermally molten materials that then solidify in ambient temperatures” [10]. Figure 2.3.6 depicts directed energy deposition. “Directed energy deposition is essentially an automated form of welding used to build up 3D shapes” [10]. “Powder or wire is fed into a melt pool which has been generated on the surface of the part where it adheres to the underlying part or layers by using an energy source such as an arc, laser, or electron beam.” [10]. Figure 2.3.7 depicts material
extrusion, one of the most well-known types of additive manufacturing. Material extrusion uses a nozzle to extrude and deposit material layer by layer to build an object. Typically, thermoplastic filaments or pellets are used for material extrusion. Support materials can also be deposited during the print via a separate nozzle. This support material has to be dissolved in a bath after the print is completed.

It can be seen that all seven types of additive manufacturing build the desired solid structure layer by layer. Lattice structures have been fabricated with all seven types of additive manufacturing. In terms of selecting an additive manufacturing method, it was primarily a matter of availability at the time of sample fabrication and the desired sample materials. The selection of an additive manufacturing type and machine will be detailed more in Chapter 3.

Figure 2.3.1 Vat Photopolymerization [10]
Figure 2.3.2 Powder Bed Fusion [10]

Figure 2.3.3 Binder Jetting [10]
Figure 2.3.4 Sheet Lamination [10]

Figure 2.3.5 Material Jetting [10]
Figure 2.3.6 Directed Energy Deposition [10]

Figure 2.3.7 Material Extrusion [10]
2.4 Materials for FDM Filament

In general, thermoplastics are most commonly used as the build material in fused deposition modeling (FDM) 3D printing. They can exhibit a range of behaviors depending on their compositions and mechanical properties as shown in Figure 2.4.1. There are many filaments commercially available for 3D printing such as nylon, polyether ether ketone (PEEK), and polycarbonate (PC). However, the most commonly used in FDM printing are acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) [11].

PLA has a reputation for being easy to print due to its lower printing temperature. TPU is the most well-known and easiest flexible filament to print. Table 2.4.1 shows some basic mechanical/material properties of common FDM filament materials. Note the glass transition temperatures for the two flexible materials (TPU and TPC) very low compared the rest of the materials. For testing at room temperature (20°C) these flexible materials would be soft and pliable compared to the other materials.

<table>
<thead>
<tr>
<th>Material Name</th>
<th>Young's Modulus (MPa)</th>
<th>Tensile Strength (MPa)</th>
<th>Density (g/cm³)</th>
<th>Print Temperature Range (°C)</th>
<th>Glass Transition Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLA</td>
<td>3600</td>
<td>50-60</td>
<td>1.24</td>
<td>190-230</td>
<td>50-80</td>
</tr>
<tr>
<td>ABS</td>
<td>1120-2870</td>
<td>33-110</td>
<td>1.03</td>
<td>230-260</td>
<td>106</td>
</tr>
<tr>
<td>Nylon</td>
<td>2100</td>
<td>48</td>
<td>1.05</td>
<td>260-270</td>
<td>52</td>
</tr>
<tr>
<td>PEEK</td>
<td>3720</td>
<td>101</td>
<td>1.31</td>
<td>370-410</td>
<td>145</td>
</tr>
<tr>
<td>PC</td>
<td>2400</td>
<td>62</td>
<td>1.21</td>
<td>255-300</td>
<td>150</td>
</tr>
<tr>
<td>TPU</td>
<td>70</td>
<td>8</td>
<td>1.23</td>
<td>220-240</td>
<td>-23.5</td>
</tr>
<tr>
<td>TPC</td>
<td>29</td>
<td>8</td>
<td>1.15</td>
<td>210-250</td>
<td>-35</td>
</tr>
</tbody>
</table>
2.5 Testing of Lattice Structures

In the current research landscape, it seems that a lot of focus is put on lattice structures. They are typically investigated for their mechanical properties and mass efficiency [19]. “They can be used in various technological field including structural lightweight design [20], [21], acoustic and thermal insulation [22], [23], [24], shock absorption [25], and as a biomaterials for implants and scaffolds for tissue engineering [26], [27], [28].

Up until relatively recently, studies regarding vibration performance of lattice structures primarily focused on strut-based lattices. For example, Monkova et al. [1] evaluated the damping and compression properties of body-centered cubic (BCC) lattice structures made from ABS fabricated using FDM. This study evaluated three volume ratios (25%, 45%, and 70%) with a unit cell size of 5x5x5 mm. Figure 2.5.1 shows the test setup. This study found “a
correlation between the investigated ABS samples’ stiffness evaluated through both compressive stress and mechanical vibration damping” [1]. However, this study did not numerically describe the damping ratio of the lattices. It mainly describes the relative damping performance of the different test configurations (different volume ratios and test mass combinations).

![Figure 2.5.1 Monkova et al. Test Setups: Compression (Left) and Vibration (Right) [1]](image)

Kladovasilakis et al. investigated the mechanical behavior of diamond, gyroid, and Schwarz lattice structures made from PLA using FDM. This study evaluated three volume ratios (10%, 20%, and 30%). Compression testing was used for evaluation. This study found that the diamond structure demonstrated the highest mechanical strength. The overall results showed that the mechanical properties of the structures decrease as the relative density decreases.

Shen et al. [29] investigated the energy absorption properties of TPU. This study used spherical-shell lattice structures shown in Figure 2.5.2 with eight volume ratios between 45.7%
and 91.8%. The samples we fabricated from powered TPU via laser sintering. Hysteretic compression testing was used to characterize energy absorption.

Beloshenko et al. [28] also investigated the mechanical properties of TPU lattices. Gyroid and honeycomb (planar) lattices were studied. Tensile, three-point bending, and compression testing were used to evaluate the effect of print slice direction on the mechanical performance of the lattices.

Şimşek et al. [30] explored the vibration characteristics of a Gyroid sandwich structure made from HS188 using direct metal laser melting (a type of powder bed fusion) shown in Figure 2.5.3. This study used natural frequencies and mode shapes to characterize vibration. Three different unit cell sizes (6, 8, and 12 mm unit cells) with a single volume ratio (20%) were evaluated in this study. While compressive testing was performed experimentally to find the effective elastic modulus of a 24x24x24 mm gyroid lattice cube, the dynamic evaluation
was performed computationally and experimentally on a 192x192x25.6 mm (64 of the aforementioned cubes sandwiched between two plates) gyroid lattice sandwich. This study fulfilled its purpose in finding that this sandwich lattice structure could be modeled (modally through the first four modes) accurately without the complex lattice geometry also needing to be modeled, as long as the effective modulus of the structure was known.

![Image of sandwiched gyroid structure](image.png)

*Figure 2.5.3 Şimşek et al. Sandwiched Gyroid Structure [30]*

Herkal et al. [31] explored how a 3D printed Schwarzite lattice structure performs in terms of vibration absorption compared to an FDM 3D printed solid rectangular prism using the same amount (~240 grams) and type (PLA) of material as the lattice structure. The study found that having Schwarzite geometry increases the damping ratio by ~80%. The vibration results of this study were not established experimentally, instead, the compression properties were first determined experimentally and then the vibration performance was determined computationally.
Figure 2.5.4 Herkal et al. Vibration Testing (a) Configuration and (b) Results [31]

2.6 Summary

The previous studies mentioned in this section explore the compressive properties of surface-based lattice structures experimentally. They show that compression testing can be valuable in and of itself and also valuable as a way to foray into simulating other aspects of lattice performance including vibrational properties. A wide range of materials and printing methods were used to fabricate test samples in previous studies.
The work proposed by the study detailed in this document aims to fill in the gaps to get a better understanding of how specific lattice geometry and material selection interact and affect vibration reduction performance. The proposed vibration testing will be done experimentally with materials common for FDM printing. TPMS lattices were chosen for this study because they seem to be the de facto surface-based lattice recently explored in literature.
Chapter 3  Design and Fabrication

3.1 Sample Design

The focus of this study is homogenous, periodic, surface-based (TPMS) lattice structures. The general concept for the test sample design was established based on previous work that was done on strut-based lattice structures [32]. Each lattice sample was to consist of four 5x5x5 mm³ cells resulting in a 20x20x20 mm³ lattice with a 2mm thick base plate and a 2mm thick top plate [33].

After several attempts to create the lattice cells using SOLIDWORKS, it became apparent that this method would not be practical due to the processing time required to generate a single cell. A MATLAB-based TPMS designer tool was also evaluated [34]. While this tool was able to generate single-cell TPMS geometry and even export it as an STL file for use in other software. SOLIDWORKS was limited in its ability to consistently convert the STL mesh into a STEP solid body. This conversion would be required to pattern the cell geometry into a complete lattice structure for testing, not to mention adding the top and base plates. nTopology was found while researching a solution to these issues. nTopology is a commercial software used for generative design, lattice structure generation, topology optimization, design automation, field-driven design, and simulation [35]. Of course, for the purposes of this research, lattice structure generation was of the most interest.

The first step in designing the lattice structure in nTopology was to select the overall shape, size, and position of the structure that the lattice would ultimately inhabit. This was done using the ‘Cube’ function as seen in Figure 3.1.1. The next step was to generate the lattice using
the ‘Walled TPMS’ function, see Figure 3.1.2. The position of the center point of the cube generated in the first step would determine the layout of the TPMS structure. Figure 3.1.3 shows a schematic of this concept. It was important to select a center point such that each TPMS shape would be free of dramatic overhangs and discontinuities for printing purposes. Table 3.1.1 shows the center points used in the design of the test samples. The last steps were to generate the top and bottom plates with the ‘Box’ function and then combine the now three solid bodies together with the ‘Boolean Union’ function as shown in Figure 3.1.4. At this point, the complete structure can be exported as an .STL file for use in the slicer.

Figure 3.1.1 Generating Basic Cube Structure for Lattice
### Table 3.1.1 Center Points Used for Each TPMS Shape

<table>
<thead>
<tr>
<th>TPMS Shape</th>
<th>Center Point (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Diamond</td>
<td>0</td>
</tr>
<tr>
<td>Gyroid</td>
<td>1</td>
</tr>
<tr>
<td>Schwarz</td>
<td>2.5</td>
</tr>
</tbody>
</table>

### Figure 3.1.2 Generating TPMS Lattice Structure within Base Shape
Figure 3.1.3 Schematic of Center Point Concept

Figure 3.1.4 Adding Base and Top Plates to Existing Structure and Combining
17.8%, 30%, and 40% volume ratios were selected as the targeted volume ratios. In this context volume ratio is the ratio of the volume of the lattice structure (not including base or top plates) over the volume of a 20 mm cube. In nTopology, using the ‘Walled TPMS’ lattice option, TPMS shape, cell size, and overall lattice size were direct inputs. Lattice volume ratio was not a direct input. However, since approximate wall thickness was one of the inputs for the ‘Walled TPMS’ lattice option and nTopology would output the total lattice volume, the wall thickness corresponding to a specific volume ratio was calculated by first arbitrarily inputting wall thicknesses to determine the relationship between wall thickness and volume ratio. The relationship between wall thickness and volume ratio is linear, each lattice type has a unique relationship between wall thickness and volume ratio. These relationships are shown in Equations 2.1.1, 2.1.2, and 2.1.3 for diamond, gyroid, and Schwarz respectively.

\[
\text{Volume Ratio} = 0.4660 \times \text{Wall Thickness} - 0.0008 \quad (3.1.1)
\]

\[
\text{Volume Ratio} = 0.3927 \times \text{Wall Thickness} - 0.0022 \quad (3.1.2)
\]

\[
\text{Volume Ratio} = 0.6883 \times \text{Wall Thickness} - 0.0009 \quad (3.1.3)
\]

3.2 Fabrication of Test Samples

At the time of fabrication, vat photopolymerization printers and material extrusion printers were available. The plan originally was to use a Stratasys uPrint SE Plus FDM printer. Due to the difficulty removing the dissolvable support material after printing and the inability to disable the inclusion of support material in the built-in GrabCAD slicer software, an alternative needed to be found. Test samples ultimately were fabricated using a homebuilt, open-source, core XY, FDM printer with a 0.4mm nozzle. The design of the printer was created
by Voron Design and is shown in Figure 3.2.1. Two materials were selected for this study: polylactic acid (PLA) and thermoplastic polyurethane (TPU) without support material. Six samples were printed for each material, TPMS shape, and volume ratio, resulting in a total of 106 samples being fabricated.

![Voron 2.4 FDM Printer](image)

**Figure 3.2.1 Voron 2.4 FDM Printer [36]**

<table>
<thead>
<tr>
<th>Table 3.2.1 Filament and Print Parameters for the Fabrication of Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material</strong></td>
</tr>
<tr>
<td><strong>Color</strong></td>
</tr>
<tr>
<td><strong>Brand</strong></td>
</tr>
<tr>
<td><strong>Durometer</strong></td>
</tr>
<tr>
<td><strong>Nozzle Temp. (°C)</strong></td>
</tr>
<tr>
<td><strong>Bed Temp. (°C)</strong></td>
</tr>
<tr>
<td><strong>Layer Height (mm)</strong></td>
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<tr>
<td><strong>Diameter (mm)</strong></td>
</tr>
<tr>
<td><strong>Max Extrusion Speed (mm/s)</strong></td>
</tr>
<tr>
<td><strong>Infill</strong></td>
</tr>
</tbody>
</table>
3.3 Print Quality

The PLA and TPU printer settings took several iterations to select. The print settings used to fabricate PLA samples of satisfactory visual quality were more straightforward and were achieved using the temperature recommendation of the PLA filament’s manufacturer. The printing of the PLA samples was straightforward and was able to be done at extrusion speeds up to 50 mm/s. A layer height of 0.1 mm was achieved for the PLA samples.

On the other hand, finding print settings to fabricate TPU samples of satisfactory visual quality took more iterations of settings after failed prints to finally arrive at the settings shown in Table 3.2.1. The setting that seemed to have the greatest effect on print quality was maximum extrusion speed. It was found that the extrusion speeds for the TPU printing would need to be limited to 30 mm/s to maintain satisfactory print quality. While visual print quality was of major importance, there was a desire to have the prints be as quick as possible. For example, the layer height for the TPU sample was set to 0.16 mm. While this increased layer height allowed for shorter total print times, more importantly, it solved the issue observed with TPU using the 0.1mm layer height where a semi-cooled wick of the TPU filament would bind to the partially printed sample below during non-extrusion travel causing an extra build-up of material which at some point later in the build would bind to the print nozzle itself due to lack of clearance causing the print to fail. Through the methods referred to above, satisfactory visual print quality was achieved, though there are some deformities evident in some of the low-volume ratio TPU samples which can be seen in Figure 3.3.1, Figure 3.3.2, and Figure 3.3.3.
Figure 3.3.1 Example of printed diamond lattice sample from each material: PLA (red) and TPU (white)
Figure 3.3.2 Example of printed gyroid lattice sample from each material: PLA (red) and TPU (white)
3.4 Mass measurements

Beyond qualitative visual inspections, mass measurements were also used to better understand print quality. All printed samples used for either compression testing or vibration testing were massed and labeled before their respective tests. The mass measurements were performed using an Intelligent-Lab PX-200 analytical balance. It can be seen in Table 3.4.1,
Figure 3.4.1, and Figure 3.4.2 that for any given combination of material, TPMS shape, and volume ratio, there is very little variation in mass for that given combination. This indicates the consistency of each print. For a given combination of material and shape, the mass increased with respect to volume ratio. However, this increase was not linear as expected. The other notable trend was for a given combination of material and TPMS shape, the TPU samples were 15.7% lighter on average than the PLA samples.

<table>
<thead>
<tr>
<th>Material</th>
<th>TPMS Shape</th>
<th>Designed Volume Ratio (%)</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Min</th>
<th>Max</th>
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<td>Diamond</td>
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<td>4.5810</td>
<td>0.0151</td>
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<td>40.0</td>
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<td>Gyroid</td>
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<td>Schwarz</td>
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Figure 3.4.1 Individual Value Plot of Mass for PLA Samples

Figure 3.4.2 Individual Value Plot of Mass for TPU Samples
To further investigate the mass of the samples, base/top plates were printed using the same print settings that were used to print the samples to be used in compression and vibration testing. These base/top plates were also weighed. Using their mass and their volume (20x20x2 mm³), an ‘as printed’ density was calculated. The ‘as printed’ density for PLA was ~2% higher than the filament density reported by the manufacturer. The ‘as printed’ density for TPU was ~3% lower than the filament density report by the manufacturer. The mass of the top/bottom plates was also subtracted from the average sample mass shown in Table 3.4.1 to get the ‘lattice only’ mass shown in Table 3.4.2. This ‘lattice only’ mass and ‘as printed’ density were then used to calculate volume ratio. In Figure 3.4.3 it can be seen that these calculated volume ratios vary from the designed volume ratios. This is particularly pronounced in the case of the PLA diamond 30% sample. Figure 3.3.1 shows the thick stringing in the 30% PLA diamond lattice that isn’t as visually prominent in the other volume ratios and shapes. This could explain the increased printed volume ratio. While there is variation between the printed volume ratio and the designed volume ratio, for the remainder of this paper the samples will continue to be referred to by their designed volume ratio.
### Table 3.4.2 Summary of Mass Investigation

<table>
<thead>
<tr>
<th>Material</th>
<th>TPMS Shape</th>
<th>Designed Volume Ratio (%)</th>
<th>Avg. Mass of Single Base/Top Plate (g)</th>
<th>‘As Printed’ Density (g/cm³)</th>
<th>Avg. ‘Lattice Only’ Mass (g)</th>
<th>Printed Volume Ratio (%)</th>
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#### Figure 3.4.3 Comparison of Designed vs Printed Volume Ratios
3.5 Fixturing

Custom fixturing was designed and fabricated for the vibration testing. The design goals of the fixturing for the vibration testing were as follows: (1) serve as an adapter between the shaker and the test specimen and the shaker, (2) serve as an adapter between the test specimen and the mass, (3) have a way to align each sample, and (4) allow for efficient part changeout. All test fixturing was designed in SOLIDWORKS and fabricated using the previously mentioned VORON fused deposition modeling printer with the print parameters shown in Table 3.5.1. Figure 3.5.1 show an isometric view of the fixture assembly in SOLIDWORKS. Figure 3.5.2 shows the cross-section of the fixture assembly with labels denoting the various connections. Except for the five #10-32 bolts used to attach the lower base plate to the shaker, all bolted connections were made using M3 bolts. All M3 bolts were mated into threaded brass inserts that were thermoset into the PLA+ after printing. This was done to make sure the fixture was as stiff as possible relative to the test sample.

| Table 3.5.1 Filament and Print Parameters for the Fabrication of Vibration Test Fixturing |
|----------------------------------------|-----------------|
| **Material**                          | PLA+            |
| **Color**                             | Green/Purple   |
| **Brand**                             | Inland          |
| **Nozzle Temp. (°C)**                 | 220             |
| **Bed Temp. (°C)**                    | 60              |
| **Layer Height (mm)**                 | 0.10            |
| **Diameter (mm)**                     | 1.75            |
| **Max Extrusion Speed (mm/s)**        | 50              |
| **Infill**                            | 75%             |
Figure 3.5.1 Isometric View of Fixture Assembly from SOLIDWORKS

Figure 3.5.2 Cross-Section of Fixture w/ Notes on Connections
Chapter 4  Test Setup

4.1 Compression Testing

Compression testing was completed on a servo-hydraulic MTS test stand, loaded under constant displacement at a rate of 6 millimeters per minute until 50% of the starting sample height was reached. The PLA samples were tested using a 10,000-lbf load cell. The TPU samples were tested using a 1,000-lbf load cell. Displacement was captured with an onboard linear variable differential transformer (LVDT). Displacement was zeroed with 50 lbf applied directly to the test base. The primary outputs for this compression testing were applied load and the corresponding displacement.

Figure 4.1.1 Picture of Compression Test Setup w/ PLA Sample
4.2 Vibration Testing

Vibration testing was performed using an electrodynamic shaker from The Modal Shop. Custom fixturing was fabricated to attach the sample to the shaker and to retain the test mass as detailed in 3.5. Two PCB 352C22 accelerometers were used in this testing. One accelerometer (S/N: LW253632) was attached to the base plate to control the input frequency and amplitude. The other accelerometer (S/N: LW253635) was attached to the top of the mass to measure the response signal. Each accelerometer was attached using wax. Each sample was attached using Gorilla brand gel super glue. A sine sweep was performed on each of three samples for a given combination of TPMS shape, material, and volume ratio for a total of 54 samples. The sweep had a frequency range from 20 Hz to 2,000 Hz at a rate of 1.7 octaves per minute with an amplitude of either 5 g’s or 10 g’s. It became apparent during testing that a 10-g input at resonance would result in an output greater than the 100-g limit of the response accelerometer, thus a 5-g input was used for the remaining sweeps. The primary data outputs
for this vibration testing were control acceleration, response acceleration, and driving frequency.

**Figure 4.2.1 Simple Model of Spring-Mass-Damper System**

**Figure 4.2.2 Picture of Vibration Test Setup on Shaker w/ Labels**
Chapter 5  Test Results and Discussion

5.1 Compression Testing

Since the main outputs of the compression testing were load and displacement; and for the purposes of this study, the elastic region is of most interest, the results of the compression testing can best be characterized by stiffness. A custom LabVIEW program was used to identify the slope of the load vs displacement traces in the elastic region. Figure 5.1.1 shows data traces that are representative of the typical load versus displacement behavior observed for the two materials during this study. This highlighted area of interest is from where the data to calculate stiffness was taken.

![Figure 5.1.1 Typical PLA (left)/TPU (right) Data Trace w/ Elastic Region Highlighted](image)

Figure 5.1.2, Figure 5.1.3, Figure 5.1.4, Figure 5.1.5, Figure 5.1.6, and Figure 5.1.7 show compression test data traces. While three compression tests were performed per combination of material, lattice shape, and volume ratio, for clarity, only one of those three traces are shown in the figures. The consistency in this data, makes it such the traces shown are representative of the traces not shown for the same respective combination.
The first four figures (two for each material) are graphs for the diamond and gyroid lattice shapes. They show data traces that are well aligned, in shape, with what would be expected for that given material. For example, the traces in the two PLA graphs exhibited the characteristic behavior of a “hard & tough plastic” as shown in Figure 2.4.1. While the TPU traces exhibited the characteristic behavior of an “elastomer” as also shown in Figure 2.4.1. When comparing the effects of lattice volume ratio, the 17.8% samples have a lower yield load than that of their 30% and 40% counterparts. The 40% samples have the highest yield load.

Figure 5.1.6 shows the data traces for PLA Schwarz samples. While the 40% trace exhibit similar behavior to that of the PLA diamond and gyroid traces, the 17.8% and 30% (to a lesser degree) exhibit undulations. These types of undulations were present in compression data of BCC strut-based lattices and corresponding to the yielding of a layer of struts [37]. In the case of the 17.8% PLA Schwarz lattice, there are a total of four yield points in the data trace corresponding to the yielding of the four rows of cells.
Figure 5.1.2 PLA Diamond Compression Graph

Figure 5.1.3 TPU Diamond Compression Graph
Figure 5.1.4 PLA Gyroid Compression Graph

Figure 5.1.5 TPU Gyroid Compression Graph
Figure 5.1.6 PLA Schwarz Compression Graph

Figure 5.1.7 TPU Schwarz Compression Graph
Figure 5.1.8 Pre and Post-Test Images of Samples

Figure 5.1.9 Individual Value Plot of Stiffness in Elastic Region for PLA Samples
As expected, the PLA samples exhibited a significantly higher stiffness in its elastic region than the TPU samples. There was more than a 140X difference between the two materials average stiffness. Except for in the case of the 17.8% volume ratio TPU samples, the diamond samples exhibited the highest stiffness for a given volume ratio followed by the gyroid samples then Schwarz.

Returning to the main purpose of the compression testing: to size a mass for vibration testing. Even though there was a wide range of stiffnesses and the sweep frequencies were broad, the combinations could just be limited to the following two cases. (1) With the most stiff sample, what is the minimum mass to have a resonance at 2000Hz? And (2) with the least stiff sample, what is the maximum mass to have a resonance at 20 Hz? These prompts were answered
by leveraging Equation 4.1.1. Prompt (1) resulted in 347 grams and prompt (2) resulted in 72.6 grams. A mass of 200 grams was selected plus an additional 53.6 grams of fixturing resulting in a 253.6-gram mass assembly for vibration testing.

\[ \omega_n = \sqrt{\frac{k}{m}} \]  

(5.1.1)

5.2 Vibration Testing

Figure 5.2.1, Figure 5.2.2, and Figure 5.2.3 show the transmissibility data from the PLA samples. Figure 5.2.4, Figure 5.2.5, and Figure 5.2.6 show the transmissibility data the TPU samples. Transmissibility, in this case, is the ratio of output acceleration at the top of the mass assembly over input acceleration at the fixture base. The horizontal axis of the graphs is frequency ratio, which is the ratio of the driving frequency over the natural frequency of a given trace. Transmissibility vs frequency ratio is a common way of displaying and analyzing this type of data. Note how the data from the PLA samples generally exhibit higher and sharper peaks than that of the TPU samples. This behavior is expected when comparing materials with dramatically different stiffnesses and damping. Some of the data traces show a second peak to the left of the first peak. This second peak could be indicating a resonance elsewhere in the system. For the purpose of this study, only the main resonance frequency is of interest.
Figure 5.2.1 PLA Diamond Vibration Graph

Figure 5.2.2 PLA Gyroid Vibration Graph
Figure 5.2.3 PLA Schwarz Vibration Graph

Figure 5.2.4 TPU Diamond Vibration Graph
The goal of the vibration testing was to understand the damping performance of each sample. In this case, damping performance would be characterized by a given sample’s damping ratio. All calculations from the vibration testing portion of this study were performed...
using custom MATLAB code (see Appendix A). Using Equation 4.2.1 and Equation 4.2.2, the transmissibility $T$, natural frequency $f_n$, and driving frequency $f_{dr}$ were used to calculate the damping ratio $\zeta$. Natural frequency was determined by finding the frequency at which the maximum response acceleration was observed. While this frequency would technically be the damped natural frequency, it is a commonly accepted assumption to treat it as the natural frequency for the aforementioned calculations. In fact, making this frequency the damped natural frequency does not change the observations of this study, so for simplicity that data will not be included.

$$T = \frac{A_{out}}{A_{in}} = \sqrt{\frac{1 + (2\zeta r)^2}{(1 - r^2)^2 + (2\zeta r)^2}}$$ \hspace{1cm} (5.2.1)

$$r = \frac{f_{dr}}{f_n}$$ \hspace{1cm} (5.2.2)

Figure 5.2.7 and Figure 5.2.8 are individual value plots of natural frequencies. The color lines show the trend of the mean for each configuration. There is a clear separation between the natural frequencies of the PLA samples versus that of the TPU. This was expected based on the dramatic separation in stiffness discussed previously. What was not expected was the inconsistent relationship between natural frequency and volume ratio for a given TPMS shape. This inconsistency is especially noticeable for PLA samples, where there was greater variation in natural frequency than that of TPU samples.
Figure 5.2.7 Individual Value Plot of Natural Frequencies for PLA Samples

Figure 5.2.8 Individual Value Plot of Natural Frequencies for TPU Samples
Figure 5.2.9 and Figure 5.2.10 show clear separation between the damping ratios of the PLA samples and that of the TPU. As expected, the TPU samples exhibited higher damping performance. Amongst TPU samples, the 40% volume ratio samples consistently exhibited the lowest damping ratios. Also, amongst TPU samples, the 17.8% volume ratio samples exhibited the highest damping ratios when the TPMS shape was diamond or gyroid. In general, for the TPU samples, the Schwarz samples exhibited to lowest damping performance. The PLA sample set was much less consistent with respect to trends in damping performance.

![Interval Plot of Damping Ratio](image)

*Figure 5.2.9 Individual Value Plot of Damping Ratios for PLA Samples*
Figure 5.2.10 Individual Value Plot of Damping Ratios for TPU Samples
Chapter 6  Conclusion

6.1 Summary

3D printed surface-based lattices have been investigated under compression testing and vibration testing to understand damping performance. Two materials (PLA and ABS), three TPMS shapes (Diamond, Gyroid, and Schwarz), and three volume ratios (17.8%, 30%, and 40%) were considered in this study. Six samples of each combination of material, TPMS shape, and volume ratio were fabricated, resulting in a total of 106 samples being fabricated. Three samples of each combination were used for compression testing and three samples of each combination were used for vibration testing.

Compression testing primarily provided stiffness data for the lattice structure which was helpful in the sizing of the mass for vibration testing and giving additional insight to the effect of volume ratio and material. Vibration testing provided transmissibility data at the system natural frequency which was used to calculate the damping ratio of the system. Table 6.1.1 shows a high-level summary of test data.
Table 6.1.1 Summary of Test Data

<table>
<thead>
<tr>
<th>Material</th>
<th>TPMS Shape</th>
<th>Designed Volume Ratio (%)</th>
<th>Average Lattice Mass (g)</th>
<th>Average Stiffness (N/mm)</th>
<th>Average Damping Ratio</th>
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<td>31.4</td>
<td>0.101</td>
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</table>

6.2 Conclusions

For a given amount of deposited material and volume ratio, diamond was the stiffest TPMS shape while Schwarz was the least stiff for most volume ratios. This observation is in agreement with previous studies. In terms of damping, TPU consistently outperformed PLA. The TPU samples exhibited an average damping ratio of 0.126 while their PLA counterparts exhibited an average damping ratio of 0.044. Zooming into TPU, the 17.8% volume ratio generally outperformed the other volume ratios when it came to damping. The 17.8% volume ratio TPU samples exhibited an average damping ratio of 0.158 compared to 0.120 and 0.101 damping ratio average for the 30% and 40% TPU samples respectively.
6.3 Recommendations for Future Work

Based on the results of this study, it may be prudent to focus future efforts specifically on TPU. Also increasing lattice cell size and overall sample size may help to improve print resolution and avoid some of the deformities observed in the low volume ratio TPU samples in this study. Hopefully the combination of these changes will result in the effect of each TPMS shape being more pronounced. Even if focusing on PLA in the future, increase the lattice cell size would help to minimize the effects of stringing during the printing process. For more stiff materials like stiff plastics and metals, the effect of sweep speed should be explored with respect to its effect on data resolution near resonance.
Appendix A

MATLAB code to find natural frequency and damping ratio

clear; clc;
data_files=dir('D:\Users\Imabin\OneDrive\Documents\Thesis\Testing\Vibration Testing\Final\Matlab Data Files\*.mat');

%pre-alocate cell
A=cell(size(data_files,1),13);
for i=1:size(data_files,1)
data_files_names=getfield(data_files,{i},'name');
importfile(data_files_names);
T=Rec001Sine_Ch002_CH_2./Rec001Sine_Ch001_CH_1;
phase_lag=Rec001Sine_Ch002_CH_2_Phase-Rec001Sine_Ch001_CH_1_Phase;
fdr=Hz;
[XX,fpeakloc]=max(T);
fn1=fdr(fpeakloc);
fd=fdr(fpeakloc);
phaseatpeak=phase_lag(fpeakloc);

%Method 1 take peak as natural frequency fn
r=fdr/fn1;
z1=sqrt(((T.^2).*r.^4)+(2*(T.^2).*r.^2)+((1-(T.^2)))./(((T.^2)-1).*r.^2))/2;
damping_ratio1=z1(fpeakloc);

%Method 2 take peak as damped natural frequency fd
s=fdr/fd;
a=((T.^2).*s.^4)-(4*(T.^2).*s.^2)+(4*s.^2);
b=(10*(T.^2).*s.^2)-(2*(T.^2).*s.^4)-4*s.^2;
c=-(2*(s.^2)-(s.^4)-1)+1;
z21=(-b+sqrt((b.^2)-4*(a.*c)))./(2.*a);
z22=(-b-sqrt((b.^2)-4*(a.*c)))./(2.*a);
z2=sqrt(z21);
damping_ratio2=z2(fpeakloc);
fn2=fd/sqrt(1-damping_ratio2^2);

x=fdr;
y1=T;
y2=phase_lag;
%cell definitions
A{i,1}=data_files_names;
A{i,2}=T;
A{i,3}=phase_lag;
A{i,4}=fdr;
A{i,5}=z1;
A{i,6}=z2;
A{i,7}=fn1;
A{i,8}=fn2;
A{i,9}=phaseatpeak;
A{i,10}=damping_ratio1;
A{i,11}=damping_ratio2;
A{i,12}=fd;
A{i,13}=i;

figure(1)
%plot(A{i,4}/A{i,7},A{i,2},'DisplayName',A{i,1})
semilogy(A{i,4}/A{i,7},A{i,2},'
DisplayName',A{i,1})
grids on
hold on

figure(2)
plot(A{i,4}/A{i,7},A{i,3},'
DisplayName',A{i,1})
grids on
hold on

end

figure(1)
xlabel('Frequency Ratio')
ylabel('Transmissibility')
xlim([0 4])
%legend

figure(2)
xlabel('Frequency Ratio')
ylabel('Phase Lag (deg)')
xlim([0 4])
References


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