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2020

Yang, W., An, J., Chua, C. K., & Zhou, K. (2020). Acoustic absorptions of multifunctional polymeric cellular structures based on triply periodic minimal surfaces fabricated by stereolithography. *Virtual and Physical Prototyping*, 15(2), 242-249.
doi:10.1080/17452759.2020.1740747

<https://hdl.handle.net/10356/143430>

<https://doi.org/10.1080/17452759.2020.1740747>

This is an Accepted Manuscript of an article published by Informa UK Limited, trading as Taylor and Francis in *Virtual and Physical Prototyping* on 19 Mar 2020, available online:
<http://www.tandfonline.com/10.1080/17452759.2020.1740747>

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Acoustic Absorptions of Multifunctional Polymeric Cellular Structures Based on Triply Periodic Minimal Surfaces Fabricated by Stereolithography

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Abstract

Polymeric cellular structures based on triply periodic minimal surfaces (TPMS) have been widely studied for applications in multiple disciplines due to their multifunctionality. However, there is limited acoustic application by TPMS-based structures as their acoustic properties remain largely unknown. In this paper, TPMS-based structures are fabricated by additive manufacturing and investigated as a novel solution to sound absorption in the upper midrange frequency. Structures based on three typical surface types (Primitive, Gyroid and Diamond) with three geometry-related parameters (volume fraction, unit cell size and height) are manufactured by stereolithography and tested by two-microphone impedance method in the frequency range of 2000-6000 Hz. The results show that the structures based on Diamond surfaces exhibit excellent absorption abilities among the three types in a wide bandwidth. High absorption coefficients can be achieved by a large volume fraction or a small unit cell size while the effective frequency ranges can be adjusted by the height. This study extends the multifunctionality of TPMS-based cellular structures to include acoustic absorption and will facilitate the development of guidelines on designing the optimal acoustic absorbers by cellular structures in future.

Keywords: additive manufacturing; acoustic absorption; triply periodic minimal surfaces; multifunctional; stereolithography

Introduction

Architected cellular structures are cellular solids with voids arranged in periodicity, for example, naturally honeycombs and synthetic lattices. These structures are potential replacements of bulk structures owing to their competitive mechanical properties while the weight and materials of the structures are reduced by the voids [1, 2]. The recent research has focused on cellular structures based on triply periodic minimal surfaces (TPMS). TPMS are mathematically defined continuous

surfaces that exhibit periodicity in three perpendicular dimensions with zero mean curvatures and locally-minimized surface areas [3, 4]. These surfaces divide the space into two interlocked sub-domains while maintaining the voids [5, 6]. The unique geometries motivated various studies on the properties of the structures based on TPMS for multifunctional applications. The TPMS-based cellular structures can be employed for structural engineering owing to the superior mechanical properties such as high stiffness and strength [7, 8], and these mechanical properties can even be customized for different design requirements [9]. These structures also exhibit optimal energy absorption abilities [10, 11], thermal and electrical conductivities [12], fluid permeability [13] and vibration isolation abilities [14], and thus have the potential for multifunctional engineering applications.

The research on TPMS was restricted to theoretical studies until the introduction of additive manufacturing (AM). AM has enabled the fabrication of the complex structures including TPMS-based structures for multi-discipline applications through layer-by-layer buildup of pre-designed computer models [15-26]. The advanced AM techniques, selective laser melting (SLM) and selective laser sintering (SLS), have been mostly utilized for manufacturing of TPMS-based structures made of metal and polymers respectively, for investigations on the mechanical and multifunctional properties of the structures [2, 8, 11, 14, 27]. In addition to metal and polymers, ceramic was applied as the material of TPMS-based structures as bone tissue scaffolds printed by fused deposition modeling (FDM) technique [28]. The unit cell sizes of the structures fabricated by SLM, SLS and FDM rang from 7 mm to 20 mm, while stereolithography (SLA) technique can fabricate structures in smaller sizes (less than 5 mm in unit size) with high dimension accuracy and good surface finish [29, 30].

As one of the ideal solutions to complex structures, AM has been introduced to the manufacturing of various acoustic devices since 2007 [31, 32]. However, the studies on the acoustic properties of the TPMS-based structures are very limited. The acoustic absorptions of these structures remain largely unknown. Until recently, only the acoustic band gaps and the sound attenuation of the TPMS-based structures have been reported, and the results showed that wide band gaps in high frequency ranges (over 6000 Hz) could be obtained by these structures [33]. This study suggests that TPMS-based structures are multifunctional structures with sound attenuation ability

as an additional function. However, the conclusions were based only on simulation results without experimental validations and therefore motivated the acoustic tests on physical cellular structures to investigate the sound absorption properties in the upper midrange (2000 Hz to 6000 Hz), a frequency band that is most sensitive to human hearing.

TPMS-based cellular structures could have several advantages compared to the traditional cellular structures and materials (fibers and foams). Traditional cellular structures and materials including fibers and foams have been widely used as the sound absorbers with strong absorption abilities while the poor mechanical properties have restricted the applications [34, 35]. However, TPMS-based cellular structures are multifunctional, providing not only acoustic absorption abilities but also excellent mechanical and thermal performances. Moreover, studies on the optimal energy absorption abilities of the TPMS-based structures indicated the potential to absorb sound wave energy in multiple means rather than transmission and reflection [10, 11]. In addition, compared to the traditional fibers and materials whose acoustic absorption abilities and absorbed sound wave frequency ranges are determined by the intrinsic structures and the properties of the materials, the adjustable geometric parameters of these regular cellular structures are able to tune the frequency range and bandwidth of the absorbed sound wave. Furthermore, the wideband acoustic absorption in high frequency ranges by TPMS-based structures are expected in acoustic engineering as the common sound absorbers including micro-perforated panels, traditional porous materials and newly-introduced metamaterials are focusing on wideband absorptions in low-frequency ranges, wideband absorptions in middle frequency ranges and narrowband absorptions with extremely high efficiency, respectively [36].

In this paper, structures based on TPMS of Gyroid, Primitive and Diamond surfaces were designed and fabricated by SLA for the investigations on the acoustic absorption abilities of the TPMS-based structures, as these three types of structures have optimal energy absorption abilities and excellent mechanical properties [11, 37]. The acoustic absorption tests were applied to the manufactured TPMS-based structures. The optimal type of the TPMS for acoustic absorption was determined and analyzed. In addition, the effects of the cell size, volume fraction and the heights of the structures on the absorption abilities and the absorption frequency ranges were

studied and analyzed for optimum absorptions in aimed frequency ranges.

Materials and methods

Three types of the surfaces, Primitive (P), Gyroid (G) and Diamond (D) were employed to create the cellular structures for acoustic absorption. The three structures can be generated by the following approximation equations [5]:

$$\Phi_p = \cos(\omega x) + \cos(\omega y) + \cos(\omega z) - t, \quad (1)$$

$$\Phi_G = \cos(\omega x)\sin(\omega y) + \cos(\omega y)\sin(\omega z) + \cos(\omega z)\sin(\omega x) - t, \quad (2)$$

$$\Phi_D = \sin(\omega x)\sin(\omega y)\sin(\omega z) + \sin(\omega x)\cos(\omega y)\cos(\omega z) + \cos(\omega x)\cos(\omega y)\sin(\omega z) - t \quad (3)$$

where x, y, z are the spatial coordinates and ω is the function periodicity given as

$$\omega = \frac{2\pi}{l}, \quad (4)$$

where l is the length of unit cell. The arbitrary parameter t is the controller of the volume fraction of the lattice cell. The regions are defined to be solid when $\Phi \leq 0$ and to be void when $\Phi > 0$. The isosurface is defined at $\Phi = 0$ to separate the solid and the void regions and the triangular mesh can be exported as an STL file for AM process. *Matlab* was used to generate the surfaces, *Blender* was used to ad convert the surfaces to solid bodies and *Materialise Magics* was used to offset and repair the structures.

Tortuosity τ is the structure shape factor that describes the degree of the twist of the structures as well as the paths of the air flow passing through the structures. A larger τ will increase the length of the path and thus also the viscous losses of the sound wave, thereby achieving larger acoustic absorptions [38]. The values of the tortuosity τ of the P, G and D surfaces have been obtained by Nawada (2018) using Lattice-Boltzmann simulations [39].

Besides the surface types of the structures, the geometric parameters will affect τ of the structures. For example, the complexity and the twist of the structures can be increased by reducing the unit cell size and increasing the volume fraction (the volume portion of the rigid parts of the TMPS-based structures) so that the path passed by the sound wave increases. To study the effects of the geometric parameters including unit cell size l , volume fraction ρ and sample height h on the acoustic absorption coefficients and the effective ranges of the frequency, the structures based

on three types of TMPS with varied l , ρ and h were designed. The designed parameters are listed in **Table 1**.

Table 1. The surface types and parameters of the unit cell size, volume fraction and height of the designed cellular structures.

Sample	Type	ρ (%)	l (mm)	h (mm)	Sample	Type	ρ (%)	l (mm)	h (mm)
S1	D	15	5.6	11.2	S10	D	25	7.0	11.2
S2	D	25	5.6	11.2	S11	D	25	9.3	11.2
S3	D	35	5.6	11.2	S12	G	25	7.0	11.2
S4	D	45	5.6	11.2	S13	P	25	7.0	11.2
S5	G	15	5.6	11.2	S14	D	25	5.6	5.6
S6	G	35	5.6	11.2	S15	D	25	5.6	16.8
S7	P	15	5.6	11.2	S16	G	25	5.6	16.8
S8	P	35	5.6	11.2	S17	P	25	5.6	16.8
S9	D	25	4.7	11.2					

The samples were designed to be cylinders with 29 mm diameter and 1 mm wall thickness to fit the dimension of the experiment apparatus. The values of the unit cell size l were determined by the largest cell number of the top surface of the cylindrical samples. As the number decreased from 6 to 3, l increased from 4.7 mm to 9.3 mm. Similarly, the values of the height h were designed by the number of the cells at the height of the cylindrical structures. As the number of the cells increased from 1 cell to 3 cells, h increased from 5.6 mm to 16.8 mm while the unit cell size l was fixed at 5.6 mm.

SLA, a vat photopolymerization technology [40-42], was used to fabricate the designed small-size samples by photopolymerization of the polymer resin for sound absorption in the high frequency range from 2000 Hz to 6400 Hz. The SLA printer Form 2 with a laser power of 250 mW and building speed of 6 ml/h along the z-axis was used and the printing material was a commercial resin (Tough FLTOTL04, Formlab). The structures were cleaned by isopropyl alcohol and were cured by a 405 nm UV light. **Figure 1** shows the unit cell, the designed samples and the printed samples based on the three surface types.

Figure 1. The unit cell, the tortuosity τ , the designed samples and the printed samples based on the three surface types: Primitive (P), G (Gyroid) and D (Diamond).

The two-microphone impedance method with impedance tube type 4206 (Brüel and Kjær Sound and Vibration) was used to measure the sound absorption. In this paper, the impedance tube with an inner diameter of 29 mm was used to measure the frequency range from 500 to 6400 Hz. The mechanical performances of the printed structures were not tested here as the focus was on the acoustic properties. There was an extensive literature on the mechanical properties and the structure-property requirements of photopolymer-based cellular structures or sandwich structures printed by SLA [7, 8, 43-45].

Results and discussion

This section presents the tested acoustic absorption performances of the TPMS-based structures, discusses the effects of the surface type, the volume fraction ρ , the unit cell size l and the height h on the acoustic absorption coefficients and the effective absorption frequency ranges and concludes the preferable structural designs

for optimal sound absorption by TPMS-based structures. The parameters ρ , l and h are designed values as the accuracy of the SLA is high and the impact of the deviation on the parametric effect can be ignored [40].

Effect of the surface type

Figure 2 shows the comparisons of the acoustic absorptions of the structures based on the three types of TPMS. The D-type structures exhibit obvious higher absorption coefficients than the G-type and P-type structures with the same l , h and ρ in the aimed frequency range. The D-type structures hold the optimal absorption performance among the three types of structures despite the changes of the designed l , h and ρ , while the G-type and P-type structures show the similar performances and the G-type structures are able to achieve slightly higher absorption coefficients. Only the peak values of the absorption coefficients and the respective frequencies at the peak values are affected by the changes of l , h and ρ . The results agree with the predictions that the larger τ will provide better absorptions with larger absorption coefficients. It can be concluded that the D-type structures with the largest τ is the optimal surface type among the three candidate types for acoustic absorption. In the subsequent sections, to study the effects of l , h and ρ , all the structures were all designed in type D for highly effective acoustic absorption.

Figure 2. Comparison of the acoustic absorptions of structures: (a) S1, S5 and S7, (b) S3, S6 and S8, (c) S10, S12 and S13, and (b) S15, S16 and S17.

Effect of the volume fraction

Figure 3 shows the sound absorption abilities of S1, S2, S3 and S4. They are all D-type structures with increasing ρ . The height h was kept at 11.2 mm while the unit cell size l was kept at 5.6 mm. The results show that the overall absorption coefficients increase as ρ increases from 15% to 45% while the effective absorption frequency ranges are kept at around 4000–6400 Hz. A similar tendency can be observed from Figure 3(a) and Figure 3(b) that the G-type and P-type structures exhibit higher absorption coefficients with a larger ρ . The increase of the volume fraction ρ has the positive effects on the absorption coefficients since τ is increased at the same time. However, for the D-type structures that have the most complicated structural configurations among the three types, although the increase of the volume fraction will benefit the acoustic absorption with higher absorption coefficients, the structures with a ρ larger than 50% are difficult to realize since the void parts of the

structures will be blocked by the materials of the solid parts. In addition, the reduction of the weight and materials of the acoustic absorbers is preferable in the industrial and architectural applications. The structures that can achieve the targeted absorptions at acceptable absorption coefficients with the lightest weight (smallest ρ) will be the ideal solution in the multifunctional applications.

Figure 3. Comparison of the acoustic absorptions of the D-type structures with various ρ .

Effect of the unit cell size

Figure 4 shows the sound absorption abilities of S2, S9, S10 and S11. They are all D-type structures with increasing l , the height h was kept at 11.2 mm while the volume fraction ρ was kept at 25% for these structures. It is obvious that as l increases, the absorption coefficient decreases while the effective frequency ranges do not change. It can be explained by the decrease of τ due to the increase of l . However, when the largest cell number at the top surface increased to 7 and l decreased to 4 mm during the experiment, the fabrication of the D-type structures failed due to the restricted spot size of the laser beam. For the applications of the D-type structures as acoustic absorbers, the designed l is suggested to be larger than 4 mm or an advanced printer with a smaller laser spot size is required for the manufacturing.

Figure 4. Comparison of the acoustic absorptions of the D-type structures with various l .

Effect of the height

Figure 5 shows the sound absorption abilities of S2, S14 and S15. They are D-type structures with increasing h . The volume fraction ρ was kept at 25% while the unit cell size l was kept at 5.6 mm. It can be observed that when h is 5.6 mm, the acoustic absorption is poor since the overall absorption coefficients are low. When h is 11.2 mm, the effective absorption frequency range is around 4000–6400 Hz and the absorption coefficients can achieve high values larger than 0.8. When h increases to 16.8 mm, the peak of the absorption curve shifts to the left, causing the effective absorption frequency range to shift to 3000–5000 Hz and the peak value of the absorption coefficients to decrease to 0.74. **Figure 2(d)** reflects similar shifts of the effective frequency ranges of the G-type and P-type structures with large h while the overall absorption coefficients are lower when compared with **Figure 2(c)**. Thus, the effective absorption frequency ranges can be tuned by adjusting the height of the absorbers when applying the TPMS-based structures in acoustic absorption.

However, the wall of the cylindrical samples for the tight contact between the testing tube and the structures can change the propagation routes of the sound wave in the cellular structures, and thus the height of the wall, which equals to the height h of the structure, is preferably to be small to reduce the effects of the wall for the testing samples with the restricted size. The designed structure sizes will depend on the requirements of the applications, and the suitable h for the acoustic absorptions in the aimed frequency ranges will be varied for different structure sizes. Furthermore, the

height should be minimized to reduce the space and weight of the structures for the industrial and architectural applications.

Figure 5. Comparison of the acoustic absorptions of the D-type structures with different h .

Conclusion

In this paper, TPMS surfaces as sound absorbers have been investigated. Structures based on D, G, and P types of surfaces with varying geometric parameters have been designed and tested for acoustic absorptions. The samples for the acoustic tests have been realized by SLA. The results showed that the D-type structure was ideal to absorb the sound wave with high absorption coefficients in the high frequency ranges while the traditional cellular structures focused on the acoustic absorption in the low and middle frequency ranges. The effective frequency ranges were tunable by adjusting the geometric parameters including the unit cell size, volume fraction and sample height. These parameters also had effects on the absorption coefficients. The results showed that the small cell size and the large volume fraction resulted in large absorption coefficients and the height had the main effect on tuning the effective frequency range. All of the factors including the surface type of the structures indicated that the absorption abilities would increase as the tortuosity of the structure increased. When designing the TPMS-based structures for sound absorption applications, the geometric parameters with a larger tortuosity resulting in the optimum absorption performance should not be the only factor to be considered, the restrictions on space, weight and manufacturing should not be ignored. Overall, the

feasibility of TPMS surfaces serving as multi-functional structures especially on acoustic absorption has been demonstrated. There is a great potential to provide the guidelines on designing the TPMS-based structures as the optimal sound absorbers in the upper midrange (the most sensitive band to human hearing) in future.

Acknowledgement

This research is supported by the National Research Foundation, Prime Minister's Office, Singapore under its Medium-Sized Centre funding scheme.

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