Vibration Characteristics of Periodic-Structured Cantilever Rods

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Abstract: The model struts are mainly used in wind tunnel test and plays a supporting role in the model tester. In order to reduce the influence of the model struts on the wind tunnel flow field and ensure the accuracy of the test data, the model strut is usually designed as a rod and installed at the tail of the model tester to form a support structure which similar to the cantilever beam[1]. The support structure has certain requirements for the strength of the support rod. When the model tester bear a certain pressure load, the model struts should not occur strength failure. On the other hand, A structure with concentrated mass at the front end of a cantilever beam has low dynamic stiffness[2-5]. The first natural frequencies of the system consisting of a model support and a model tester are liable to couple with the low-frequency pressure fluctuation of the flow field, resulting in resonance.Vibration of model struts not only affects the accuracy of test data, but also leads to breakage of struts and wind tunnel damage. With the development of new concepts of material structure, more and more studies and applications of periodic structure have been carried out. Periodic structures have periodicity in spatial distribution, usually the same structural units are connected repeatedly in the same way. By reasonably designing structural elements of periodic structures, the geometric or material parameters between structural elements can be changed periodically. Vibration of periodic structures has always been one of the hotspots in the field of engineering and technology, such as national defense, military, aerospace, ship, mechanical power, etc. There are some main honeycomb structure, grid structure, truss structure and other forms[6-8]. This research innovatively uses periodic structural to design model struts. Several kinds of periodic struts are designed, and the stiffness and inherent characteristics of the struts are compared and analyzed. The stiffness characteristics and anti-vibration (resonance/flutter) capability of struts in different periodic structural models are studied.

Keywords: Model Struts; Periodic Structure; 3D Printing

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1 Introduction

In the wind tunnel test, the model strut is cantilever structure, as shown in Figure 1. The model vibration is mainly reflected in three directions: pitch, yaw and roll. When the angle of attack test is carried out, the vibration in pitch direction is the most intense, followed by the other two directions. In addition, there are different vibration modes in different positions of the model, and the vibration of the trunk is the most harmful to the model system. For the model strut, pneumatic action on the model tester will exert force on the strut. Generally, it can be decomposed into pitch and yaw directions, generate bending deformation in both directions, and the maximum stress at the end of the connection between the strut and the model.

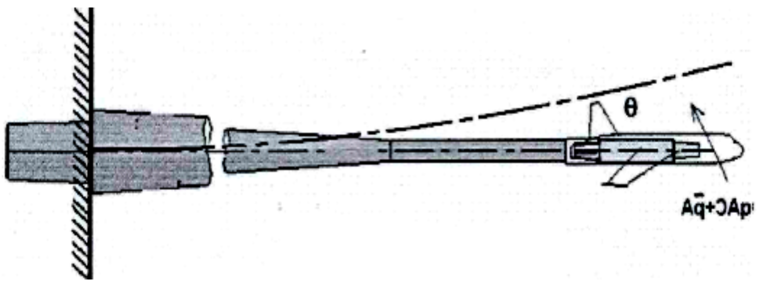

Fig.1. Model Struts and Its Aerodynamic Loads

In order to minimize the interference of the model strut to the flow field around the model, it is necessary to optimize the strut structure, reduce its cross-sectional area, increase its length, increase the stiffness and strength of the strut as much as possible[9]. The existing model struts are cylindrical structures made of high strength steel. In many cases, it is difficult to further improve the stiffness and strength under given size constraints. With the development of 3D printing technology, it is possible to fabricate complex periodic structures with tiny characteristics. In this study, the principle of periodic structure is used to innovate the design and fabrication of the strut by 3D printing technology to improve its super-resonance ability. Firstly, the structural design of the new type of strut is carried out by using two different types of periodic structures: honeycomb and regular hexahedron. Then, the finite element method is used to calculate and compare the static and dynamic characteristics of the struts with different periodic structures. Then, the vibration characteristics of the struts are tested and evaluated by using the simulators. Finally, the corresponding conclusions are obtained. Finally, the corresponding conclusions are obtained. It provides a basis for the subsequent detailed analysis and the design and optimization of the new periodic structure.

2 Design and Static Analysis of Periodic Strut

2.1 Periodic Structures Design of Model Strut

The structure size of a scaled model strut is shown in Fig. 2. The strut is redesigned with a honeycomb-shaped hexagonal prism space truss structure.

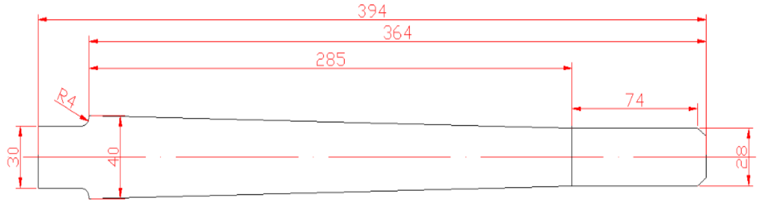

Fig. 2. Dimensions of scaled strut

Honeycomb Periodic Structures Design of Model Strut

Honeycomb-shaped periodic structure uses regular hexagonal as unit structure. Each layer of unit structure is connected by several 4mm high regular trigonometric prisms, forming a truss structure of honeycomb regular hexagonal prism. The size of honeycomb unit is shown in Figure 3. The honeycomb type periodic truss structure is designed according to the shape of the strut. The honeycomb type structure is embedded in the shell of the model strut with thickness of 3 mm, forming the honeycomb periodic truss strut, as shown in Fig. 4.

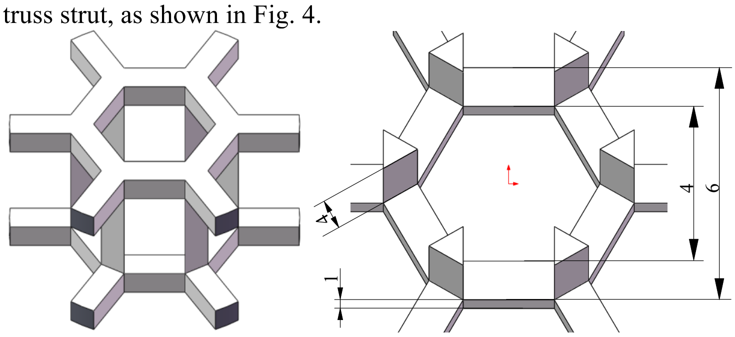

Fig. 3. Dimensions of Honeycomb Periodic Element

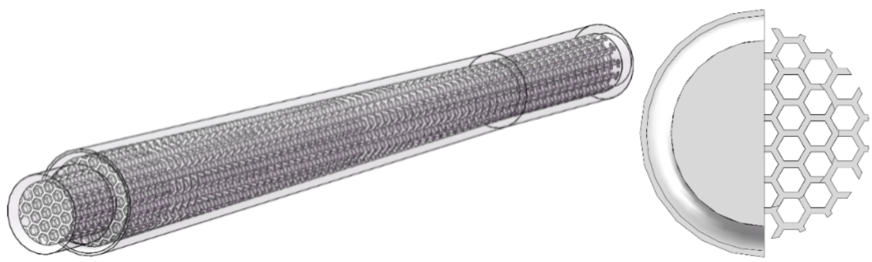

Fig. 4. Side View and Axis View of Honeycomb Periodic Strut

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Regular Hexahedral Periodic Structures Design of Model Strut

The 6mm regular hexahedral periodic truss structure uses the square as the unit to form a regular hexahedral truss structure. As shown in Figure 5. The shell thickness of the model strut is 3mm, and the regular hexahedral periodic truss structure is designed according to the shape of the model strut. The regular hexahedral periodic structure is embedded in the model strut shell, forming the regular hexahedral truss periodic model strut, as shown in Figure 6.

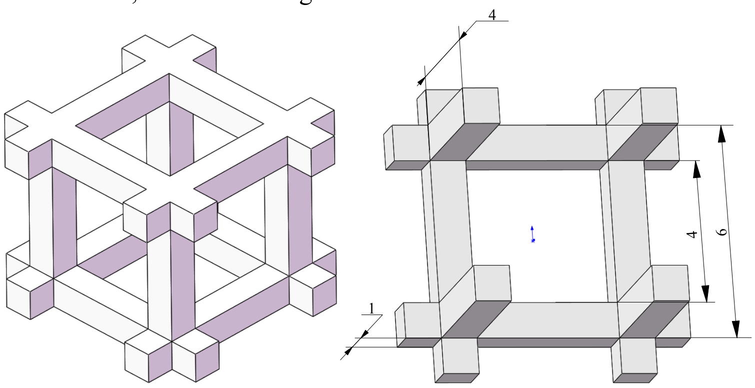

Fig. 5. Dimensions of Regular Hexahedron Periodic Element

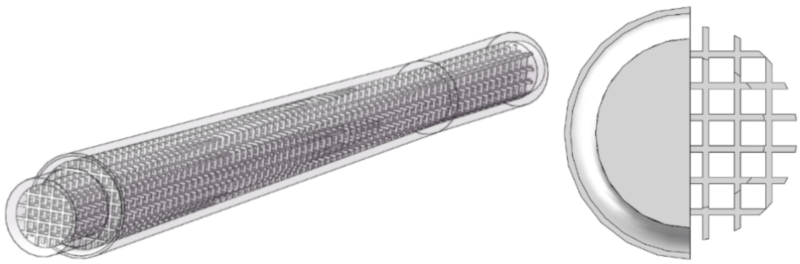

Fig. 6. Side View and Axis View of Regular Hexahedron Periodic Strut

2.2 Static Analysis of Model Strut

The finite element method (FEM) is used to calculate the statics of the new type periodic struts. The deformation and stress distribution of the struts are obtained by applying radial loads and radial loads on the struts. The results are compared with the traditional solid struts.

The model strut is made of polylactic acid material (PLA) parameters. Its modulus of elasticity is set to 3000MPa, Poisson's ratio is 0.3, and its density is 1300 kg/m3. Fixed constraints are imposed on the blue A side of the strut root, and the equivalent gravity of the model tester is 19.6N on the red B side, as shown in Figure 7.

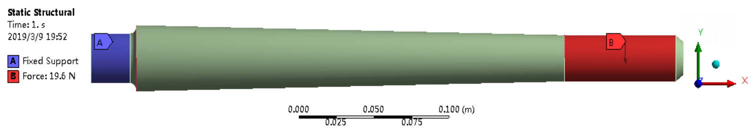

Fig.7. Boundary Conditions for Static Analysis of Solid Strut

Firstly, the static analysis of solid model strut is carried out. The grid is divided into 40359 nodes and 24068 elements by sweeping method. Solid185 element is used for calculation. The deformation results of the model strut is shown in Fig. 8, and the stress distribution of the model strut is shown in Fig. 9. The maximum deformation of solid strut occurs at the head, the maximum deformation is 1.223 mm, the maximum stress occurs at the root, and the maximum stress is 4.56 MPa.

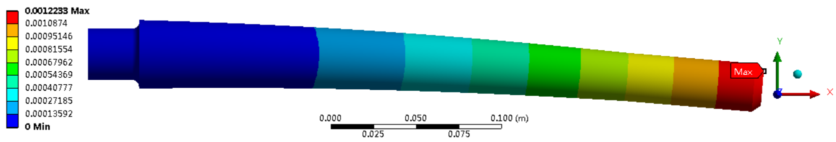

Fig. 8. Deformation Diagram of Solid Strut

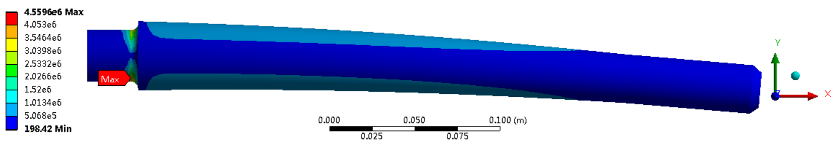

Fig.9. Stress Diagram of Solid Strut

Static analysis of honeycomb periodic struts and regular hexahedron periodic struts is carried out respectively. The results are shown in Table 1. The maximum deformation of the two kinds of periodic structure strut occurs at the right end and the maximum stress occurs at the left root of the internal periodic structure; the maximum deformation displacement of the honeycomb periodic struts is 2.3616 mm and the maximum stress value is 6.0173 Mpa; the maximum deformation displacement of the regular hexahedron periodic struts is 2.296 mm and the maximum stress value is 5.542 Mpa.

Table 2 shows the comparison of maximum deformation and maximum stress of honeycomb periodic strut, regular hexahedron periodic strut and solid strut. Under the same load and constraint conditions, the maximum deformation and stress of the honeycomb periodic strut are the largest of the three kinds of strut. The maximum deformation of the three kinds of strut occurs at the top of the struts, and the maximum stress occurs at the root of the struts. Compared with solid strut, the maximum deformation of honeycomb periodic strut is 93.13% more than that of solid strut. The maximum stress of honeycomb periodic strut is 31.95% more than that of solid strut, and the maximum deformation of regular hexahedron periodic strut is 87.74% more than that of solid strut. The maximum stress of regular hexahedron periodic strut is 21.54% more than that of solid strut.

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Table.1. Comparison of stress and deformation nephograms of honeycomb struts and regular hexahedron struts

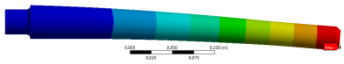
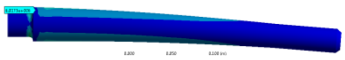
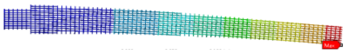
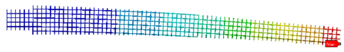
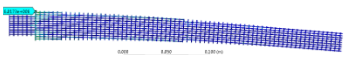
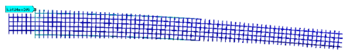
	honeycomb struts	regular hexahedron struts
Deformation of Strut		
Stress of Strut		
Deformation of internal truss		
Stress of internal truss		

Table.2. Comparisons of Deformation and Stress between Periodic Strut and Solid Strut

	Solid Strut	**Honeycomb Periodic Strut**	**Regular Hexahedral Periodic Strut**
Maximum Deformation(mm)	1.223	2.362	2.296
Maximum Stress(MPa)	4.56	6.017	5.542
Deformation difference	1	93.13%	87.74%
Stress difference	1	31.95%	21.54%

$$\text{Deformation difference} = \frac{\text{Periodic Strut Deformation} - \text{Solid Strut Deformation}}{\text{Solid Strut Deformation}} \times 100\%,$$

$$\text{Stress difference} = \frac{\text{Periodic Strut Stress} - \text{Solid Strut Stress}}{\text{Solid Strut Stress}} \times 100\%.$$

3 Modal and Response Analysis of Model Strut

3.1 Modal Analysis of Three Kinds of Model Strut

The material of the scaled strut is polylactic acid, the material of model equivalent mass which located at the top of the strut is structural steel. Fixed constraints are applied at the root of the strut, and modal analysis of the periodic structural model strut is carried out. The results of the analysis are shown in Tables 3 and 4.

Table 3 shows the natural frequency comparison among honeycomb periodic strut， regular hexahedron periodic strut and solid strut. The first four frequencies of honeycomb strut and regular hexahedron periodic strut are 35%-50% lower than the solid scale strut, and the difference of the fifth and sixth frequencies are less than 1%.

Table 4 shows the modal comparison results of honeycomb periodic struts, regular hexahedral periodic struts and solid struts, which are consistent with the first six modes.

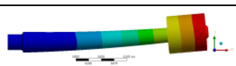
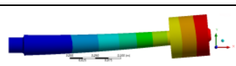
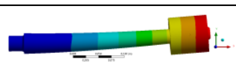
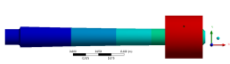
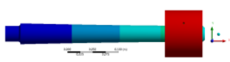
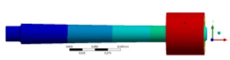
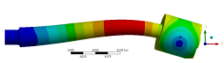
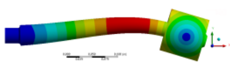
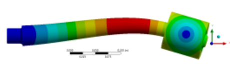
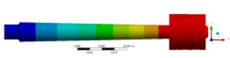
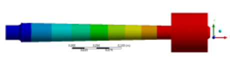
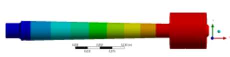
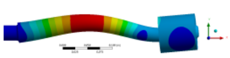
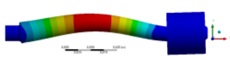
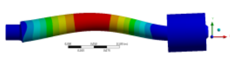
Table.3. Comparison of Natural Frequencies of Honeycomb, Regular Hexahedron Periodic Struts and Solid Struts

Order	name	Solid Strut Frequency	Honeycomb Strut Frequency	Hexahedral Strut Frequency	Honeycomb difference	Hexahedron difference
1	Pitch mode	15.188 Hz	9.62 Hz	10.869	-36.6%	-28.4%
2	Torsional mode	87.715 Hz	53.45 Hz	66.286	-39.1%	-24.4%
3	First Bend	164.5 Hz	116.14 Hz	133.98	-29.4%	-18.6%
4	Tension mode	321.34 Hz	172.8 Hz	194.61	-46.2%	-39.4%
5	Second Bend	522.03 Hz	521.73 Hz	527.12	-0.06%	0.96%
6	Third Bend	1258.7 Hz	1266Hz	1268.4	0.58%	0.77%

$$\text{Honeycomb difference} = \frac{\text{Honeycomb Strut Frequency} - \text{Solid Strut Frequency}}{\text{Solid Strut Frequency}} \times 100\%$$

$$\text{Hexahedron difference} = \frac{\text{Hexahedron Strut Frequency} - \text{Solid Strut Frequency}}{\text{Solid Strut Frequency}} \times 100\%$$

Table.4. Comparison of Vibration Modes of Three Kinds of Supports

name	Solid Strut	Honeycomb Periodic Strut	Regular Hexahedral Periodic Strut
Pitch mode			
Torsional mode			
First Bend			
Tension-compression mode			
Second Bend			

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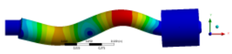
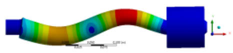
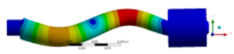
Third Bend			

3.2 Harmonic Response Analysis of Three Kinds of Model Struts

The material of the scaled strut is polylactic acid, the material of model equivalent mass which located at the top of the strut is structural steel. Fixed constraints are applied at the root of the strut, harmonic response of the model strut is analyzed, A vertical sinusoidal exciting force F is applied to the strut where the center of gravity of the equivalent mass located, The exciting force F is 500 N, and the vibration response is picked up at the root of the support rod in the direction of Y, as shown in Figure 10. The low frequency band sweeps frequency from 0 Hz to 50Hz, and the analysis step is set to 50 steps; the high frequency band sweeps frequency from 50 Hz to 3000Hz, the analysis step is set to 300 steps, the damping ratio is set to 0.1, and four resonance peaks are excited.

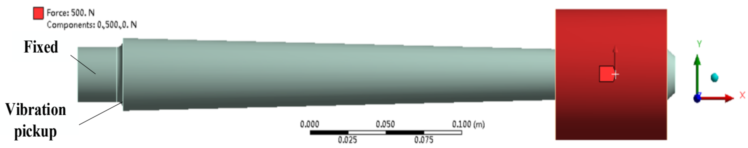


Fig. 10. Load and Boundary Conditions for Harmonic Response Analysis of Strut-Mass System

The harmonic response of three kinds of struts in low frequency band and high frequency band are analyzed. Fig. 11 shows the acceleration response of three kinds of struts in low frequency band. The response peak value of solid strut is the lowest and the first-order frequency is the largest. The peak response of honeycomb periodic strut is lower than that of hexahedron periodic strut.

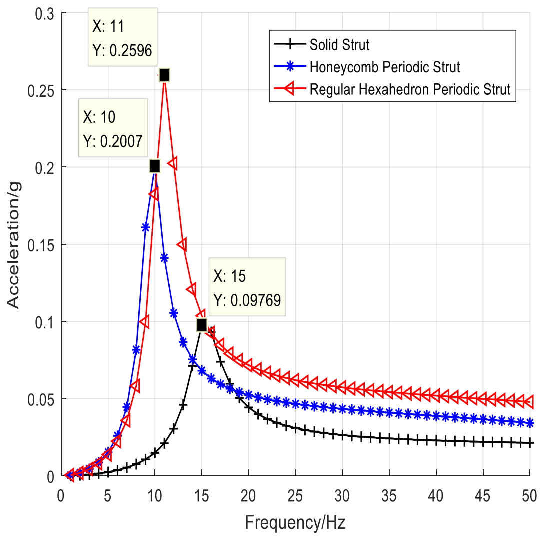


Fig.11. Acceleration Response of Three Kinds of Struts in Low Frequency Band

The results of harmonic response of three kinds of struts in high frequency band are shown in Fig. 12. From 50Hz to 3000Hz, solid strut has the lowest response, honeycomb strut takes the second place, and regular hexahedron strut has the largest response.

By comparing the Y-directional harmonic responses of three kinds of struts, it can be seen that the modal characteristics are basically the same, and the frequency of peak response is basically the same. The harmonic response peaks of the three struts are shown in Table 5.

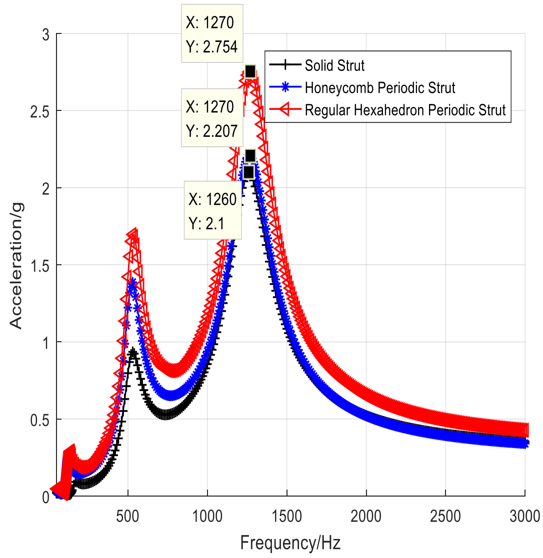


Fig. 12. Acceleration Response of Three Kinds of Struts in High Frequency Band

Table.5. Peak Acceleration of Harmonic Response of Three Struts

name	Solid Strut	Honeycomb Periodic Strut	Regular Hexahedral Periodic Strut
Pitch mode	0.09769 g	0.2007 g	0.2596 g
First Bend	0.09324 g	0.2414 g	0.2928 g
Second Bend	0.9357 g	1.354 g	1.686 g
Third Bend	2.1 g	2.207 g	2.754 g

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4 Vibration Test of Model Strut Made by Polymer Material 3D Printing

Using 3D printing technology and polymer PLA material, solid scale strut, 6mm-honeycomb strut and 6mm-hexahedral strut were printed out. The test was carried out on the shaker.

4.1 Solid Strut

As shown in Fig.13, a solid scaled strut with 3D printing of polymer PLA material and the equivalent mass installed on the strut head formed a solid strut-mass system.

Under the condition of loading equivalent mass of the model, 5-20Hz sweep frequency by using electromagnetic vibration shaker is carried out for the model solid strut system, the excitation acceleration is 0.3G is 0.3G, and the time is 2 minutes.

Fig. 13. Frequency Swept Test of Solid Strut-Mass System on Shaker

Solid strut-mass system 5-25Hz sweep three-dimensional waterfall diagram is shown in Fig. 14. The sweep results show that the first order frequency is 10.94Hz and the vibration acceleration is 0.3893G.

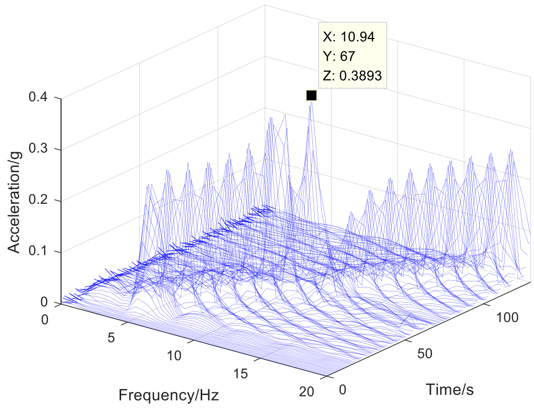

Fig. 14. Frequency Swept Waterfall Diagram of Solid Strut-Mass System

4.2 Honeycomb Periodic Strut

As shown in Fig.15, a honeycomb periodic strut with 3D printing of polymer PLA material and the equivalent mass installed on the strut head formed a honeycomb periodic strut-mass system.

Under the condition of loading equivalent mass of the model, 5-20Hz sweep frequency by using electromagnetic vibration shaker is carried out for the honeycomb periodic strut-mass system, the excitation acceleration is 0.3G, and the time is 2 minutes.

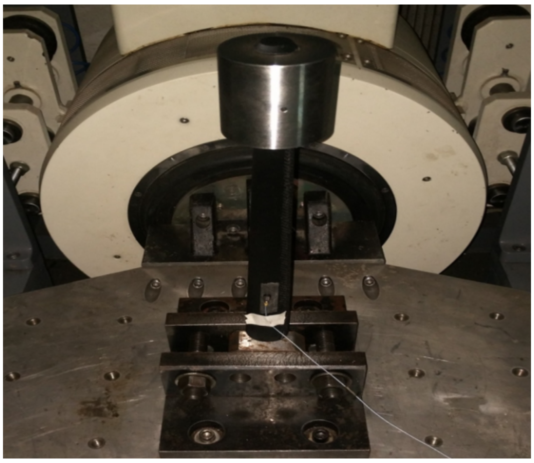

Fig. 15. Frequency Swept Test of Honeycomb Periodic Strut-Mass System on Shaker

The honeycomb periodic strut-mass system 5-25Hz sweep three-dimensional waterfall diagram is shown in Fig. 16. The sweep result shows that the first order frequency is 7.813Hz and the vibration acceleration is 0.3078G.

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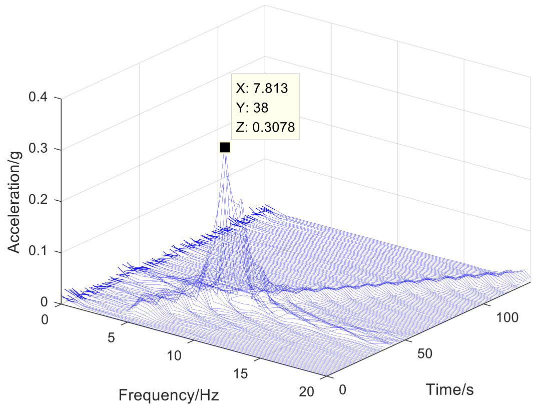

Fig. 16. Frequency Swept Waterfall Diagram of Honeycomb Periodic Strut-Mass System

4.3 Regular Hexahedral Periodic Strut

As shown in Fig.17, a regular hexahedron periodic strut with 3D printing of polymer PLA material and the equivalent mass installed on the strut head formed a regular hexahedron periodic strut-mass system.

Under the condition of loading equivalent mass of the model, 5-20Hz sweep frequency by using electromagnetic vibration shaker is carried out for the honeycomb periodic strut-mass system, the excitation acceleration is 0.3G, and the time is 2 minutes.

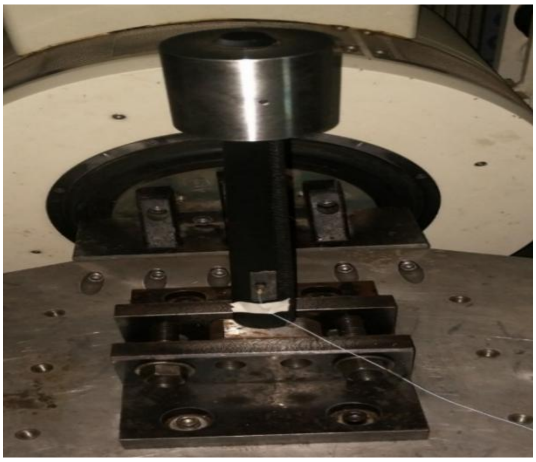

Fig. 17 Frequency Swept Test of Regular Hexahedron Periodic Strut-Mass System on Shaker

The 3D waterfall diagram of the regular hexahedral strut-mass system with 5-25HZ sweep frequency is shown in Fig. 18. The sweep results show that the first order frequency is 8.594Hz and the vibration acceleration is 0.7563G.

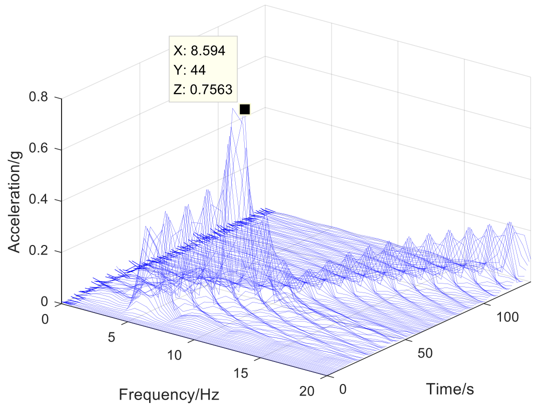

Fig. 18 Frequency Swept Waterfall Diagram of Regular Hexahedron Periodic Strut-Mass System

Table 6 shows the simulation and test results of the first-order frequency and its corresponding peak vibration response.

Table.6. First-order Frequency and Vibration Amplitude of Three Kinds of Struts

name	Solid Strut	Honeycomb Periodic Strut	Regular Hexahedral Periodic Strut
First-order simulation frequency	15.188 Hz	9.62 Hz	10.869 Hz
First-order test frequency	10.94 Hz	7.813 Hz	8.594 Hz
Simulated vibration peak	0.09769 g	0.2007 g	0.2596 g
Testing vibration peak	0.3893 g	0.3078 g	0.7563 g

5 Conclusions

Comparing the calculation with the test, it can be concluded that:

The maximum deformation and stress of the honeycomb periodic strut are the largest of the three kinds of strut. The maximum deformation of the three kinds of strut occurs at the top of the struts, and the maximum stress occurs at the root of the struts. Compared with solid strut, the maximum deformation of honeycomb periodic strut is 93.13% more than that of solid strut. The maximum stress of honeycomb periodic strut is 31.95% more than that of solid strut, and the maximum deformation of regular

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hexahedron periodic strut is 87.74% more than that of solid strut. The maximum stress of regular hexahedron periodic strut is 21.54% more than that of solid strut.

This is the elastic deformation of the local part. Static strength optimization is needed to avoid static strength failure. The maximum static deformation and the maximum stress position of the three kinds of struts are identical.

The first four frequencies of honeycomb strut and regular hexahedron periodic strut are 35%-50% lower than the solid scale strut, and the difference of the fifth and sixth frequencies are less than 1%. The modal results of honeycomb periodic struts, regular hexahedral periodic struts and solid struts are consistent within the first six modes.

The vibration shaker test results of polymer material struts show that the first-order frequency of periodic struts is lower than solid strut. In the sweep test of 0.3 G excitation acceleration, the first-order resonance response peak of honeycomb periodic strut is the lowest among the three struts, and its response peak value is 0.3078 G.

Both simulation and test results show that the response amplitude of honeycomb struts is lower than that of hexahedron struts.

The shape, size and distribution of different periodic structural elements are compared and analyzed to achieve the goal of improving the resistance to low frequency vibration, high strength and high stiffness margin. Further study is to fill the inner cavity of periodic strut with high damping material to improve the anti-vibration ability of the strut by improving the overall damping capacity of the system.

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