Study on dynamic characteristic of closed-cell aluminum foam

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Abstract. Closed-cell aluminum foam has been widely used in aerospace, rail transit and mechanical for its outstanding performance. But for a long time, the research on its vibration damping performance is only limited to the material damping test, there are relatively few studies on its dynamic characteristics. In this paper, we studied the relationship between dynamic characteristic and feature parameters. Modal assurance criterion and Finite element method were used to verify the accuracy of experimental model. It turned out that the average pore diameter of closed-cell aluminum foam conforms to Gaussian distribution. The modal analysis method can be used in the research of dynamic characteristic of closed-cell aluminum foam. Its damping ratio showed increasing trend with the increase of porosity, natural frequency and the decrease of mean pore size. Each order natural frequency increases along with the increase of porosity.

Keywords: closed-cell aluminum foam, feature parameters, dynamic characteristic, MAC, FEM.

1. Introduction

Closed-cell aluminum foam is a new kind of multifunctional metal porous material, which has the characteristics of both metal and bubbles. It's becoming one of the hot research topics in the current metal material field for its excellent mechanical and physical properties [1], such as low density, high specific strength, high specific stiffness, high energy absorption, high damping vibration, phonics, electromagnetic shielding and its multi-function compatible [2]. One of its main uses is as damping material; it can effectively reduce the vibration and noise that has a great significance to improve the accuracy and life of equipment as well as the working environment.

Now, some aspects of closed-cell aluminum foam have been deeply researched by experiment and FEM, such as the production process [3], dynamic and static compression [4] and energy absorption [5]. For its dynamic characteristics, especially the vibration damping performance mainly concentrated in the damping test referenced the standard of ASTM E756-05. Han et al. [6] and Liu et al. [7] have researched the factors influencing the damping property of closed-cell aluminum foam and damping mechanism. Golovin and Sinning [8] have researched its mechanical damping in a wide range of deformation amplitude. L. Dahil et al. [9] have studied the relationship between density and damping ratio of foamed aluminum using modal analysis method.

In this article, first, describe the analysis of feature parameters, adopted a new and simple method to analyze the porosity, characteristics of pore. Then using the modal analysis method to research the relationship between dynamic characteristic and feature parameters. Modal assurance criterion (MAC) and coherence function were used to verify the correctness of the model. We also compared the results by Finite element method (FEM). Last, the conclusions.

2. Experimental procedures

2.1. Feature parameters

The samples were made by melt foaming method and incised by wire-electrode cutting method. The sample size, outside diameter is Ø440 mm, inside diameter is Ø280 mm and the height is unequal.

Porosity is an important parameter to describe the closed-cell aluminum foam. The measurement method of porosity is divided into weighing method and microscopic method. For its simple and high precision, weighing method is commonly used. According to the dimension and weight of the sample, using the Eq. (1) to calculate the porosity:

$$\psi = \left(1 - \frac{m}{V\rho_s}\right) \times 100\ \%. \tag{1}$$

In which, m and V are the mass and volume of the sample, respectively, ρ_s is the density of matrix material.

The measurement of pore parameters mainly includes direct method and indirect method that using the software to analysis the surface topography of the sample [19]. In this article, we applied a new and simple method to measure the pore parameters. It has the advantages of low cost and high precision. The main equipment is digital camera and the main software is Photoshop, Matlab and Image-Pro Plus. The basic procession is shown in Fig. 1.

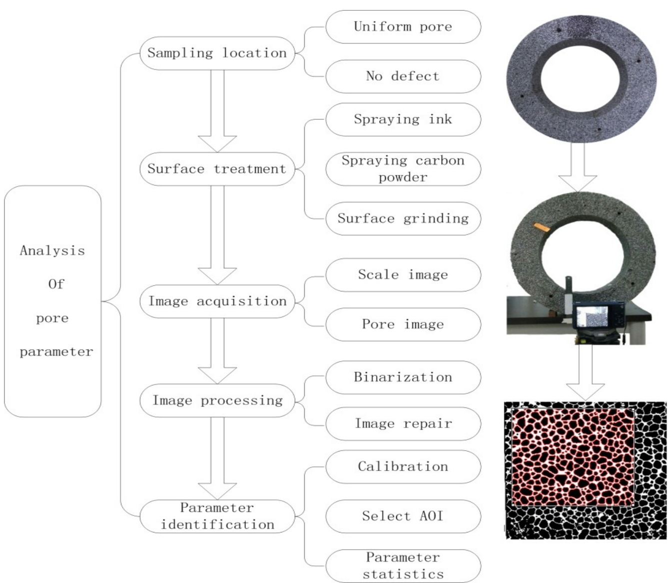


Fig. 1. The basic procession

2.2. Dynamic characteristic test

The dynamic characteristic was performed by experimental modal analysis and FEM. As shown in Fig. 2, the whole testing system composed by four parts; suspension part, shaking part, testing part and software analysis part. The suspension part includes rigid bracket and elastic soft cord to simulate the free boundary condition. The shaking part is impact hammer which is commonly used in the single-input single-output (SISO) modal analysis to produce pulse signal. The testing part is PCB accelerometer and high-speed data acquisition system. The software analysis part is Virtual lab/Modal Analysis software.

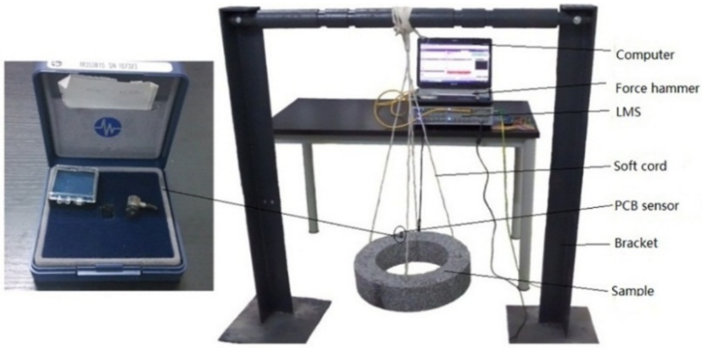


Fig. 2. The testing system

In the modeling process, the model is simplified to octagon with 48 nodes and ignores the mounting holes, as shown in Fig. 3. In which point 1:1 to 1:24 is the master node and the rest is the slave node. The PCB acceleration sensor is installed in the 1:3 points. During the experiment, using the force hammer which installed rigid head to beat the other master node, every node beats at least three times. The related experimental parameters as shown in Table 1.

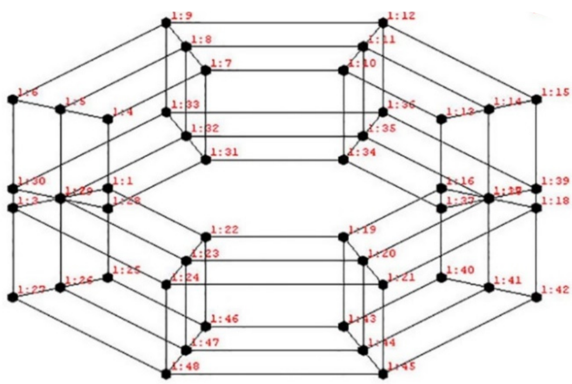


Fig. 3. The geometric model

Table 1. Related experimental parameters

Force sensor sensitivity	PCB sensor sensitivity	Bandwidth	Resolution	Averages	Response windowing
4 PC/N	101.7 mv/g	4096 Hz	1 Hz	3	Exponential

MAC was used to test the linear independence of each order. MAC is a good tool to evaluate the modal vector space angle. It can be expressed as follows:

$$MAC = mac_{ij} = \frac{[\varphi_i^T \varphi_j]}{(\varphi_i^T \varphi_i)(\varphi_j^T \varphi_j)}, \tag{2}$$

where φ_i and φ_j are the corresponding freedom of the i and j order calculation mode, respectively. The smaller of the off-diagonal matrix is the better of the independence of each calculation mode.

In this article, we also used the ABAQUS software to give a modal analysis in order to better verify the testing results. The basic steps of modal analysis in ABAQUS include modeling, select the analysis type, set the corresponding parameters, applying the boundary conditions, solve and results post processing. The parameters used in the simulation are shown in Table 2.

Table 2. Parameters used in FEM

Height	Porosity	Density (kg/m^3)	Young's modulus × 10^6 (Pa)	Poisson's ratio
50	85.8 %	380	428.61	0.28
50	86.4 %	370	401.14	0.28
80	81.9 %	490	603.07	0.28
80	85.0 %	400	484	0.28
120	83.9 %	430	524.36	0.28
120	85.2 %	400	454.67	0.28
150	84.6 %	420	502.18	0.28
150	86.0 %	380	451.43	0.28

3. Results and discussion

3.1. Feature parameters analysis

Table 3 shows the feature parameters of aluminum foam. It can be found that the porosity is among 81.9 % to 86.42 %, the relative density is among 0.136 to 0.181, the average diameter is among 2.42 to 3.23 mm.

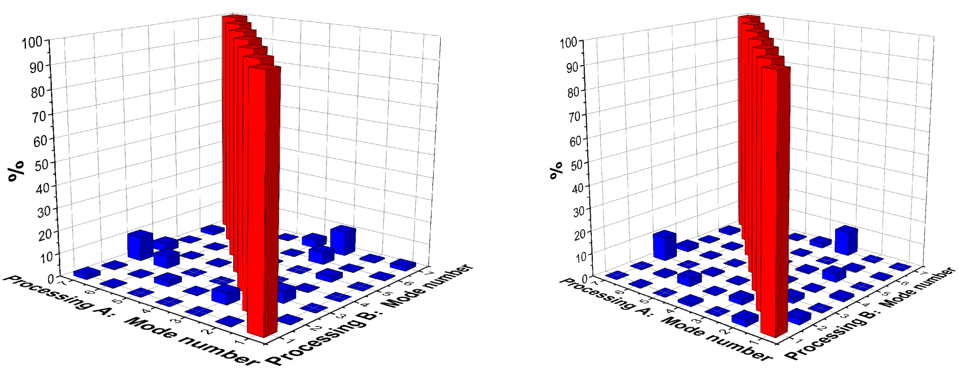
Table 3. Parameters of aluminum foam

No.	Height / mm	Mass / g	Porosity	Diameter / mm	Relative density
1	50	1761	85.79 %	3.23	0.142
2	50	1665	86.42 %	2.65	0.136
3	80	2930	85.01 %	2.77	0.150
4	80	3540	81.90 %	2.42	0.181
5	120	4694	83.92 %	2.44	0.161
6	120	4334	85.21 %	2.72	0.148
7	150	5629	84.61 %	2.70	0.154
8	150	5132	85.95 %	3.09	0.140

3.2. Experimental modal analysis

3.2.1. Results and validation

In this article, we analyzed the first six orders. As shown in Fig. 4 is the MAC of each sample. Through the MAC it can be found that except the diagonal correlation is 100 %, the other off-diagonal correlation is fewer than 10 % and mostly fewer than 5 %. According the above criteria of MAC, it can be found that the node configuration is reasonable, and each order modal has higher orthogonality.



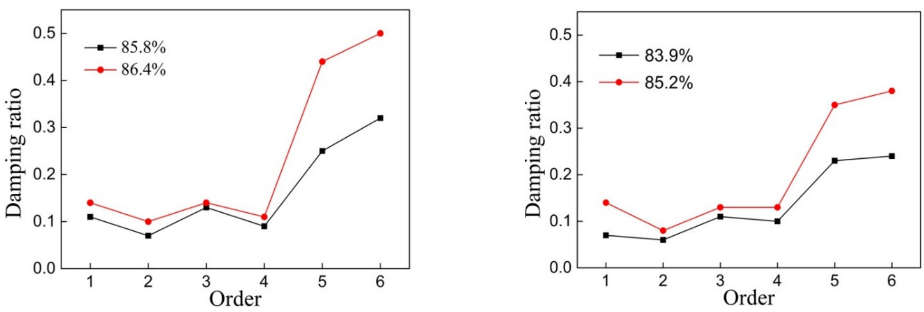
a) Sample one　　b) Sample two

Fig. 4. Modal assurance criterion

3.2.2. Discussion of experimental modal results

(1) Relationship between damping ratio and porosity.

As shown in Fig. 5 is the result of damping ratio of each sample. It can be seen from Fig. 5 each order damping ratio increases with the increase of porosity, the damping ratio and porosity is positively correlated. But in some orders the damping ratio decreases with the increase of porosity for the manufacturing defect.

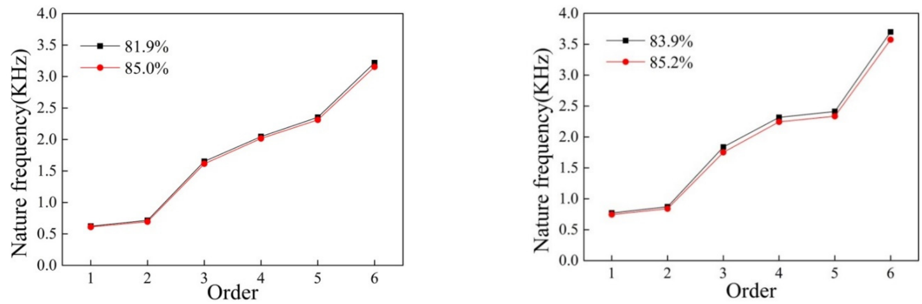


a) Sample one b) Sample two

Fig. 5. Relationship between damping ratio and porosity

(2) Relationship between natural frequency and porosity.

Material's vibration damping performance and damping ratio are closely related, but there is another important factor that affects the vibration damping performance is the natural frequency of the sample. As shown in Fig. 6, it can be found that the natural frequency of each order decreases with the increase of porosity and increases with the increase of height of the sample. In this experiment, the sample's axial dimension is less than the radial dimension, the stiffness of axial increases greater than the increase of mass, its natural frequency is increased with the increase of height.



a) Sample one b) Sample two

Fig. 6. Relationship between natural frequency and porosity

3.3. Comparison between experiment and FEM

By comparing the simulation results and experimental results can make a mutual authentication between the two methods. The results are shown in the Table 4. As it can be seen the simulation results can be good fit with the testing results. So, in the next study, we can use the FEM to study its dynamic characteristic.

4. Conclusions

First, modal analysis method can effectively analyze the dynamic characteristics of closed-cell aluminum foam. Second, the natural frequency of closed-cell aluminum foam is negatively correlated to porosity and it increases with the increase of sample height when the axial dimension smaller than the radial dimension.

Third, FEM can be used to study the dynamic characteristic of closed-cell aluminum foam and compared with experiment it has some advantages; it can make a further optimization analysis of the sample shape by FEM.

Table 4. Comparison between FEM and experiment

Height	Porosity	Item	First order frequency	Second order frequency	Third order frequency	Forth order frequency	Fifth order frequency	Sixth order frequency
50	0.8579	Test value	412.521	467.224	1156.314	1569.274	1991.156	2275.407
		FEM value	441.43	464.18	1172	1558.6	2041	2259.5
		Error	0.07	–0.0065	0.014	–0.0068	0.025	–0.0069
50	0.8642	Test value	403.873	465.858	1147.42	1550.125	1924.597	2261.659
		FEM value	432.93	445.16	1144.3	1572.7	1957.4	2166.9
		Error	0.072	–0.044	–0.0027	0.015	0.017	–0.042
80	0.819	Test value	624.184	715.786	1652.535	2046.163	2352.014	3219.411
		FEM value	627.88	712.81	1855.4	2084.4	2312.3	3259.3
		Error	0.0059	–0.0042	0.123	0.019	–0.0017	0.012
80	0.8501	Test value	611.275	694.411	1614.625	2016.47	2312.069	3153.054
		FEM value	635.52	649.99	1607.7	2109.8	2314.9	3123.4
		Error	0.04	–0.064	–0.0043	0.046	0.0012	–0.0094
120	0.8392	Test value	771.856	871.648	1838.794	2316.829	2412.699	3698.126
		FEM value	784.96	869.53	1871	2407.3	2423.7	3701.1
		Error	0.017	–0.0024	0.018	0.039	0.0046	0.001
120	0.8521	Test value	745.5	839.099	1751.82	2244.576	2335.451	3574.857
		FEM value	767.51	849.5	1806.4	2324.2	2340	3598.4
		Error	0.03	0.013	0.03	0.035	0.002	0.007
150	0.8461	Test value	805.083	918.122	1790.455	2343.469	2972.636	3238.733
		FEM value	789.37	914.77	1770	2298.6	3034.9	3203.2
		Error	–0.02	–0.004	–0.01	0.019	0.021	–0.011
150	0.8595	Test value	794.044	895.565	1766.027	2315.208	2931.719	3118.055
		FEM value	786.83	911.79	1764.3	2291.2	3025.1	3137.9
		Error	–0.01	0.018	–0.001	–0.01	0.032	0.007

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