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EXPERIMENTAL RESEARCH OF PRE-TIGHTENED CYLINDRICAL STRUCTURE WITH VISCOELASTIC MATERIAL IN AXIAL VIBRATION

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In aerospace and automotive fields, there are lots of pre-tightened cylindrical structures with viscoelastic material. In order to study interlayer rotary slippage property in axial vibration, the pre-tightened cushion layered cylindrical structure was designed and constructed. Then, the compression characteristics of silicon foam cushion material were measured, and the modes of the structure based on different pre-tightened loads were investigated. After that, in order to study interlayer rotation property, the experiments of the structure in axial vibration were carried out. The slip phenomena between the layers were obtained. And the influence of preloads and vibration levels were studied. Finally, through the results of the vibration test, the range of the preload and the vibration level were obtained, in which the rotation or slippage should happen. These results will give the guidance for the practical design.

1. Introduction

In the field of aerospace and automobile and others, there are lots of multilayer cylindrical structures. When the material characteristics of the multilayer cylindrical structure, especially its coefficient of linear expansion has large difference, in order to realize effective connectivity of those parts, we often adopt the viscoelastic material as filling material of cylindrical structure between layers, and through compressing the viscoelastic material, which can produce preload, to promise the accordance of the relative location of different parts of the structure under the effect of mechanical environment, reduce the structure’s mechanical response under the effect of vibration and impulsive load, decrease the inner stress of different layers because of the difference of coefficient liner expansion and temperature variation, and finally enhance the adaptive capacity of the structure under the mechanical environment and temperature variation.

The pre-tightened multilayer cylindrical structure was composed of more than two layer cylindricity and interlayer cushion layer. In the practical engineering design, when the preload is oversize, it is easy to cause the structure in high stress state for a long time, and influence its service life; otherwise, when the preload is undersize, it is easy to generate relative slippage(or rotation) between layers, and influence its function. Because there are many nonlinear factors existed in the multilayer cylindrical structure, it is difficult for us to calculate its dynamic performance. At present, lots of references mainly are concentrated on considering factors of the preload, viscoelasticity, stiffness, external excitation and mass distribution between layers to analyse the dynamic response and rotation characteristics of the structure. In the aspect of the dynamic analysis and calculation, Liu Zhanfang[1] combined engineering application to design a contact-type damping structure with pre-tightening cushion layer, established the numerical model of the dynamic response of the structure on the basic of the viscoelasticity constitutive equation of the cushion material, and concluded the effects of the pre-tightening state, viscosity factor, and external excitation. Chen Ying[2] set up an equivalent mass-rigidity concentration model for a damping structure, and got the result of the smaller for the rigidity of the damping structure, the better for the high frequency filtering function, and draw a conclusion that the mean square root value of displacement mainly focused on the low frequency range. Guo Ran[3] used the direct restraint method and Coulomb friction method to present the stress and strain analysis of a three-layer structure subjected to a concentrated force. Farough Mohammdi[4]、Horng-Jou Wang[5]、Xiong-tao Cao[6] respectively used semi-analytical finite element method, discrete layer theory and wave propagation method to analyse the response characteristics of cylindrical shells with a constrained damping layer. V. G. Piskunov[7] divided the cylindrical shell across its thickness by concentric circumferential surfaces into a series of constituent cylindrical shells and analysed dynamics characteristics of the cylindrical shell structure with length-to-thickness ratios less than 5.

In terms of the interlayer slippage, Xumao[8] studied the simplified pre-tightening contacted spring-damping system, set up the dynamic model of the pre-tightening contacted cushion structure, and got an interpretation of the mechanism of the slip phenomenon. Wang Jiang[9] established the structure model with the modified coulomb friction model, and considered that the relative sliding velocity between the contact surface. Jon Juel Thomsen[10] aiming at the classical “mass-on-moving-belt” model, derived the analytical expressions of considering the amplitude and the base frequencies of friction-induced stick-slip and pure-slip oscillations. P.De Baets[11] verified the mechanisms causing stick-slip motion originating from relative deceleration. The experiment showed the risk of stick–slip during deceleration is enhanced by an increase of the time-length of deceleration and by an increase of the tangential stiffness of the mechanical system. M.B.Nates[12] analysed the slip of a particle on the inside of a rotating cylinder and studied the interaction between the angle of slip and the cylinder rotational velocity with experimental investigation.

For the multilayer pre-tightened cylindrical structure, when the preload was different, the rigidity of the structure also different, so the structure’s dynamic characteristic will be changed. Because, currently, it is difficult for us to quantitative analysis the slip phenomena of the pre-tightened structure under vibration environment using theoretical analysis, in order to study the interlayer slippage property of the pre-tightened structure under vibration environment, the cylindrical structure with pre-tightening cushion was designed and constructed, which can conveniently adjust and measure the preload. The modal characteristics of the structure under different preloads were investigated. In order to study interlayer slippage property, the experiments of the structure under different vibration levels were carried out, on the basis of that, the range of preloads and vibration levels were obtained, in which slippage will not occur. These results will give guidance for the practical design.

2. The design of the test specimen

For researching relative interlayer rotation property under axial vibration, and meanwhile, avoiding the structural eccentricity which may have effect on interlayer slippage, so the test specimen with cushion was designed as following Figure 1. The test specimen was made of the upper connector, lower connector, support barrel, cushion, loading nut, fixed bolt and force sensor. The cushion was pasted among upper connector, lower connector and support barrel. Through tightened the loading nut to make the preload produced by the compression of the cushion, the preload of the specimen could be arbitrarily adjusted according the test requirements, and can be directly read by the force sensor. In the vibration experiment, the test specimen was connected to vibration table through fixed bolt, the relative slippage or the rotation centered on the axial can be produced between the upper-lower connector and support barrel.

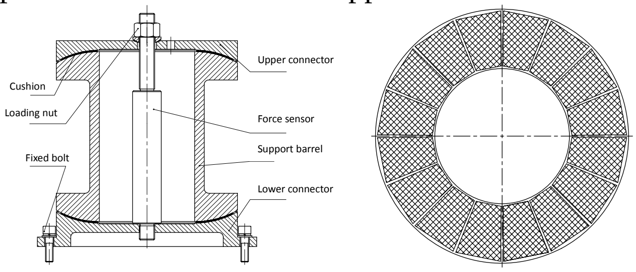


Figure 1. The axial vibration specimen and cushion layer pasting form

3. The research of the cushion compression mechanical properties

The cushion layer was made of the silicone foam and adhesive coating, as following Figure 2, of which the silicone foam was made from silicone rubber foamed. During used in the multilayer pre-tightened cylindrical structure with cushion layer, the cushion materials between inside and outside shell were always in a state of compression, and the preload of the cushion layer was existed along the thickness direction. The size of the preload will directly affect the dynamic characteristics of the structure, and the relative slippage occurred or not. So the static compressive property of the cushion material was important for analysing and assessing the dynamical anti-rotation performance of the multilayer pre-tightened cylindrical structure with cushion.

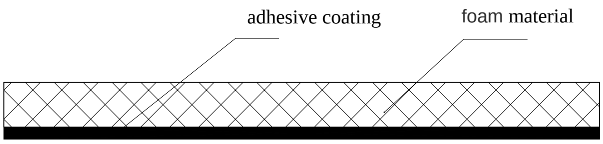


Figure 2. The Constitute of Cushion Layer

The tested samples were took from large cushion layer, and compressed on the material testing machines. It was compressed from the tested samples starting deformation to 7kN. The thickness of the test samples was 0.75mm. The compressed data from the tested samples of the cushion layer was shown in Table 1, and the stress-strain curve was shown in Figure 3.

From Figure 3, we can see that the compression and deformation of the foam material appeared the discipline as below: the deformation in the initial stage mainly was elastic bending of the cell wall, and with the increment of the compression, escaping gas diffusion from internal cell, and the cell wall bucked and part cell wall collapsed will occur until the cell entirely collapsed. And at the same time, the stress-strain curve of the silicone foam also showed up three different deformation characteristics: 1. the linear elasticity zone in the initial stage, 2. the plateau zone caused by the cell wall bucked and the starting collapse of the cell structure, 3. the sharply boosted zone of the modulus caused by the whole cell collapsed. The plateau zone was used as working range. From the Figure 3 we can see that the platform of the strain was about 10%~35%, and the relevant stress increased slower.

Table 1. The key data of compression tests

Stress/MPa	0	0.06	0.12	0.25	0.38	0.51	0.64	0.76	0.89
Strain/%	0	0.11	0.20	0.33	0.39	0.42	0.44	0.45	0.47
Stress/MPa	1.02	1.15	1.28	1.41	1.53	1.66	1.79	1.92	-
Strain/%	0.48	0.49	0.49	0.50	0.50	0.51	0.51	0.51	-

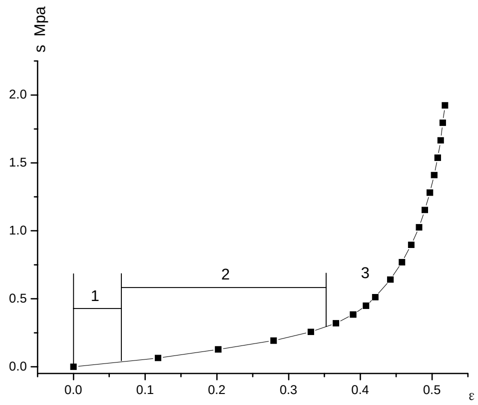


Figure 3. The stress-strain curve of silicon foam cushion material

4. The experimental modal analysis of the axial vibration specimen under different preloads

For researching the effect of the preload of the structure with cushion on the modal parameter, the experimental modal analysis of the structure with different preloads was carried out. The specimen was winded by the elastic rope as free support. And the vibration exciter was used as excitation source, as following Figure 4. The whole layout of measuring points was shown in Figure 5.

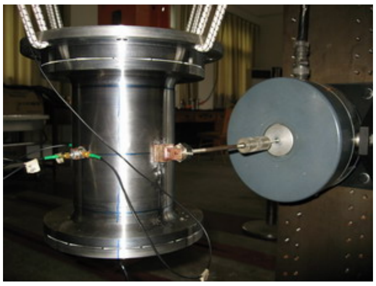


Figure 4. The exciting mode of the modal test

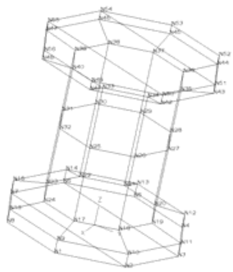


Figure 5. Measuring points of the modal test

After relaxation and stabilization, the preload of the modal experiment was 1007N. The single point of the random excitation was used during the test, the exciting point was N27, and the direction of the excitation was X+. The vibration exciter was used to generate random excitation signal, and the hanning window was added. X and Y direction responses of all points were measured. The frequency response function of the random excitation was shown in Figure 6. The result of the modal experiment of the preload 1007N was shown in Table 2, the figure of the modal assurance level was shown in Figure 7, and modal shapes were showed in Figure 8 to Figure 10.

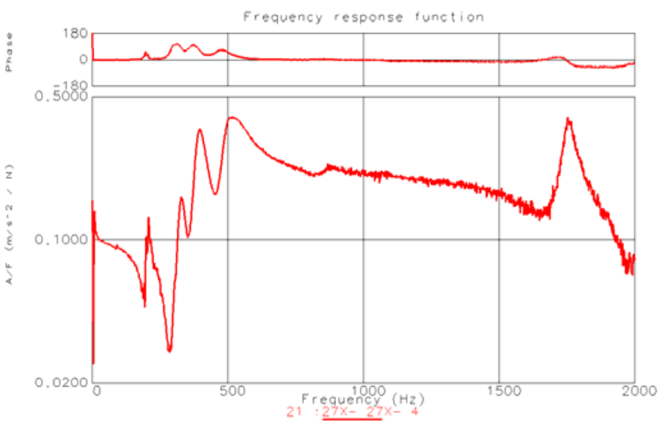


Figure 6. The FRF at the location of the force excitation

Table 2. The modal test results of the specimen with the preload 1007N

Orders	Frequency/Hz	Damping ratio ％
1	324.6	4.78
2	389.8	5.15
3	493.2	6.45

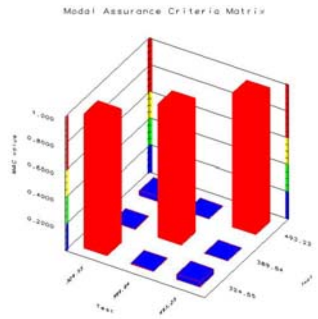


Figure 7. Modal assurance level

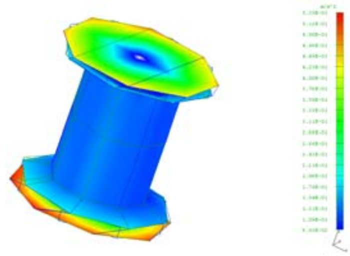


Figure 8. The first order vibration mode

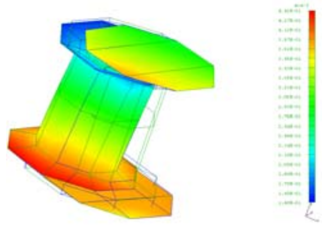


Figure 9. The second order vibration mode

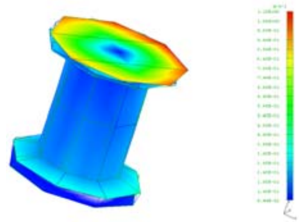


Figure 10. The third order vibration mode

From Table 2 and Figure 6 to Figure 10, we can know that the first three order modal in the whole structure separated each other, and hardly existed coupling phenomena. The damping ratio in the first three order modal was larger. The first-order modal of the whole structure showed that the upper and lower connector rotated in the same direction relative to the support barrel, and the second-order modal showed dislocation with each other, and the third-order of the modal showed the reversing rotation.

The specimen had more order resonance frequencies in the range of the analytical frequency. For convenience of analysis, the first-order modal frequency of the whole structure was selected as the characteristic parameter, and the relationship with the preload was investigated.

The frequency response characteristic experiment with seven preloads was conducted. After the preload was adjusted, the placed time of the specimen was greater than 2h until the preload was relatively stable. The signal amplitude of the excitation source was not changed during testing, and the tap position of the power amplifier was not also changed. The repeatedly measure and compare were carried out in the testing: with constant preload, when the excitation source signal amplitude was not changed and repeatedly measured, the frequency response function of all points was hardly changed. The vibration rod was reinstalled 3 or 4 times, the frequency response function of all points had a better repeatability and the preload was not changed too.

Table 3. The first-order natural frequency with different preloads

Preload/N	The first-order natural frequency/Hz	Preload/N	The first-order natural frequency/Hz
1008	331.25	1900	368.75
3126	431.25	4016	482.5
4853	547.5	6078	613.75
6926	641.25		

The frequency response functions of all points with different preloads were shown in Figure 11, and the preload gradually increased with the curve from left to right. The first-order frequencies of different preloads were shown in Table 3. The fitting curve of the first order natural frequency with preloads was shown in Figure 12.

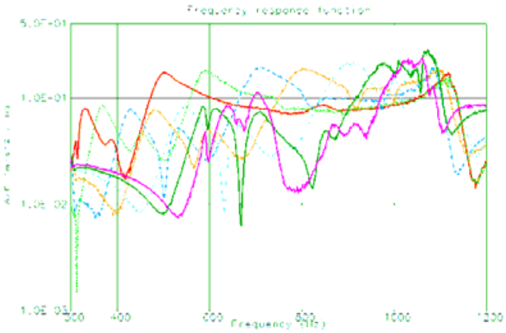


Figure 11. The FRF with different preloads

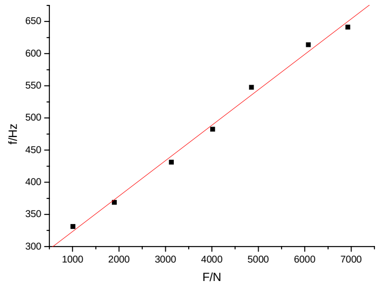
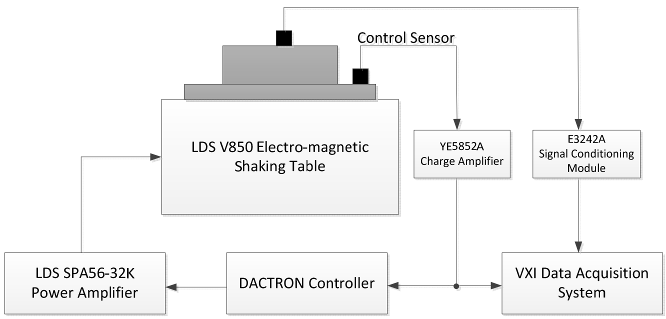


Figure 12. The fitting curve of the first order natural frequency with preloads

During the experiment, the preload basically remained unchanged, and the repeatability of the experiment in the same preload was better. From the result of the experiment, we can see that the first-order modal frequency of the structure with cushion had the linear increased whereas with the increase of the preload. So it showed that, the change of the cushion stiffness caused by different preloads had an obvious effect for the structure.

5. The interlayer rotating testing system of the axial vibration

The result of the modal experiment showed that, if the preload of the multilayer cylindrical structure with the cushion was different, the modal was also changed, and meanwhile, the lower-order vibration mode of the structure was interlayer relative rotation or slippage. In order to analyse the behaviour of the interlayer relative slippage of the structure under the vibration environment, the dynamic experiment of the structure was carried out with different preloads and vibration levels.



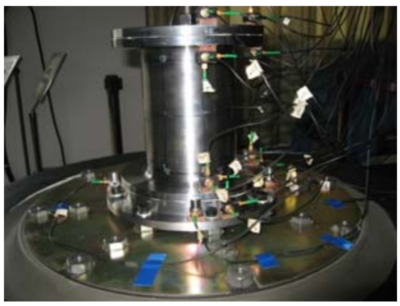


Figure.13 The vibration experiment system **Figure.14** The vibration test apparatus

The axial vibration experiment system was shown in Figure 13. The lower connector of the pre-tightened structure with cushion was fixed on vibration table with bolts. The vibration behaviour of the structure was monitored by acceleration sensor and displacement sensor. Reference line was painted between the upper-lower connector and support barrel, and calibration paper was pasted to measure relative slip value. The relationship of the preload and relative slippage was established through the test data analysis. The vibration test apparatus was shown in Figure 14.

According to the power spectral density of random vibration shown in Figure 15, the vibration test was carried out through the four-point average control, of which the value G was carried out in accordance with the testing situation, and the time of the vibration test was 300s. The vibration test was carried out with different preloads and different vibration levels according to the condition of the previous statement, and there are total 25 kinds of different cases. The specific testing parameters were shown in Table 4.

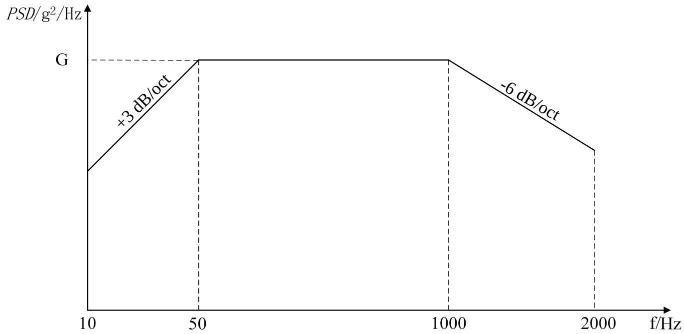


Figure 15. The power spectral density of random vibration

Table 4. The parameters of vibration experiment

Preload N	794	824	805	1022	1047	1048	1501	1560	1508
Vibration level g^2/Hz	0.005	0.01	0.05	0.005	0.01	0.03	0.01	0.03	0.03
Preload N	1514	1472	1956	1927	2509	2509	2495	3012	3060
Vibration level g^2/Hz	0.03	0.05	0.03	0.05	0.03	0.05	0.08	0.05	0.06
Preload N	3102	4040	4066	4072	5025	4996	5998		
Vibration level g^2/Hz	0.08	0.06	0.08	0.1	0.1	0.13	0.13		

6. The result of the experiment and analysis

Vibration experiment results under different testing condition were shown in Table 5 and Figure 16.

From Figure 16 we can see that, when the preload was smaller, the vibration level leading to relative slippage was relatively lower, for example, the preload was about 800N, the vibration level was $0.01g^2$/Hz, and the interlayer slippage was happened during the vibration test. With the preload raised, the vibration level leading to relative slippage was relatively enlargement, and as the preload increased to about 4000N, the interlayer slippage of the structure would not occur until the vibration level reached to $0.10g^2$/Hz. When the preload increased to a certain value (such as more than 6000N), it was difficult to observe the relative slippage phenomena below the vibration level ($0.13g^2$/Hz). In terms of the relative slippage value, the regularity was not obvious with the preload and vibration level, it is difficult to quantify.

Therefore, whether the relative slippage of the vibration specimen took place or not, it was not only related to the preload, but also related to the vibration level. Under the constant vibration level, with the increasing of the preload, the relative slippage of the test specimen can be restrained validly. The higher the vibration level is, the greater preload which restrain the relative slippage is needed. When the preload was reduced and the vibration level was increased, the trend of the relative slippage of the test specimen was increased; otherwise, when the preload was increased and the vibration level was reduced, the trend of the relative slippage of the test specimen was reduced.

Table 5. The vibration experiment results with different preloads and vibration levels

Preload N	Vibration level g^2/Hz	Rotating phenomenon	Relative slippage value mm
794	0.005	No rotation	-
824	0.01	Rotation	1.34
805	0.05	Rotation	1.58
1022	0.005	No rotation	-
1047	0.01	Unobvious	-
1048	0.03	Rotation	0.60
1501	0.01	No rotation	-
1560	0.03	No rotation	-
1508	0.03	Rotation	0.32
1514	0.03	Rotation	0.54
1472	0.05	Rotation	0.80
1956	0.03	No rotation	-
1927	0.05	Rotation	1.70
2509	0.03	No rotation	-
2509	0.05	Unobvious	-
2495	0.08	Rotation	2.70
3012	0.05	No rotation	-
3060	0.06	Rotation	0.64
3102	0.08	Rotation	1.48
4040	0.06	No rotation	-
4066	0.08	No rotation	-
4072	0.10	Rotation	0.60
5025	0.10	No rotation	-
4996	0.13	Unobvious	-
5998	0.13	No rotation	-

Note: The relative slippage value was measured when the vibration test finished. In the processing of the vibration test, the relative slippage value was much larger.

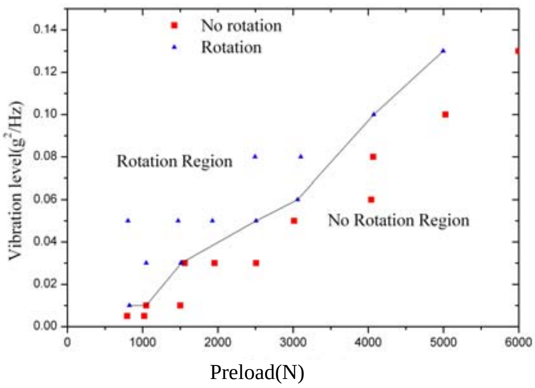


Figure 16. The vibration experiment results with different preloads and vibration levels

7. The validity evaluation of the preload

It was the most direct means of all evaluation methods that the preloaded anti-slippage effectiveness evaluation based on vibration experiment. Through the vibration experiment of the pre-tightened cylindrical structure with cushion, the relationship between the external environment and the characteristics of the system itself and the relative slippage could be known, which can offer the technological support for the preloaded anti-rotation effectiveness evaluation of products.

For the axial vibration specimen, the test results in accordance with different preloads and different vibration levels (as shown in Table 5) were gained. The relationship of the relative slippage of cylindrical structure with cushion, the preload and the vibration level was as shown in Figure 17.

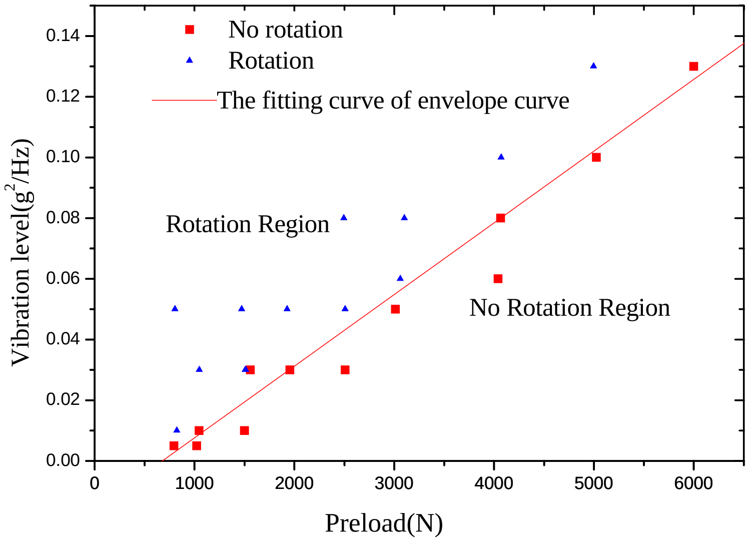


Figure 17. The relationship between relative slippage of cylindrical structure and preload, vibration level

Table 6. The key data of the interlayer rotation envelope curve

Preload/N	794	1047	1956	3012	4066	5025	5998
Vibration level/g^2/Hz	0.005	0.01	0.03	0.05	0.08	0.1	0.13

According to Figure 17, we can know that there was an envelope curve between the preload and the vibration level. The region above the envelope curve was rotation region, and it was non-rotation region below the curve. For researching the threshold value of vibration level and preload, according to the test results, the non-rotation points(as shown in Table 6) between the non-rotation region and the rotation region were chosen to establish the fitting line of the envelop curve.

The relationship between the preload and the vibration level of the fitting line was defined as:

$$A = m + bF \tag{1}$$

In the formula:

A——Vibration magnitude (g^2/Hz),

F——Preload (N),

m, b——fitting parameters.

On the basis of fitting analysis result, the function expression of the fitting line between the preload and the vibration level was:

$$A = -0.016 + 2.36\times10^{-5} F \ (g^2/\mathrm{Hz}) \tag{2}$$

From Figure 17, we can see that the test data where the relative slippage took place were all left upon at the top of the fitting line. There are only four test data where the relative slippage didn't take place were left upon at the top of the fitting line, and other non-rotation data were all left on or at the bottom of the fitting line, which showed that the fitting line was not the strict boundary that divided the rotation region and the non-rotation region. However, the fitting line served as the critical line of preload and vibration level to judge rotation or not of the structure with cushion could still have certain feasibility.

8. Conclusion

According to dynamical characteristics of pre-tightened cylindrical structure with viscoelastic material, the test specimen with cushion was designed, and the compression performance of the cushion material was measured. And then, the experiment modal analysis of the specimen was carried out, and it was concluded that in a certain range of preload, the first-order modal frequency of the structure with cushion had a linear relation with the preload .

The vibration experiment of the pre-tightened cylindrical structure with cushion was carried out, and the relationship between preload, vibration level and interlayer slippage property of the structure was investigated. Whether the relative slippage of the vibration specimen took place or not, it was not only related to the preload, but also related to the vibration level and there was an envelope curve. According to the fitting analysis of the vibration test data, we can obtain the boundary of the preload and the vibration level where the relative slippage didn’t take place, and the functional expression was established which could offer the guidance for the decision of initial preload. The achievement of this paper can provide support for the decision of initial preload and vibration level of the pre-tightened cylindrical structure with cushion in the engineering.

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