Study on dynamic mechanical properties of viscoelastic damping materials based on finite element theory

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Abstract. The relationship between the vibration parameters and the dynamic mechanical properties of the rubber material is established through the vibration reduction experiment and the finite element theory of the ZN-35 silicon rubber damper, which provides a new method for the prediction of the wide-band dynamic mechanical properties of the viscoelastic damping material.

1. Introduction

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High technology entities such as launch vehicles, satellites and missiles will vibrate due to fluid friction during flight. These vibrations have the characteristics of wide-band and random, and damage the spacecraft and the internal electronic instruments. The damping technology based on viscoelastic damping material has been widely used in aircraft, but at present, the design of shock absorber is based on the main curve of viscoelastic material, or relies on experience. The lack of theoretical design results in long design cycle and relatively large capital investment of rubber damper[1]-[3].

The dynamic mechanical parameters of viscoelastic materials are the parameters those characterize the characteristics of viscoelastic materials, including storage modulus $E'$, loss modulus $E''$. The key to improve the theoretical design is to establish the relationship between the dynamic mechanical properties of the material and the damping effect of the material shown in the main curve of the viscoelastic damping material[4]-[6].

In this paper, firstly, the vibration test is carried out by the electronic instrument model of a launch vehicle and its attached ZN-35 silicon rubber damper, and the mathematical model of the working process of the damper is established to identify the stiffness and damping of ZN-35 silicone rubber[7].

Then the relationship between the stiffness of ZN-35 silicone rubber damper and the young's modulus of the material is established by using the finite element theory. On this basis, the dynamic mechanical properties of ZN-35 silicone rubber are obtained, and the relationship between the dynamic mechanical properties of ZN-35 silicone rubber and the damping effect of ZN-35 silicone rubber damper is established[8][9].

2. Introduction to vibration experiment

According to the drawings provided by Beijing Institute of Aerospace Automatic Control, the aluminum model block and ZN-35 silicon rubber damper for electronic instruments are manufactured.
The vibration table is used to simulate the working conditions of the vibration damper in X, Y and Z directions at 5-1000HZ. LMS signal collector is used to collect the acceleration signal before and after the vibration reduction of the instrument model. Finally, the working process of the rubber damper is simplified into a vibration mathematical model, and the stiffness and damping of ZN-35 silicone rubber are identified. Figure 1 shows the actual rubber damper and Figure 2 shows the rubber damper installation.

2.1. Z-direction experiment design
The experimental structure in Z direction is installed as follows. The electronic instrument model and rubber damper are installed on two C-blocks. The upper end of the C-block is firmly connected with the rubber damper, and the lower end is fixed on the vibration table by bolts. Figure 3 is the three-dimensional model of the device, and No. 5, 6, 7 and 8 are the positions of the sensors for collecting the pre vibration signals, No. 1, 2, 3 and 4 are the positions of the sensors for collecting the post vibration signals; Figure 4 is the physical figure of the experiment.

2.2. X-direction experiment design
Since the vibration table can only be controlled by axial vibration, the electronic instrument model and rubber damper are installed on the inverted T-block in the X-direction vibration test. The vibration of the vibration table is the vibration in X-direction of the electronic instrument model and rubber damper. Figure 5 is the three-dimensional model of the device, with No. 3, 4, 5 and 6 as the position of the sensor for collecting the pre vibration signal, No. 1 and 2 as the position of the sensor for collecting the post vibration signal, and Figure 6 as the physical figure of the experiment.
2.3. Y-direction experiment design
The installation mode of Y-direction vibration experiment is similar to that of X-direction vibration experiment. The electronic instrument model and rubber damper are installed on the inverted T-block in the Y-direction vibration test. The vibration of the vibration table is the vibration in Y-direction of the electronic instrument model and rubber damper. Figure 7 is the three-dimensional model of the device, with No. 3, 4, 5 and 6 as the position of the sensor for collecting the pre vibration signal, No. 1 and 2 as the position of the sensor for collecting the post vibration signal, and Figure 8 as the physical figure of the experiment.

![Figure 7. 3D model of Y-direction experiment.](image)
![Figure 8. Y-direction experimental object.](image)

2.4. Experimental process
The experimental test process in each direction of ZXY is carried out in the following three stages:

(1) Step vibration test in the range of 5-50 HZ. The starting frequency of the vibration table is 5 HZ, the cut-off frequency is 50 HZ, the acceleration is 2g, the step size is 1 HZ, the vibration duration of each frequency is 30s, and the sampling frequency is 4096 HZ.

(2) Step vibration test in the range of 52-200 HZ. The starting frequency of the vibration table is 52 HZ, the cut-off frequency is 200 HZ, the acceleration is 2g, the step size is 2 HZ, the vibration duration of each frequency is 20s, and the sampling frequency is 4096 HZ.

(3) Step vibration test in the range of 205-1000 HZ. The starting frequency of the vibration table is 205 HZ, the cut-off frequency is 1000 HZ, the acceleration is 2g, the step size is 5 HZ, the vibration duration of each frequency is 10s, and the sampling frequency is 16384 HZ.

As shown in Figure 9, the signals before and after the vibration collected by sensors 1 and 5 in the vibration experiment of 5-50 HZ in Z direction.

![Figure 9. Signal diagram.](image)

3. Identification of vibration parameters
According to the vibration experiment in the first section, the vibration of the damper can be simplified as a single degree of freedom vibration model. The simplified vibration model is shown in Figure 10, where the mass m represents the electronic instrument model, the K represents the stiffness of the rubber damper, and the C represents the damping of the rubber damper.
X2 represents the vibration signal before vibration reduction, and X1 represents the vibration signal after vibration reduction.

Figure 10. Vibration model.

The actual working state of rubber damper is the vibration of single degree of freedom system, which can be listed in equation (1):

\[ m \ddot{x}_1 + c(\dot{x}_1 - \dot{x}_2) + k(x_1 - x_2) = 0 \]  

In the formula, \( m \) represents the known mass of the electronic instrument model; \( \ddot{x}_2 \) and \( \ddot{x}_1 \) represent the acceleration signal before and after the vibration reduction, which are collected by the sensor experiment; \( \dot{x}_2 \) and \( \dot{x}_1 \) represent the velocity signal before and after the vibration reduction, which are obtained by the acceleration signal integration; \( x_2 \) and \( x_1 \) represent the displacement signal before and after the vibration reduction, which are obtained by the acceleration signal integration. According to the above data identification, the stiffness \( K \) and damping \( C \) of the rubber damper under different working conditions and frequencies can be obtained[10].

Figure 11 and Figure 12 are the curves drawn by the identified stiffness \( K \) and damping \( C \) at each frequency in X, Y and Z directions respectively.

It can be seen from Figure 11 and Figure 12 that the stiffness in X and Y direction is basically the same at the same frequency, the damping in X and Y direction is basically the same at the same frequency, and the stiffness and damping in Z direction are greater than the values in X and Y direction at the same frequency. This is because the upper and lower plane of the rubber damper is stressed in the vibration test in the Z direction, and the side of the rubber damper is stressed in the vibration test in the X and Y directions. The difference of stress direction and stress area results in the difference between them.

4. Establish the relationship between modulus and vibration parameters

4.1. Theoretical introduction
There is a relationship between the stiffness $K$ and its modulus, which can be obtained by using the known conditions and the results of finite element analysis. Therefore, the relationship between the stiffness $K$ and storage modulus $E'$ of ZN-35 silicone rubber, the relationship between the damping $C$ and the loss modulus $E''$ of ZN-35 silicone rubber can also be obtained.

According to Hooke's Law (2) and the relationship between stiffness and modulus (3),

$$F = Kx$$

$$K = \frac{EA}{L}$$

the formula (4) can be obtained.

$$F = \frac{EA}{L}x$$

Set

$$a = \frac{L}{A}$$

formula (6) can be obtained.

$$F = \frac{E}{a}x$$

According to formula (4), (5) and (6), the relationship between stiffness and storage modulus is shown in formula (7), and the relationship between damping and loss modulus is shown in formula (8).

$$E' = aK$$

$$E'' = aC$$

In the ANSYS software, the rubber damper model is established, and the rubber damper model is applied with certain pressure, and the displacement of the rubber damper is obtained, so the coefficient ‘a’ can be calculated. Then according to the identified stiffness and damping at the frequency of 5-1000HZ, the corresponding storage modulus and loss modulus are calculated.

4.2. Modeling and solving with ANSYS

The model is built according to the experiment, and the material parameters are set in ANSYS software. The rubber damper is ZN-35 silicone rubber, the set material density is 31100kg/m³, and the Young's modulus of 6Mpa. The bracket and bushing are made of steel, with a density of 37200 kg/m³ and the Young's modulus of 200GPa. Select static analysis, add full constraints on the support base, apply 1000KN force on the beam in X direction as shown in Figure 13, and the finite element solution results are shown in Figure 14. A force of 1000KN is applied at the side of the mass block in the Y direction as shown in Figure 15, and the finite element solution results are shown in Figure 16. A force of 1000KN is applied to the upper end of the mass block in the Z direction as shown in Figure 17, and the finite element solution is shown in Figure 18.
Formula (9) can be obtained from formula (6)

\[ a = \frac{E_x}{F} \]  

(9)

After calculation, the scale coefficients ‘a’ in X direction, Y direction and Z direction are 9.24, 9.31 and 4.05 respectively. The storage modulus and loss modulus can be obtained from formulas (7) and (8), as shown in Figure 19 and Figure 20.
Through Figure 19 and Figure 20, it can be seen that after the vibration parameters in the X, y and Z directions of the ZN-35 silicone rubber damper are converted into the dynamic mechanical properties of the material, the dynamic mechanical properties in the three directions are basically the same.

5. Conclusion
In this paper, the dynamic mechanical properties of ZN-35 silicon rubber damper are analyzed by finite element theory. And through the vibration data of different directions of the rubber damper, the basic consistent broadband mechanical properties are obtained. The relationship between the vibration parameters and the dynamic mechanical properties of the rubber material is established, which provides a new method for the prediction of the wide-band dynamic mechanical properties of the viscoelastic damping material.

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