Experimental Study of Scissor-like-structure Vibration Isolator

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Abstract. Considering the problem of low-frequency vibration isolation and disadvantages of existing models, an optimized model is established. Based on optimized model, the expression of displacement transmissibility is derived. Then an experimental model of scissor-like-structure vibration isolator (SLS-VI) is established. The comparison of experimental curve and theoretical curve proves the feasibility of model optimization. The effective vibration isolation bandwidth is 10Hz-16Hz which proves the SLS-VI have excellent vibration isolation performance at low frequency. Experimental results are basically consistent with theoretical analysis in displacement transmissibility of the vibration isolator. It proves the correctness of the theoretical analysis of scissor-like-structure at low frequency.

1. Introduction
Vibration is a common problem in nature, engineering, daily life and social life. Such as sound waves and ultrasound, mechanical vibration. From the smallest particle to huge celestial bodies, vibration problems exist in everywhere [1]. Although there are many related studies in the field of vibration isolation, most of them are based on traditional linear vibration isolation theory. Traditional linear vibration isolators have significant effects on high-frequency isolation, but still cannot solve low-frequency isolation problems such as the influence of vehicle seats on drivers [2].

For solving the problem of low-frequency vibration isolation, Carrella, Kovacic et al. [3-5] proposed a quasi-zero stiffness vibration isolation system with two or more oblique springs and a vertical spring. Through the interaction between springs, to make the overall stiffness of the system approximately equal zero. However, the traditional quasi-zero stiffness isolators are not very stable and can not to adjust structural parameters [6]. Then, Sun et al. proposed a scissor-like structure vibration isolator (SLS-VI) which has geometric nonlinear characteristics [7-8]. Studies have shown that the SLS-VI can obtained the ideal nonlinear vibration isolation performance by adjusted structural parameters. Zhang et al. [9] introduced unified expression of springs full-type installation into the structure of SLS-VI. Studies have shown that it is more convenient to obtain the ideal nonlinear vibration isolation performance, only through changing springs installation parameters [10].

Besides, there have many studies on principle, dynamic characteristics analysis and engineering application of zero-stiffness isolators. Such as, Wang et al. tested the performance of bi-annular-
shaped permanent magnets type isolator and the tri-magnets type isolator. Results of tests were compared with the performance of equivalent linear vibration isolation system [11]. Hang et al. carried out an experimental study on the dynamic characteristics of aero-engine vibration isolators in two special materials [12]. However, there were few experiments to analyze the dynamic characteristics of the SLS-VI.

By referring to the relevant experimental methods of above studies, the SLS-VI theoretical formula was simplified. And simplified model can reduce theoretical calculation time. Scissor-like-structure experimental model and test platform were set up. Its purpose was to verify the correctness of theoretical results and the vibration isolation performance of SLS-VI at low frequency.

2. Theoretical analysis

For simplifying the existed mathematical model and reducing theoretical calculation time, the coulomb friction and the mass of scissor arms are not considered in this study. Besides the spring installation type 5 is selected as the research object. The mathematical model is shown in Figure.1.

![Figure 1. Simplified model of full-type configuration SLS-VI](image)

The differential equation of motion of the vibration isolation system can be expressed as:

\[ m\ddot{y} + F_k + F_{c1} + F_{c2} = -m\ddot{z} \]  \hspace{1cm} (1)

where \( \dot{\delta} = (\frac{d\delta}{dy}) \cdot (\frac{dy}{dt}), \dot{x} = (\frac{dx}{dy}) \cdot (\frac{dy}{dt}) \), \( \delta \) is the rotation angle of each arm.

\[ F_{c1} = 6c_1\dot{\delta} \frac{d\delta}{dy} = 6c_1(\frac{d\delta}{dy})^2 \ddot{y} = f_1\ddot{y} \] \hspace{1cm} (2)

\[ F_{c2} = 2c_2\dot{x} \frac{dx}{dy} = 2c_2(\frac{dx}{dy})^2 \ddot{y} = f_2\ddot{y} \] \hspace{1cm} (3)

\[ F_k = k(\Delta I - \lambda_0) \frac{d\Delta I}{dy} \] \hspace{1cm} (4)

The formula \( F_k, f_1, f_2 \) are replaced by their Taylor expansions at \( \dot{y} = 0, \lambda_0 = 0 \). And the coefficients are determined by structural parameters and spring installation parameters.

After the Taylor expansion was obtained, the perturbation method (PM) and the average method (AM) are combined to solve the dynamic equation. The displacement transmissibility equation is obtained:
\[ T_d = \frac{a_0^2 + 2a_0z_0 \cos \phi + z_0^2}{z_0} \]
\[ \Phi = \sqrt{\frac{a_0^2}{z_0} + a_0(4y_0'/z_0 - 2\sigma)} + 1 \]  
where \( \gamma_1, \gamma_2 \) are related to the spring installation parameters.

3. Experimental model

3.1 The main components
The experimental model of the SLS-VI is shown in Figure 2. It is made up of two scissor arms, two compression springs, top and bottom platforms. The left end of two arms can horizontally move along the slideway. Two scissor arm brackets are hinged together through a central connecting shaft to form an "X" shape. In this experimental model, the compression spring is hung vertically between top platform and bottom platform.

![Figure 2. Experimental model of SLS-VI](image)

3.2 Parameters of each parts
Silicon-manganese spring steel has good elastic limit and mechanical characteristics. So the material is 60Si2Mn spring steel, the shear modulus is \( G = 79000 \text{ MPa} \). Linear springs are simple and stable.

According to the spring design criteria and spring stiffness requirements in the mechanical design manual, the spring stiffness is:

\[ k = \frac{Gd^4}{8nD^3} = 634N/m \]  

Other important component parameters: top platform weight is 2.5kg, the scissor arm weight is 0.12kg, and the scissor arm length is 0.34m, spring installation parameters \( d=a=0.09m \).

4. Experimental equipment
The experimental system consists of three parts: SLS vibration isolation system which is shown in Figure 2, excitation system which is shown in Figure 3, and signal acquisition system which is shown in Figure 4.

Excitation system includes computer (with vibration control software), signal controller, and power amplifier (in the control cabinet). Electric vibration table is shown in Figure 3. The computer is used to select the type of vibration and set the vibration parameters. Finally the built-in power amplifier was used to transmit the signal to start the vibration table.

Signal acquisition and processing system: It includes voltage sensor, signal acquisition instrument and analysis software(in the computer). Voltage sensors are used to collect the dynamic response signal of the system. The signal acquisition instrument can receive the electrical signals transmitted by sensors. Analysis software is installed on the computer. The data point information can be obtained,
stored and processed in the computer.

Scissor-like-structure vibration isolation system is shown in Figure 2: it is made up of SLS vibration isolator, vibration-isolated object, and positioning bolts. The bottom platform is connected to the vibration table with positioning bolts. The vibration-isolated object is mass, as shown in Figure 1. The bottom of mass is processed with internal threads and connected to the top platform with bolts. When the vibration excitation system starts to work, sensors receive displacement signals from bottom platform and top platform. Finally, the displacement transmissibility can be obtained.

5. Experimental analysis of dynamic characteristics

5.1 Sensors position
In experiment, two sensors are used to control the vibration table and collect dynamic characteristic signals of the SLS-VI. As shown in Figure 2, sensor a is placed on the bottom platform, it can be used to both control vibration table and collect input signals at the same time. The top platform and the mass are considered as a whole, with a total weight of 4.5kg. Sensor b is placed on the right side of top platform, it is used to collect output signals of vibration isolation system.

5.2 Experimental conditions
The vibration table simulates external excitation type which is applied to the SLS-VI. Then the dynamic characteristics of system is tested under different excitation amplitude and excitation frequency. The displacement transmissibility curve of experiment is compared with the curve of theoretical analysis. In addition, vibration isolation performance of the SLS-VI under low frequency excitation is analysed. After a series of experiments, a set of most practical experimental points is selected. Their frequency sweep range is 2-20 Hz and the peak-to-peak displacement limit is 0.6 mm. Experimental curve of displacement transmissibility is shown in Figure 5. Due to the influence of surrounding experimental environment, there is a certain amount of interference. So the most obvious part which is 3-10Hz was selected to observe. Comparison of displacement transmissibility is shown in Figure 6.
5.3 Analysis of experimental results

Through the comparison of output and input signals in Figure 7 and Figure 8, it can be seen that the scissor-like-structure vibration isolator has obviously vibration isolation effect on the excitation from bottom.

The dynamic characteristics of the SLS-VI are shown in the following figures:
Figure 8. Output time domain signal

Considering the influence of environmental factors on sensor signal acquisition during experiment, all images are further processed. Some experimental data points are selected to compare with theoretical data points. It can be seen from Figure 6 that the experimental resonance frequency of 6.4 Hz is very close to theoretical resonance frequency of 6.2 Hz.

It is found that the theoretical analysis of vibration isolator is basically consistent with the experimental test results in displacement transmissibility. The reason for the deviation may be the disturbance of external environment during the signal acquisition. In addition, because the scissor-like-structure vibration isolator and the vibration table are connected by screws, there is a slight movement, which is also a reason for deviation.

It can be seen from Figure 6 that the experimental datas of SLS-VI agree well with the theoretical analysis, which proves the rationality of theoretical analysis. The displacement transmissibility of SLS-VI under spring installation type five increase first then decrease with the increase of excitation frequency. When the excitation frequency reaches 10Hz, the displacement transmissibility is less than 1, which can completely achieve low frequency vibration isolation effect.

6. Conclusion
In oder to solve the problem of low-frequency vibration isolation in engineering technology field, experimental system is established in combination with vibration table, signal acquisition equipment and experiment of SLS-VI. The signal acquisition equipment is used to collect the vibration signals of bottom and top platform of the scissor-like-structure. The following results are got from experiment.

1. It can be seen from Figure 6 that the resonance frequency of isolator is 6.4 Hz, which is very close to the resonance frequency of 6.2 Hz in theoretical curve. And the peak value of displacement transmissibility is basically consistent.

2. The effective vibration isolation bandwidth is 10Hz-16Hz, which proves that the SLS-VI can achieves low frequency vibration isolation.

3. It is found that the resonance duration and peak value of SLS-VI under the excitation of reverse frequency sweep are higher than those under the forward frequency sweep.

4. Experimental results are basically consistent with theoretical analysis, which verify the correctness and feasibility of theoretical analysis.

In summary, the experimental system proposed in this study has reasonable structure and achieves the experimental requirements. The experimental results are obvious. The improved scissor-like-structure vibration isolator can effectively solve the problem of low frequency vibration isolation in the field of engineering technology.

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