Experimental study on dynamic characteristics of wire-cable vibration isolator

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Abstract. This study considers the dynamic experimental characteristics of the wire-cable vibration isolator. Orthogonal design scheme is adopted to reduce the test times. A wire-cable vibration isolator will be experimentally tested in the tension-compression mode to analyze its hysteretic behavior in more detail. Experimental data of restoring force and displacement are obtained through periodic test loading. The shape of hysteresis loops of vibration isolator under different excitation amplitudes, excitation frequencies and number of wire-cable loops have been obtained; the area of each hysteresis loop will be calculated by definite integral. The hysteresis loops under different conditions are studied, the results show that the wire-cable vibration isolator has excellent shock isolation characteristics; the isolator exhibits asymmetric hysteresis loops, which possess a hardening loading overlap in the loading curves. Finally, the key influence parameters of the dynamic characteristics are obtained, which establishes the foundation for designing the high performance wire-cable vibration isolator.

1. Introduction
Wire-cable isolator is a typical nonlinear hysteresis characteristics of vibration isolation device. In order to fully understand the cushioning performance of vibration isolation of the isolator, its dynamic characteristics is investigated experimentally, while would provide some exact experimental data for vibration isolator to model and identify parameter. Wu [1] took the common marine vibration isolator as the research object, analyzed the change of physical model of vibration isolator stiffness characteristics when ship tilts and rolls, and verified the theoretical research results by experiments. Wang [2] obtained the dynamic hysteresis characteristics of O-type wire-cable isolator in shearing, rolling and tension direction along with excitation amplitude and frequency by using periodic dynamic loading test method. In reference [3-5], the impact stiffness and damping of a rubber steel wire isolator were tested by falling hammer impact method. The acceleration vs. time curve of the loading mass was transformed into the hysteresis loop of the isolator to solve for the impact stiffness and the equivalent damping. To reduce the number of experiments, orthogonal design is designed firstly in this paper. Then, the shape and area of hysteresis loops of vibration isolator under different excitation amplitudes, excitation frequencies and number of wire-cable loops are obtained by means of data processing and numerical integration. Finally, the dynamic characteristics of hysteresis loops under different conditions would be studied.

2. Dynamic test of isolator
2.1. Test purpose and design scheme
In practical engineering applications, the isolator has always used in the dynamic environment, so, it is very important to study the isolator’s dynamic characteristics in different conditions for design optimization of the wire-cable isolator. The test purpose would be to study the influence of displacement amplitude, frequency and number of wire-cable rings of isolator on the stiffness and damping of isolator. In order to reduce the number of tests, the specific implementation scheme of the test is designed as shown in table 1.

| Test number | Amplitude/mm | Frequency/Hz | Number of wire cable rings |
|-------------|--------------|--------------|----------------------------|
| 1           | 6            | 3            | 6                          |
| 2           | 6            | 4            | 6                          |
| 3           | 6            | 5            | 6                          |
| 4           | 6            | 6            | 6                          |
| 5           | 6            | 7            | 6                          |
| 6           | 6            | 8            | 6                          |
| 7           | 6            | 9            | 6                          |
| 8           | 1            | 5            | 6                          |
| 9           | 2            | 5            | 6                          |
| 10          | 3            | 5            | 6                          |
| 11          | 4            | 5            | 6                          |
| 12          | 5            | 5            | 6                          |
| 13          | 6            | 5            | 4                          |
| 14          | 6            | 5            | 5                          |

2.2. Test setup
The setup for the quasi-static cyclic loading test was arranged on an electromagnetic vibration test bench (Model: MPA406/M232) as shown in figure 1. which can generate various types of excitation signals (sinusoidal wave, triangular wave signal, random signal, etc.). The test simplified schematic is shown in figure 1, and test installation drawing is shown in figure 2. The lower end of the vibration isolator is connected to the electromagnetic vibration table, the upper end is connected to the three-jaw chuck, the upper clamp is connected to the force sensor, and the three-jaw chuck is connected to the foundation through the frame. Considering that both the frame and the vibration table are fixed on the foundation, it can be approximately considered that the upper end of the vibration isolator is connected with the rigid body without displacement, and the lower end of the vibration isolator will be driven when the vibration table starts to vibrate. The laser displacement sensor is fixed on the frame, and the signal acquisition analyser is used to collect the signals of two force sensors and displacement sensors simultaneously, and transmits them to the computer for data processing. The excitation signal adopts sinusoidal displacement signal with $A=1-6$ mm and $f=3-9$ Hz.

Figure 1. Test simplified schematic.  
Figure 2. Test installation drawing.
3. Test data processing and analysis

3.1. Test data processing

In the test, deformation displacement excitation is adopted to the wire-cable isolator, which is used as the input signal and controlled by the closed loop system of the testing machine. Therefore, it can be considered that the excitation signal has no noise and can be used as the real deformation of the isolator. The restoring force of the vibration isolator is the output signal, which may be polluted by noise due to some reasons. Therefore, in order to more accurately display the dynamic hysteresis characteristics of the vibration isolator, it is necessary to conduct noise reduction processing on the collected restoring force data. Wavelet noise reduction [6] is a popular noise reduction method. However, this method is not suitable for wide range of white noise in practical application. For periodic vibration test, the measured restoring force is periodic signal, including multiple harmonics, which can be expressed as follows:

\[ R(t) = \frac{R_0}{2} + \sum_{j=1}^{m} R_j \cos j\omega t + \sum_{j=1}^{m} R'_j \sin j\omega t \]  

Here \( \{R\} = \{R_0, R_1, R_2, \ldots, R_m, R'_1, R'_2, \ldots, R'_m\} \) of \( R(t) \) is the Fourier order, which can be selected according to the experimental data. Ko [7] use the frequency domain non-causal filtering method prosed by Ni [8] to conduct discrete Fourier series high-frequency noise deduction of the sampled data, obtain the harmonic component of the measurement restoration force, and then reconstruct the measurement periodic signal.

3.2. Test data analysis

The purpose of this test is to explore the influence of excitation frequency \( f \), amplitude \( A \), number \( N \) of wire-cable loops on the stiffness and damping characteristics of wire-cable isolator. Since the sampling frequency of displacement sensor and force sensor is 512 Hz, a large number of test data points are collected, and the data of each period are roughly same in the stable state, so the data of a steady-state period can be arbitrarily selected to analysis and research.

4. Analysis of test results

The collected experimental data are processed by 3.1 sections to obtain the hysteresis loop curves of wire-cable isolator at different frequencies, different loading amplitudes, different number of wire-cable rings. Through study, the influence of these three factors on dynamic characteristics of wire-cable isolator is analyzed.

4.1. Influence of amplitude \( A \)

The amplitude would influence the dynamic characteristics of the wire-cable isolator with certain parameters. For different amplitudes, the resilience of the elastic components of the isolator varies at the same frequency. The control variable method is used to study the dynamic stiffness and damping characteristics of wire-cable isolator under different amplitude displacement excitation. There are three parameters involved in this study, keeping the number \( N \) of wire-cable rings, frequency \( f \) unchanged, that is, the parameters \( N=6 \), frequency \( f=5 \) Hz are determined. The hysteresis curves, when excitation amplitude \( A=1-6 \) mm, are obtained as shown in figure 3. Meanwhile, in order to explore the changes of the area between hysteresis loops under different amplitude, select the test data with amplitude of 3 mm, and then use the nonlinear functions \( R_u(x) \) and \( R_l(x) \) to fit the data (upper and lower hysteresis restoring force) at the loading and unloading stages respectively, and obtain the nonlinear function expressions as follows:

\[ R_u(x) = 0.289x^5 - 0.7232x^4 - 1.764x^3 + 4.127x^2 + 49.08x + 49.47 \]  

(2)
\[ R_l(x) = 0.648x^5 + 1.432x^4 - 3.921x^3 - 3.573x^2 + 38.33x - 75.1 \]  

(3)

Figure 3. Hysteresis loop at different amplitude.  

Figure 4. Area of each hysteresis loop.

Here, the difference \( \Delta R \) between the upper and lower fitting curves is required, and then the area \( S \) enclosed by the difference curve and \( x=0 \) is calculated by definite integral, that is, the area of the hysteresis loop when \( A=3 \text{ mm} \). Similarly, the area of each hysteresis loop with different amplitudes can be obtained by using this method. The variation of the area \( S \) enclosed by the hysteresis curve under different amplitudes is shown in figure 4.

\[ \Delta R = -0.359x^5 - 2.155x^4 + 2.175x^3 + 7.7x^2 + 10.75 + 124.57 \]  

(4)

\[ S = \int_{-3}^{3} \Delta R \, dx = 676 \text{ Nmm} \]  

(5)

It can be seen from figure 3, the stiffness of the vibration isolator gradually becomes harder when loading, while that of unloading gradually becomes softer when unloading, and the loading stiffness is larger than that of unloading, but the change of stiffness is more obvious when unloading. With the increase of amplitude, the inclination degree of each hysteresis loop of wire-cable isolator gradually flattens, the dynamic stiffness of wire-cable isolator increases gradually. It can be seen from the figure 4, with the increase of amplitude, the hysteresis area \( S \) significantly increases, the energy consumed by the elastic element also greatly increases, and the damping isolation performance is significantly enhanced.

4.2. Influence of frequency \( f \)

In this section, the influence rule of frequency factors on stiffness and damping of steel isolator is studied. The parameters \( N=6, A=6 \text{ mm} \) are determined. The hysteresis curve of the isolator in the tension and pressure direction when frequency \( f=3-9 \text{ Hz} \) is obtained, as shown in figure 5. The change of area \( S \) enclosed by the hysteresis curve at different frequencies is shown in figure 6.

According to figure 5, when the loading amplitudes are all 6 mm, the hysteresis curves are not very different. In other words, with the same excitation amplitude, the shape of hysteresis loops changes slightly with the change of excitation frequency, and the shapes of hysteresis loops are basically identical. As can be seen from figure 6, the area of hysteresis loop increases with the increase of loading excitation frequency, but the change is not obvious, which is consistent with the dynamic hysteresis and frequency independent characteristics of traditional wire-cable isolator.
Figure 5. Hysteresis loop at different frequencies.

Figure 6. The area of each hysteresis loop.

4.3. Influence of $N$
Figure 7 shows the hysteresis curve of the elastic element when the amplitude $A=6$ mm, frequency $f=5$ Hz, and $N=4, 5, 6$. Figure 8 shows the change of the area $S$ of hysteresis ring encircling when $N$ changes.

As can be seen from figure 7 with the increase of $N$, the inclination degree of hysteresis loop obviously steepens, indicating that increasing $N$ can improve the dynamic stiffness of the vibration isolator. According to figure 8, the area gradually increases with the increase of $N$, but it does not increase linearly. The main reason is that the wire-cable vibration isolator consists of a nonlinear system, and the superposition principle is only applicable to linear systems.

5. Conclusion
The dynamic characteristics of the wire-cable isolator are designed by orthogonal test. The dynamic restoring force hysteresis characteristics of the isolator under excitation displacement are obtained. The shape and area of hysteresis loops of vibration isolator under different excitation amplitudes, excitation frequencies and number of wire-cable loops are obtained by means of software processing and analysis data and numerical integration. The following conclusions are obtained by analyzing the test results:

With the increase of frequency, the shape of hysteresis loop is basically unchanged, which indicates that the dynamic performance of vibration isolator is independent of the loading frequency. With the increase of amplitude, the area of hysteresis loop gradually increases and the stiffness of vibration isolator decreases, the amplitude is negatively correlated with the stiffness and positively correlated with the damping. With the increase of the number of wire-cable loops, the dynamic stiffness of the vibration isolator increases, and the area of hysteresis loops increases in nonlinear relation. Therefore, increasing the number of wire-cable loops can improve the vibration isolation ability of the vibration isolator. The results showed that the excitation amplitudes and the number of wire-cable loops are the key influence
parameters of the isolator’s dynamic characteristics, which establishes the foundation for designing the high performance wire-cable vibration isolator.

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