Experimental study on dynamic characteristics of a quasi-zero stiffness vibration isolator

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Abstract. In this paper, a kind of quasi-zero stiffness isolator with cam-roller nonlinear spring mechanism as negative stiffness mechanism is studied by sinusoidal sweep frequency experiment, sinusoidal constant frequency experiment and half-sinusoidal impact experiment. The dynamic response characteristics and impact resistance of quasi-zero stiffness isolator are analyzed. The experimental results show that when the excitation is constant, the dynamic response of the quasi-zero stiffness isolation system has a response peak, and the response acceleration and displacement all increase first and then decrease with the increase of frequency. When the excitation amplitude increases, the initial isolation frequency becomes large and the effective isolation bandwidth becomes narrow. For the half-sinusoidal acceleration impact with the pulse width less than 10ms and excitation acceleration less than 13.0g, the quasi-zero stiffness isolation system has excellent isolation and cushioning performance.

1. Introduction

More and more researchers are devoted to the theoretical study of the quasi-zero stiffness. The static characteristics\cite{1}, dynamic characteristics\cite{2} and vibration isolation performance\cite{3} of the zero-stiffness isolator are studied in depth\cite{4}. In this paper, an experimental platform of quasi-zero stiffness isolator is built to conduct sinusoidal sweep frequency experiment, sinusoidal constant frequency experiment and half-sinusoidal impact experiment. Then the dynamic response and impact resistance characteristics of the quasi-zero stiffness isolation system are experimentally analyzed.

2. Experimental model

The experimental model is mainly composed of cam-roller spring negative stiffness mechanism, vertical spring, vertical guide rod, vertical adjustment device, horizontal adjustment bolt, etc. The experimental device of vibration isolator is shown in Fig.1.
Figure 1. Experimental model of quasi-zero stiffness isolator and layout of measuring points

The vibration experimental system consists of three subsystems: the excitation system, quasi-zero stiffness isolation system and signal acquisition and processing system.

3. Experimental and analysis

Based on the above experimental system, the sinusoidal sweep frequency experiment, sinusoidal constant frequency experiment and half-sinusoidal impact experiment are carried out and the dynamic response of the quasi-zero stiffness isolation system are experimentally analyzed.

3.1. Sinusoidal sweep frequency experiment

Under the condition of sinusoidal sweep frequency, the sweeping frequency range is 2~500Hz, the peak-to-peak displacement limit is 2mm, and the acceleration excitations are 2.0g, 2.5g and 3.0g respectively.

Figure 2. Dynamic response of isolation system when the acceleration is 2.0g

Figure 3. Dynamic response of isolation system when the acceleration is 2.5g

Figure 4. Dynamic response of isolation system when the acceleration is 3.0g

When the acceleration is 2.0g, shown as Fig.2, the resonance frequency of the quasi-zero stiffness isolation system is 4 Hz, and the maximum response acceleration is 0.057697g. Although there are errors in the data measured by the three acceleration sensors arranged on the isolation platform, they are overall consistent. When the frequency is greater than 6Hz, the response acceleration at the measuring points 1, 2 and 3 is less than the excitation acceleration at the measuring point 4, and the response displacement at the measuring points 1, 2 and 3 is also less than the excitation displacement at the measuring point 4, indicating that the initial isolation frequency of the quasi-zero stiffness isolator is both 6 Hz for force excitation and displacement excitation.
From Fig.3, in order to clearly see the curve trend of acceleration excitation, acceleration excitation and response within 0-100Hz are selected, and the frequency range of displacement excitation and response is 0-50Hz. According to Fig.3, when the acceleration excitation increases to 2.5g, the initial isolation frequency of the quasi-zero stiffness isolation system is 9Hz for both acceleration and displacement excitation. Fig. 4 shows that when the acceleration excitation increases to 3.0g, the initial isolation frequency of the quasi-zero stiffness isolation system increases to 14Hz. Based on the above experimental analysis results, with the increase of excitation, the initial isolation frequency of the quasi-zero stiffness vibration isolation system gradually increases, and the effective vibration isolation bandwidth narrows.

3.2. Sinusoidal constant frequency experiment

According to the above analysis, under the sinusoidal harmonic excitation with acceleration of 2.0g, the resonance frequency of the quasi-zero stiffness vibration isolation system is 4 Hz. Therefore, in the sinusoidal constant frequency experiment in this section, the magnitude of the excitation is selected as 2.0g, and the specific working conditions of the excitation frequency 4Hz, 30Hz and 50Hz are considered respectively.

Under the acceleration excitation 2.0g, Fig.5, Fig.6 and Fig.7 respectively show the spectrums of acceleration response with the excitation frequency 4Hz, 30Hz and 50Hz. In Fig.5, when a sinusoidal harmonic excitation with frequency 4Hz is applied, there occurs resonance phenomenon at 4Hz, and the response acceleration increases sharply. At this time, the excitation acceleration is 0.060895g, and the response acceleration is 7.35 times (0.447632g) of the excitation. In addition, in the spectrum diagram, high octaves such as 8Hz, 12Hz and 16Hz appear, and the response acceleration value is significantly lower than that at 4Hz.

![Figure 5. Response acceleration with 4Hz](image)

![Figure 6. Response acceleration with 30Hz](image)

Under the excitation frequency 30Hz, as can be seen from Fig. 6, the main component of dynamic response is the response acceleration at the frequency of 30 Hz, also have high octaves response at 60Hz and 120Hz and the response acceleration at 30Hz is much larger than that at 60Hz and 120Hz. Under the excitation frequency 50Hz, shown as Fig.7, the response acceleration is mainly concentrated at 50Hz, while high octaves response at 100Hz and 150Hz is relatively small. In addition, the response acceleration values at 30Hz and 50Hz are significantly lower than the excitation acceleration values, indicating that the quasi-zero stiffness isolator has superior isolation performance in high frequencies region (greater than 30Hz).

![Figure 7. Response acceleration with 50 Hz](image)
3.3. Half-sinusoidal impact experiment

Fig.8, Fig.9 and Fig.10 show the response acceleration waveform under the different half-sinusoidal acceleration impacts when the pulse width is 5ms, 10ms and 15ms respectively. For the convenience of analysis, only the waveform within a period of time is selected for amplification analysis.

![Figure 8](image1)

![Figure 8](image2)

![Figure 8](image3)

![Figure 8](image4)

**Figure 8.** Response acceleration for different acceleration impacts with 5ms pulse width

![Figure 9](image5)

![Figure 9](image6)

![Figure 9](image7)

![Figure 9](image8)

**Figure 9.** Response acceleration for different acceleration impacts with 10ms pulse width
Figure 10. Response acceleration for different acceleration impacts with 15ms pulse width

When the impulse acceleration and pulse width are small, the acceleration response of quasi-zero stiffness isolation system is small. It can be seen from Fig.10 (c) that, when the pulse width is 15ms, the accelerations at different measuring points of the quasi-zero stiffness isolation system differ greatly, and the system is in an unstable state. The response acceleration at measuring point 3 is much larger than the excitation acceleration. In order to ensure the integrity of the quasi-zero stiffness vibration isolation system, the experiment of excitation acceleration 13.0g is stopped.

Based on the above experiment results, the maximum response acceleration under different accelerations and pulse widths is given in Table 1. It can be seen from Table 1 that, when the pulse width is fixed, the excitation acceleration increases and the maximum response acceleration increases. When the excitation acceleration is constant, the maximum response acceleration increases with the increase of pulse width. Excitation acceleration 9.0g, pulse width 10ms, the maximum response acceleration is only 0.546611g, while when the pulse width increases to 15ms, maximum response acceleration rise to 16.8509g, about 1.87 times of excitation acceleration, and the phenomena observed in Fig.10(c), show that when the excitation is given, pulse width is too large, the isolation performance of the quasi-zero stiffness isolation system becomes less. Therefore, in practical application, the quasi-zero stiffness isolator with appropriate parameters should be selected according to the impact size and pulse width time.

| Table 1. Maximum response acceleration for different working conditions |
|----------------------------------------------------------|
| Working condition | 1.0g | 5.0g | 9.0g | 13.0g |
|-------------------|------|------|------|-------|
| pulse width 5ms   | 0.042867g | 0.161613g | 0.231731g | 0.502660g |
| pulse width 10ms  | 0.170606g | 0.277758g | 0.546611g | 0.790647g |
| pulse width 15ms  | 0.187079g | 0.766054g | 16.8509g |       |
4. Conclusion

The dynamic response and impact resistance characteristics of the quasi-zero stiffness isolation system are analyzed by the sinusoidal sweep experiment, sinusoidal constant frequency experiment and half-sinusoidal impact experiment.

The results of sinusoidal sweep experiment show that, in the frequency domain of 0–50Hz, the dynamic response of the quasi-zero stiffness isolation system has a response peak when the excitation is constant, and the response acceleration and displacement increase first and then decrease with the increase of frequency. When the excitation acceleration increases from 2.0g to 3.0g, the initial isolation frequency of system increases from 6Hz to 13Hz, and the effective isolation bandwidth becomes narrow.

For half-sinusoidal acceleration impact with pulse width less than 10ms and excitation acceleration less than 13.0g, the quasi-zero stiffness isolation system has a good cushioning performance.

The sinusoidal harmonic excitation with frequency of 4Hz and acceleration of 2.0g is selected for constant frequency experiment. The dynamic response acceleration is 7.35 times that of the excitation acceleration and the response acceleration is relatively large. The quasi-zero stiffness isolation system has superior isolation performance for sinusoidal harmonic excitation with frequency of 30Hz and 50Hz and the acceleration 2.0g.

5. Acknowledgments

This work was financially supported by Beijing Natural Science Foundation (1182010), Top-notch Team Funding Project of Excellent Talents Plan of Xicheng District of Beijing, Open Project Program of Jiangsu Key Laboratory of Advanced Food Manufacturing Equipment & Technology (FM-201802) and 2020 Research and Innovation Plan for Graduate Students in Jiangsu Province(KYCY20_1927).

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