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Design and Research of a Closed Active Quasi-Zero Stiffness Vibration Isolation Device

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Abstract: In order to solve the suppression of micro-vibration in the field of precision instrument measurement, a closed active quasi-zero stiffness vibration isolation device is proposed in this paper. The device is mainly composed of a bearing platform, a shell, a moving platform, an upper fixed block, a transmission rod, a spring steel sheet, a lower fixed block and a static platform, etc. According to the requirements of quasi-zero stiffness vibration isolation, the selection design and assembly design of the negative stiffness mechanism are carried out. The kinematics principle is analyzed, the mechanical analysis and feasibility calculation are researched, and the design of the vibration isolation platform is finally completed, which provides a new structural idea for the quasi-zero stiffness low-frequency vibration isolation device.

1. Introduction

Since the stiffness of the quasi-zero stiffness device at its dynamic equilibrium position is infinitely close to zero, it can effectively attenuate the random micro-vibration at low frequencies. Therefore, the quasi-zero stiffness damping platform device has a good application prospect for micro-vibration suppression in precision instrument measurement and other fields that need to ensure high stability. Generally, there are three design forms of quasi-zero stiffness low-frequency vibration isolation device: Firstly, the negative stiffness mechanism is connected in parallel to the positive stiffness system to achieve quasi-zero stiffness, using two pre-compressed horizontal springs as negative stiffness elements, and forming a quasi-zero stiffness vibration isolation system with vertical springs and dampers; The second is to realize quasi-zero stiffness by using the nonlinear relationship between force and deformation of the structure with a specific shape; The third is to adopt a brand-new vibration isolation mechanism. Based on the principle of quasi-zero stiffness and McPherson suspension[1-2]. This paper puts forward a kind of active negative stiffness of enclosed quasi zero stiffness damping platform device, this paper adopted with initial elastic bending of spring steel and the structure of helical spring in parallel, using the pre compression spring steel piece produce active negative stiffness characteristics and provide positive stiffness characteristics of helical spring is structurally reduced the complexity of the quasi zero stiffness damping platform device.

According to different excitation sources, the vibration isolation system can be divided into passive vibration isolation, semi-active vibration isolation and active vibration isolation[3]. In order to improve the low-frequency vibration isolation capability of passive vibration isolators and reduce the initial vibration isolation frequency, quasi-zero stiffness vibration isolators came into being. The basic principle of quasi-stiffness vibration isolator is to offset the positive stiffness of the vibration isolator by introducing negative stiffness mechanism, which not only ensures the high bearing capacity and strength of the shock absorber, but also makes the stiffness of the shock absorber close to 0 in its dynamic and static equilibrium position [4]. In recent years, with the progress of mechanics, computer technology, control technology, materials and other related science, active control technology has been paid attention to because it can meet the stringent requirements of vibration reduction[5]; The traditional isolation reduction methods and technologies mainly use elastic elements such as coil springs and flexible rubber as vibration reduction elements. Their disadvantage is that they can carry out single-dimensional vibration isolation in a certain direction. For multi-dimensional vibration isolation, the usual approach is to achieve multi-dimensional vibration isolation to a certain extent through the deformation of special materials in the dimension, or to achieve the purpose of multi-dimensional vibration isolation through the combination of single-dimensional vibration damping components. However, rubber material is easy to age, and its properties are unstable with different working conditions. At the same time, the multi-dimensional vibration damping system composed of unidimensional vibration damping elements is often very complex in structure [6].

The high static stiffness of the quasi-rigid vibration isolation device makes it have a large static bearing capacity, while the low dynamic stiffness makes it have a good vibration isolation effect for low frequency and ultra-low frequency vibration[7-14]. At present, the quasi-zero stiffness vibration isolation device has been applied to natural science fields with high requirements for vibration environment, such as zero-gravity environment simulation and micro-vibration isolation of high-precision instruments and equipment[15-17]. Quasi-stiffness vibration isolation device is usually composed of positive stiffness components and negative stiffness components in parallel.

In 1957, Molyneux[18] optimized the structure of the elastic body with positive stiffness, which made the passive vibration control system meet the requirements of higher load and lower system stiffness. Xingtian Liu etc[19]. designed a quasi-zero stiffness vibration isolator with buckling Euler beam as negative stiffness element.

It can be seen from the research status that the design idea of the quasi-zero stiffness damping platform device is mainly realized from the new special mechanical structure and the use of excellent elastic components. In order to further and effectively study the vibration damping platform device, this paper designs a vibration damping platform device with active and negative stiffness performance in the broadband range based on the quasi-zero stiffness principle, which provides a new structural idea for the design and research of vibration damping device in the broadband range of quasi-zero stiffness.

2. Quasi-Stiffness Low Frequency Vibration Isolation Device Model

The model of a closed active quasi-zero stiffness vibration isolation device is shown in Figure 1. The quasi-zero stiffness low-frequency vibration isolation device is characterized by compact structure, high bearing capacity and low natural frequency. It consists of a bearing platform, a shell, a moving platform, an upper fixed block, a transmission rod, a spring steel sheet, a lower fixed block and a static platform. The quasi-zero stiffness spring is shown in Figure 2. The stiffness of the linear spring is k, which supports the load. As shown in Figure 3, the negative stiffness mechanism is composed of spring steel sheet, transmission rod, shell, etc. A spherical solid part in the middle of the transmission rod with radius R; The spring plate acts on the shell together through the transmission rod, the upper fixed block and the lower fixed block; When the closed active quasi-zero stiffness vibration isolation device is in its equilibrium position, as shown in Figure 3(a), the spring steel sheet is deformed, and its deformation force does not produce vertical component; When loaded, as shown in fig. 3(b), the deformation force of the spring steel sheet provides the vertical component force; When the load continues to increase, the deformation force of the spring element will gradually decrease to 0. As shown in Fig. 3(c), the negative stiffness structure will not provide any force.

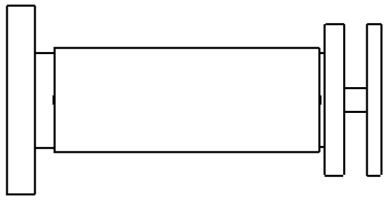


Figure 1: A closed active quasi-zero stiffness vibration isolation device

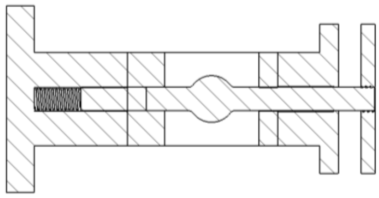
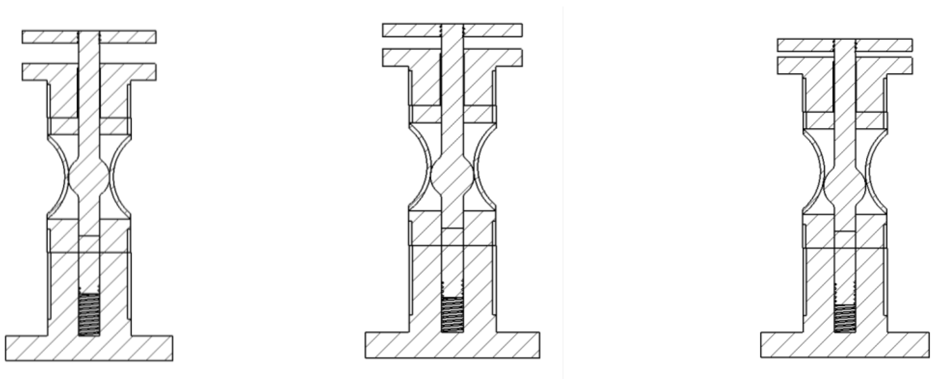


Figure 2: Quasi-zero stiffness spring



(a) Equilibrium position (b) Provide negative stiffness (c) No negative stiffness is provided.

Figure 3: Negative stiffness mechanism

By controlling the deformation of the spring element and the elastic force of the vertical spring, the active force system brought by the load can be attenuated, that is, the negative stiffness force system can be realized to attenuate the active force system. Common quasi-zero stiffness devices can be divided into three basic vibration isolation types: linear vibration isolation, nonlinear vibration isolation and new mechanism vibration isolation. Linear vibration isolation mainly depends on the parallel connection of negative stiffness to attenuate the positive stiffness of the isolator; Nonlinear vibration isolation mainly uses the structural force-deformation of a specific shape to achieve quasi-zero stiffness vibration isolation, which is the simplest and most direct vibration isolation method. Xingtian Liu et al [19]. Used the buckling Euler beam as the negative stiffness element, and realized it through its own structural force-deformation characteristics. Its disadvantage is that the buckling Euler beam will age with time, and its structural force-deformation will reduce its vibration isolation characteristics; The new mechanism vibration isolation is based on the linear vibration isolation mechanism and nonlinear vibration isolation mechanism. For the improvement and innovation of mechanical structure, there are some shortcomings such as complex structure and difficult load installation.

3. Structural Design of Key Parts of Quasi-Zero Stiffness Vibration Isolation Device

Compared with the traditional quasi-zero stiffness vibration reduction platform devices, most of the current quasi-zero stiffness vibration reduction platform devices have nonlinear elements, which have better bearing capacity performance, wider application range of vibration frequency, and more stable response to external random excitation. At the same time, the spring with positive stiffness determines the bearing capacity of the quasi-zero stiffness vibration damping device, while the structure with negative stiffness determines the dynamic stiffness of the system. In this way, it can cope with the random excitation under complex working conditions, which provides the possibility of designing the quasi-zero stiffness vibration damping platform device.

3.1. Selection Design of Negative Stiffness Mechanism

In order to broaden the applicability of the vibration reduction platform in a wide frequency range, and make the whole quasi-zero stiffness vibration reduction platform device can make the quasi-zero stiffness components respond faster and achieve better vibration reduction performance, the following principles should be followed when selecting the mechanical structure with negative stiffness:

1) When the external excitation frequency is greater than $\sqrt{2}$ times the natural frequency, the system can provide vibration isolation effect.

2) The number of components with negative stiffness should be as simple as possible, and the materials and design of components should meet the actuation range of dynamic stiffness as much as possible.

3) The selected negative stiffness mechanism should simplify the structure and facilitate the assembly as much as possible.

4) In order to realize the ease-of-use of the whole low-frequency vibration isolation device, the parallel actuators are used simultaneously to achieve the purpose of vibration isolation quickly in the face of different excitation conditions.

3.2. Assembly Design of Negative Stiffness Mechanism

1) The number of components of the selected parallel branch should be as simple as possible to ensure reliability, and each branch should have the same symmetrical structure form.

2) When designing the size of the spring steel sheet of the negative stiffness component, it should be determined according to its shell structure and its structural force-deformation range.

3) When designing the assembly of spring steel sheets of negative stiffness components, the shell, the upper fixed block, the lower fixed block and the transmission rod are used to realize the most basic actuating range.

4) When designing the assembly of spring steel sheets of negative stiffness components, the balance state under no load should be met according to the weight of the bearing platform, the weight of the transmission rod and the elastic range of the spring.

3.3. Selection of Spring for Positive Stiffness Device

The design of the closed active quasi-zero stiffness vibration isolation device has taken into account safety factors, etc., and the applied force of the bearing platform is less than 50 N. Because of its excellent damping and buffering performance, the spring of 3*18.5*80mm was selected, and the specific parameters of the spring element are as follows: Material: stainless steel; Wire diameter: 3mm; Outer diameter: 18.5mm; Length: 80mm.

4. Dynamic Principle of the New Closed Active Quasi-Zero Stiffness Vibration Isolation Platform

4.1. Fundamental Principle

When the quasi-rigidity low-frequency vibration isolation device is in the equilibrium position, the pre-compression of the spring is, the pre-compression of the spring steel sheet is, and the total mass of the transmission rod and its bearing platform is:

Set, x_1=10mm; δ=3mm

To make the stiffness of the low-frequency vibration isolation device with quasi-zero stiffness at its equilibrium position are as follows, make

$$K_1 + K_2 = 0 \tag{1}$$

$$n = \frac{l}{d} - 1 \tag{2}$$

The spring material is stainless steel and the Spring stiffness calculation is as follows:

$$K_1 = \frac{Gd^4}{8d_2^3 n} \tag{3}$$

Among them, K-Spring rate; G-8000MPa (Shear modulus of spring); d-3mm (Spring wire diameter); d_2-18.5mm (Spring pitch diameter); l-80mm (Total spring length); n-effective coil number of spring;

K_1= 4.48 N⁄mm was got Substitute to the above valid data.

Spring steel sheet:

$$K_2 = \frac{P}{\delta} \tag{4}$$

Substitution(1) and K_1= 4.48 N⁄mm, δ=3mm, P=13.44N was got.

Among them, K_2-Stiffness of spring steel sheet; P-Constant force acting on spring steel sheet; δ-Deformation displacement of the spring plate.

The spring force is:

$$F = 44.8N \tag{5}$$

The total mass of the transmission rod and its bearing platform is:

$$m_1 = 4.57kg \tag{6}$$

The added mass of the bearing platform of the quasi-rigid low-frequency vibration isolation device is m_2=5kg, g=9.8 m/s^2.

The total mass of transmission rod, bearing platform and its load is:

$$m = m_1 + m_2 \tag{7}$$

Substituting K_1= 4.48 N⁄mm and (7) into (4), x_1≈20.93mm was obtained.

With the increase of load, the structural force-deformation of spring steel sheet decreases, take

δ=1mm, so P=4.48N.

In order to make the quasi-zero stiffness damping device reach the condition of quasi-zero stiffness and improve its bearing capacity, the structural force-deformation of its spring steel sheet will decrease (increase) with the increase (decrease) of load, thus achieving the purpose of wide vibration frequency band and more stable response to external excitation.

4.2. Vibration Isolation Principle

The quasi-zero stiffness low-frequency vibration isolation device is composed of a shell, a moving platform, an upper fixed block, a transmission rod, a spring steel sheet, a lower fixed block and a static platform, etc. Based on the principle of quasi-zero stiffness, the vibration frequency band and its bearing capacity are increased by the joint action of the spring steel sheet and the spring, so as to achieve the purpose of vibration isolation.

Application scope: vibration isolation experiment, speed bump application.

5. Conclusions

In this paper, a quasi-zero stiffness vibration damping platform device based on the spring element providing quasi-zero condition is proposed. The device can achieve the vibration damping performance under wide frequency band and improve the bearing capacity at the same time, and has strong vibration damping performance.

Mechanical analysis and feasibility calculation are made on the mechanism of quasi-rigid low-frequency vibration isolation device, and the theoretical analysis results are reasonable. Under the static action, the bearing capacity can be well improved. Through the joint action of spring steel sheet and spring, the vibration isolation frequency bandwidth can be well achieved, thus realizing vibration isolation.

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