Research on Vibration Isolation Platform Based on Vibration Transfer Theory

Zhaobin Su a, Yuting Zhang b, Jianyi Zheng *
School of Aerospace Engineering, Xiamen University, Xiamen, China

*Corresponding author e-mail: zjy@xmu.edu.cn, a 35120171150989@stu.xmu.edu.cn, b 35120191151197@stu.xmu.edu.cn

Abstract. Aiming at the interference problem of various vibration sources to laboratory precision instruments, combined with the theory of vibration transmission, the basic block design research based on large vibration isolation platform is proposed. Firstly, through the theoretical analysis of the vibration isolation platform, the transfer function of the vibration isolation effect with different damping ratios is obtained. Secondly, the parameter knowledge of the basic block model is analyzed, and the basic block is analyzed based on the analysis of the system resonance. Finite element analysis; finally, the vibration of the foundation and the basic block was measured by high-precision acceleration sensor. By analyzing the data, it was verified that the vibration isolation platform has obvious blocking effect on high-frequency vibration.

Keywords: Vibration isolation platform, base block, high frequency vibration, finite element analysis.

1. Introduction

The laboratory usually has a variety of sources of interference, including not only indoor short-range sources but also long-range sources of interference. However, a variety of experimental equipment, such as scanning probe microscopes, require a low vibration and noise environment, which is often much more stringent than the environmental requirements of industrial semiconductor plants. For example, in the scanning tunneling microscope/spectrum (STM/STS) experiment, it is very important to reduce the transmission of external low-frequency vibrations to the microscope, because the subtle changes in probe sample separation are exponentially increased in the tunneling current. Scanning tunneling microscopes must be able to detect surface undulations of 0.01 nm when operating in constant current scanning mode. Such sophisticated testing requires very stringent requirements for vibration isolation of the surrounding environment.

During the entire vibration isolation process, we need to focus on the overall design of the vibration isolation platform and the overall cooperation of the platform and the air spring. Scientifically and reasonably design the vibration isolation platform so that its center of mass is in an optimal position to ensure that no unnecessary torque is generated during the vibration adjustment process. At the same time, we should also ensure that the platform and the air spring do not resonate during the process of mating, which requires natural frequency measurement and modal analysis of the platform. In this article, we report an effective vibration isolation platform that mates with six air springs and is placed on a thick
base plate that is directly connected to the building foundation. In order to compare the vibration level on the vibration isolation platform and the foundation, we evaluated the vibration isolation performance of the vibration isolation platform.

2. Vibration Transfer Analysis
The common methods of vibration isolation can be divided into active control and passive control according to the control mode [6]. As our vibration isolation platform is mounted on the air spring, for the convenience of research, we design the whole vibration isolation system into a dynamic model with damping and stiffness only in the z-direction [7], as shown in Figure 1.

\[ m \ddot{z} + c (\dot{z} - \dot{z}_0) + k (z - z_0) + f(t) = 0 \]  

where \( m \) is the mass of the vibration isolation platform, and \( z(t) \) and \( z_0(t) \) represent the vibration displacement of the vibration isolation platform and the ground respectively. Due to the air spring is simplified as a linear vibration isolation system with stiffness \( k \) and damping \( c \), and \( f(t) \) represents the external force which actively applied to the platform. Hence, the dynamic equation of the system can be derived as follows:

\[ m \ddot{z} + c (\dot{z} - \dot{z}_0) + k (z - z_0) + f(t) = 0 \]  

Therefore, according to ratio of the vibration displacement between the platform and the ground, we can characterize the vibration suppression effect of the platform, and the transfer function is given by:

\[ H(s) = \frac{cs + k}{ms^2 + cs + k} \]  

\[ \omega_0 = \sqrt{\frac{k}{m}} \]  

\[ \xi = \frac{c}{2m\omega_0} = \frac{c}{2\sqrt{mk}} \]  

and let \( s = j\omega \), therefore the vibration displacement transfer function of the platform and the ground can be described by:

\[ |H(j\omega)| = \frac{j2\xi\omega_0\omega + \omega_0^2}{-\omega^2 + j2\xi\omega_0\omega + \omega_0^2} \]  

Then we draw the transfer function diagram under different damping ratios by MATLAB, which relates the vibration isolation effect of the platform, as shown in Figure 2. From the image of
transmission rate, we can clearly see that the combination of the air spring and the vibration isolation platform can theoretically isolate the high frequency disturbance in the external vibration. However, the disadvantage is that the disturbance near the natural frequency of the platform will be amplified. If we want to solve this problem, we need to reduce the natural frequency of the platform as much as possible.

According to the natural frequency calculation formula \( \omega_n = \sqrt{\frac{k}{m}} \), we can conclude that the natural frequency of the platform can be effectively reduced by increasing the mass of the isolation platform or reducing the equivalent stiffness of the system.

Figure 2. Vibration isolation transfer function diagram.

3. Vibration Reduction Laboratory
As shown in the figure 3, we can visually see the effect of the air spring and the vibration isolation platform. The building foundation uses a thick floor that is directly connected to the building foundation. The large volume of the thick bottom plate can overcome the disadvantage of unnecessary vibration caused by the high inertia center, but it is required to reduce the vibration noise transmitted from the surrounding environment. Therefore, an important component of the vibration isolation system is the basic block placed on the air spring. Obviously we focus on the size design and natural frequency measurement of the basic block that needs attention.

Figure 3. The schematic cross-sectional view of the vibration reduction laboratory: (1) The single laboratory covers an area of about 30 square meters. (2) The vibration-damping system based on air springs and air cushions. (3) The vibration isolation platform only carries precision instruments.
3.1. Base Block and Air Spring
For this large-quality basic block, the most important thing we need to pay attention to is the centroid problem of the basic block. The multi-degree-of-freedom vibration isolating device comprises a base block and six air springs arranged on the lower edge of the base block, and the six air springs are evenly arranged in two rows. That is to say, the basic block we designed is that if it is only a rectangular parallelepiped, it is certainly not guaranteed that the center of mass is on the adjustment plane. With this in mind, we design the base block into a shape as shown in Figure 4. When the center of mass of the vibration isolation platform is at the center of the adjustment plane of the air spring, it is extremely important for us to ensure that no torque is generated during the actual adjustment process.

We can assume that the platform is composed of three rectangular parallelepipeds. The three parts are $M_1$, $M_2$, $M_3$ (top-down). The centroid coordinates are $G_1(x_1, y_1, z_1)$, $G_2(x_2, y_2, z_2)$, $G_3(x_3, y_3, z_3)$. The centroid coordinates are $\left(0, 0, \frac{c_1}{2}\right)$, $\left(0, 0, \frac{c_2}{2}\right)$, $\left(0, 0, \frac{c_3}{2}\right)$. The combined centroid are $(x, y, z)$.

\[
x = \frac{M_1x_1 + M_2x_2 + M_3x_3}{M_1 + M_2 + M_3} \tag{7}
\]
\[
y = \frac{M_1y_1 + M_2y_2 + M_3y_3}{M_1 + M_2 + M_3} \tag{8}
\]
\[
z = \frac{M_1z_1 + M_2z_2 + M_3z_3}{M_1 + M_2 + M_3} \tag{9}
\]

Then we need to ensure that the combined centroid $(x, y, z)$ is at the center of the contact surface of the assembly and the air spring, that is $(0, 0, 0)$, so that the air spring is always in the process of adjustment. An ideal state, that is, no excess torque is generated.

![Figure 4](image)

**Figure 4.** Base block details: (a) main view of the base block (b) top view of the base block.

3.2. Base Block Natural Frequency Measurement
The most common method for determining the natural frequency of the vibration isolation platform is the simple harmonic excitation method, which causes the system resonance by the simple harmonic force, so as to find the natural frequencies of the system. Hence, the equation of motion is represented as:

\[m\ddot{x} + C\dot{x} + Kx = F_0 \sin \omega_t \tag{10}\]
The solution of the equation can be written as:

\[ X = A \sin(\omega t - \varphi) \]  

(11)

\[ A = \sqrt{A_1^2 + A_2^2} = \frac{q/\omega^2}{\sqrt{(1-\mu^2)^2 + 4\mu^2D^2}} \]  

(12)

\[ \varphi = \arctan \left( \frac{A_2}{A_1} \right) = \arctan \left( \frac{2\omega e}{\omega^2 - \omega_c^2} \right) \]  

(13)

\[ \mu = \frac{\omega}{\omega_c}, \quad e = D\omega \]  

(14)

\[ A = \frac{q/\omega^2}{\sqrt{(1-\mu^2)^2 + 4\mu^2D^2}} \]  

(15)

\[ \varphi = \arctan \left( \frac{2D\mu}{1-\mu^2} \right) \]  

(16)

\[ q/\omega^2 = \frac{F_0}{m} = \frac{F_0}{mK} = x_{st} \]  

(17)

Due to the static displacement caused by the peak force of the mechanism, the amplitude can be expressed as:

\[ A = \frac{1}{\sqrt{(1-\mu^2)^2 + 4\mu^2D^2}} x_{st} = \beta x_{st} \]  

(18)

Where \( \beta \) is the called power amplification factor:

\[ \beta = \frac{1}{\sqrt{(1-\mu^2)^2 + 4\mu^2D^2}} \]  

(19)

Dynamic coefficient of forced vibration, \( \beta \), the ratio of the dynamic amplitude to the static amplitude, is important for the vibration study of the vibrator and the single-degree-of-freedom system. When \( \mu = 1 \), that is, the forced vibration frequency equals to the natural frequency of the system, and at this moment the dynamic coefficient increases rapidly, which results in the resonance of the system. From the formula: \( X = A \sin(\omega t - \varphi) \), It can be seen that both the amplitude and phase of the resonance change significantly. By measuring these two parameters, we can determine whether the system reaches the common vibration point, and thus determine the vibration frequency of each stage of the system.

3.3. Basic Block Modal Analysis

Based on the theoretical analysis of the natural frequency, combined with the actual working conditions of the basic block and the air spring, we perform modal analysis on the basic block. The following table shows the material parameters of the basic block. The total volume is about 18m and the total mass is 43ton. In order to eliminate the interference of the resonance point, we use the Ansys finite element simulation software to perform modal analysis on the basic block and take 6 for the object. The modal mode, the simulation results are shown in the figure 5.
4. Vibration Data Analysis

Through the above theoretical analysis and modal analysis, we can clearly understand that our basic block design can meet the initial vibration isolation requirements. Then, it is also necessary to compare whether the effect of the basic block and the air spring can match our original theoretical analysis. Therefore, we have made in-depth measurements of the vibration level of the foundation and the vibration level on the foundation block. The specific results of the measurement are shown in the figure 6. By analyzing the vibration image, it is obvious that the vibration isolation platform has a very direct vibration isolation effect for high frequency vibration. At the same time, due to the natural frequency of the air spring itself, there is a significant vibration amplification phenomenon in the low frequency band, which is also an element that we need to pay attention to.

Figure 6. Detailed information of vibration (a) 1~10Hz vibration ladder diagram of x-axis direction vibration isolation platform (b) 1~10Hz vibration step diagram on the x-axis direction (c) vibration line diagram on the x-axis direction vibration isolation platform (d) ground vibration line diagram in the x-axis direction
5. Conclusion
Based on the theoretical analysis of vibration transmission, the modal analysis of the basic block is performed by ANSYS, which verifies that the basic block design effectively avoids the resonance point. Finally, the high-precision acceleration sensor is used to measure the vibration of the foundation and the vibration isolation platform respectively. It is proved that the vibration isolation platform has obvious effect on blocking some high-frequency vibrations, but the blocking effect on the ultra-low frequency vibration interference is not satisfactory.

Acknowledgments
This work was financially supported by Science and Technology Planning Project of Fujian Province (2018J01082).

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