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Dynamic Structure Evaluation of Isolation Seismic Block for Primary Vibration Calibration System

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Abstract

According ISO 16063-11 the exciter and interferometer of primary vibration calibration system must be mounted on heavy seismic block so as to prevent unwanted vibration from having effects on the calibration results. To improve the current low frequency primary vibration calibration system National Measurement Laboratory (NML) design and manufacture a new heavy seismic block. The new block which is made of case iron and its mass is about 4000 kg. The block's dimension is 2000 mm×600 mm×700 mm. In order to evaluate the block dynamic characteristic we apply experimental modal method and get its first mode frequency is 314 Hz which is bigger than calibration working frequency 0.5 Hz to 70 Hz. In the other hand we want to isolate the environmental ground vibration like people walking, rotary machine, air condition etc., the block is placed on three proper designed isolators. The whole block system natural frequency should avoid the working frequency as much as possible. By using hammer to test the natural frequency of block system, we get natural frequency is 15.25 Hz for the horizontal direction of the block. From the result the block system will have effective isolation. Finally we apply the exciter to produce acceleration with different frequency and also measure the acceleration on interferometer system to compare the acceleration value between them. We find the acceleration ratio of interferometer to exciter is less than 0.0005 at most frequency. As above mention the seismic block has a perfect performance that is calibration system uncertainty component will be reduced due to unwanted vibration.

Keywords: seismic block, experimental modal, natural frequency, vibration isolation

1. Preface

Laser interferometry principle is used for the low-frequency primary calibration system, which mainly calibrate vibration sensors under 100 Hz. These sensors, including low-frequency accelerometers, can be applied to many fields, such as earthquake monitor, floor measurement, bridge structure control and etc. Interferometer in the calibration system is easily subject to environmental vibration if there is no suitable isolation block foundation. Therefore, the optimal isolation engineering is quite important for calibration system. Exciter and Interferometer of the primary low-frequency system must mount on an isolation block to prevent vibration from outside environment and exciter. According to ISO 16063-11 [1], the mass of this block must be more than 2000 times of the moving element at least and it is the design concept. In reference [2], the block is mounted on a sand tank to avoid vibration outside and reducing second-times vibration response from the earth and exciter's supporting structure. Because of the higher natural frequency of the whole system (over 30 Hz), outside vibration might disturb this calibration system. In reference [3], for isolating this vibration disturbance, the natural frequency of the optical isolation block is designed at 2 Hz to 3 Hz. At the same time, the resonance between the exciter frequency and optical isolation block is eliminated by adaptive control theory and a self-developed voice coil actuator is used for driving control source. This active vibration control device can effectively constrain the outside environmental vibration but the optical light path of the system is still easily disturbed due to the system in the quite low natural frequency condition. Therefore, this active control device is not practical. This paper describes a new isolation system for low frequency primary calibration system at National Measurement Laboratory in Taiwan. Redesigning and doing modal analysis for this new isolation block is to avoid resonance and its natural frequency is below 20 Hz for the horizontal direction. Finally, the ratio above 2000 between different excitation forces from the exciter and reaction acceleration measured from the isolation block can be obtained. That means this block has good isolation performance to lower down the uncertainty of the system.

2. Introduction of the low-frequency primary calibration system

Following ISO 16063-11, the fringe-counting method is used for calibrating vibration sensors in low-frequency calibration system at National Measurement Laboratory in Taiwan. See figure 1 for the system diagram. Counting fringes by

Michelson Interferometer is used for calculating acceleration and at the same time, accelerometer voltage output is measured. Therefore, accelerometer sensitivity can be obtained. The interference principle of the Michelson Interferometer divides into two parts, one is reference light path from laser shooting to a fixed reflection mirror(mirror 1 in figure 1); the other is to a moving mirror, which is on accelerometer (mirror 2 in figure 1), through a beam splitter. Two beams must align together as one light to form interferometric fringes. Here are the basic equations for this phenomenon. Vectors of these two laser light electric fields are:

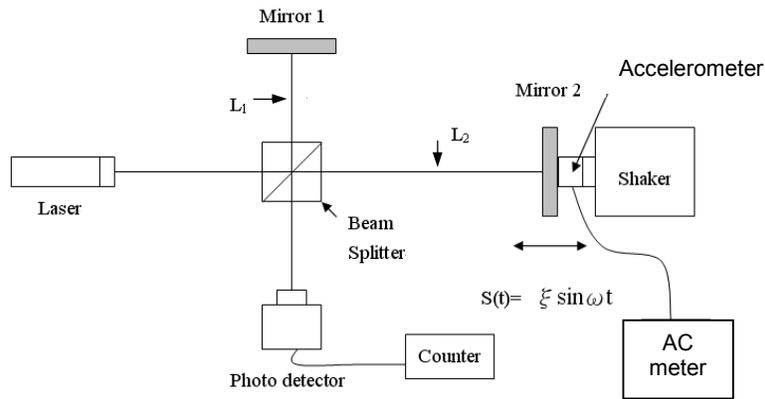


Figure 1. Michelson Interferometer for fringe-counting method

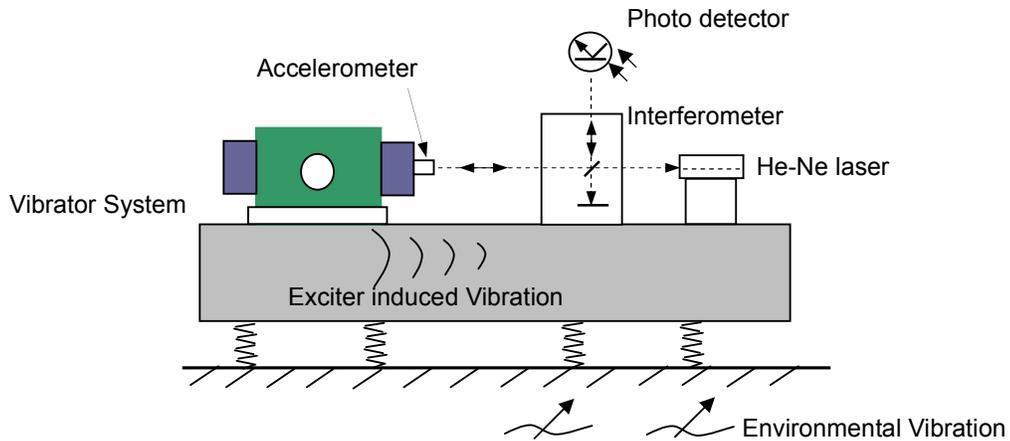


Figure 2. Possible vibration sources for the low-frequency calibration system

$$E_1 = A_1 \exp \left[j \left(\omega t + \frac{4\pi}{\lambda} L_1 \right) \right]$$

$$E_2 = A_2 \exp \left\{ j \left[\omega t + \frac{4\pi}{\lambda} (L_2 + S) \right] \right\}$$

where, $S = \xi \sin(\omega t)$: vibration displacement vector from the mirror 2;

λ : laser wave length;

L_1 : static light path of mirror 1;

L_2 : static light path of mirror 2.

$$\text{interference light intensity } I(t) = |E_1 + E_2|^2 = A + B \cos \left[\frac{4\pi}{\lambda} (L + S) \right]$$

where, A, B: constant and $L = L_1 - L_2$.

As light intensity reaches maximum, then

$$\frac{4\pi}{\lambda} (L_1 - L_2 + S) = 2n\pi$$

Therefore, the displacement of the moving mirror between two maximum light intensity is $\frac{\lambda}{2}$.

The fringes per cycle at a certain frequency is

$$N = \frac{4\xi}{\left(\frac{\lambda}{2}\right)} = 8\left(\frac{\xi}{\lambda}\right)$$

Here, displacement, $\xi = N \left(\frac{\lambda}{8}\right)$, i.e. acceleration, $A = (2\pi f)^2 \xi$.

Accelerometer voltage output, mV, is measured by a multimeter and its sensitivity, S (mV/m s⁻²), can be calculated by the following equation.

$$S = \frac{\text{mV}}{A} = \frac{\text{mV}}{(2\pi f)^2 \xi}$$

Possible disturbed vibration sources for the low-frequency calibration system are shown in Figure 2. Those vibration sources, excited by the exciter, to the supporting structure of the optical parts on the isolation block, outside environmental vibration such as person walking around and air condition operation, can be delivered to the critical optical parts and change the light static length of L_1 and L_2 . This causes the fringe counting errors and wrong calculation for the accelerometer sensitivity. Therefore, keeping the optical parts fixed relatively is the goal for this isolation system.

3. Design for iron block and isolation system

The exciter and optical parts are mounted on a big block to reduce the unwanted vibration from the environment and exciter. According to ISO 16063-11, block mass should be 2000 times heavier than system moving elements to get 0.0005 lower of exciter's vibration effect. System moving elements include parts inside the shaker, 1.056 kg, low-frequency accelerometer, QA-3000, approximately 0.387 kg, and fixture, around 0.54 kg [4]. Generally, the exciter and Michelson interferometer can be mounted on the same block or on two separate blocks. Here one block is designed for the exciter and Michelson interferometer. For reducing the vibration from the exciter to the optical parts, Iron material is chosen for this block which made of iron, FC 200, dimension is 2000 mm×600 mm×700 mm. The block mass is 4000 kg [5]. See figure 3 for details.

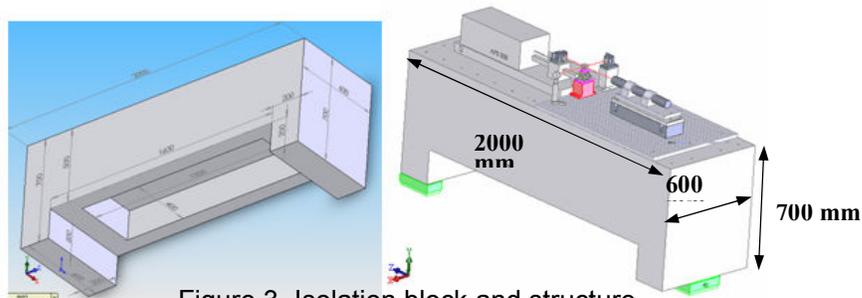


Figure 3. Isolation block and structure

For avoiding environmental vibration and easily adjusting light path, the block is put on an isolator rubber with a level adjustment device. The natural frequency of this rubber is different with the system to not form a resonance. This isolation system includes three wedged-shaped levelers for adjusting level and isolator rubber putted on the top of leveler. Isolator material is made from Bilz Company, Germany. Two PK3 wedged-shaped levelers (200 mm×95 mm) and one PK4 wedged-shaped leveler (200 mm×200 mm) with B4 isolation materials are used for the system. See figure 4 for details.

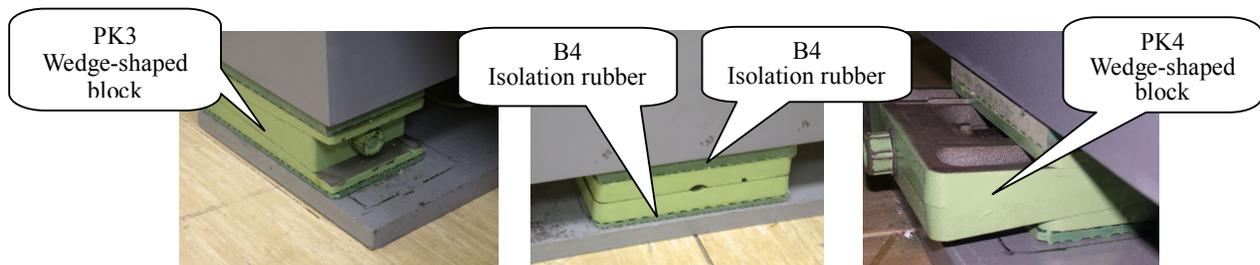


Figure 4. Wedge-shaped leveler and isolation rubber

The test report from Bilz is shown in figure 5 and the natural frequency depends on the isolator's pressure area and chosen material. Because the mass on these rubbers is 4300 kg including isolation block, exciter and optical device and the total loading area of these rubbers is 780 cm², rubber's loading pressure is 5.5 kg/ cm². From figure 5, vertical natural frequency is 57 Hz and horizontal natural frequency is 22 Hz for a single B4 [6]. Actually the natural frequency will be lower due to two pieces B4 in this system and should be verified by tests.

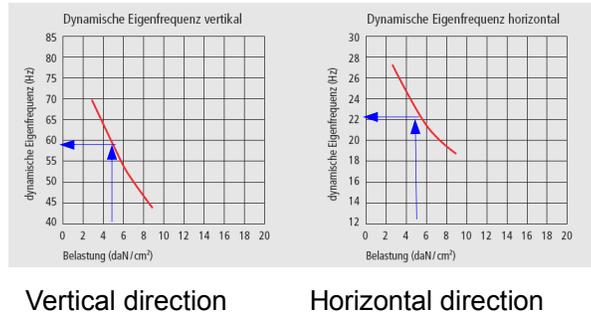


Figure 5. Performance curve of isolator rubber from Bilz, Germany

4. Modal testing and natural frequency measurement of isolation block

The purpose of modal testing is to understand the modes and its frequencies of the isolation block through the experiment. In this calibration system, exciter moves in horizontal direction (X axis) and its exciting frequency is from 0.8 Hz to 70 Hz. Therefore, only this direction is verified if resonance occurred in this modal analysis. This block is divided 56 measurement points in X direction (see figure 6), was hit at the red point, shown in figure 6, by a hammer and the frequency responses were measured at the same time from point 1 to point 56 where accelerometer was mounted with a magnet, yellow point in figure 6.

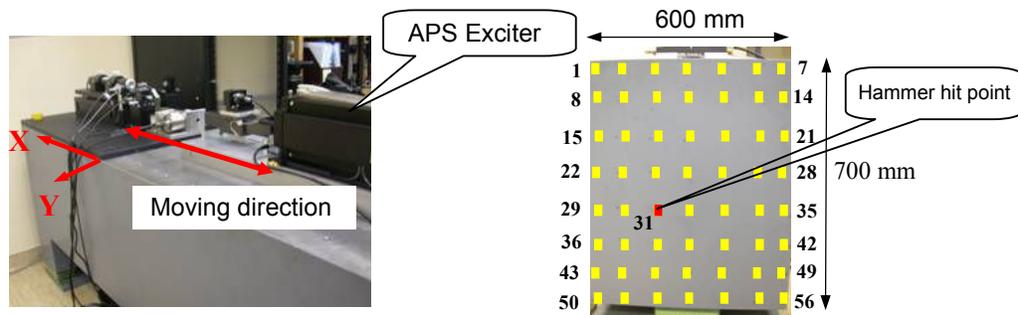


Figure 6. Exciter's moving direction and block's measurement points

After 56 data measured, the natural frequencies and modes of the block can be calculated by Me'scope software. After curve fitting with the frequency response function, the first mode of this block in x direction is at 314 Hz in figure 7(a), and deformation occurs around y direction in figure 7(b). Because the first modal frequency is higher than operation frequency, 70 Hz, it satisfies the requirement of the low frequency calibration system.

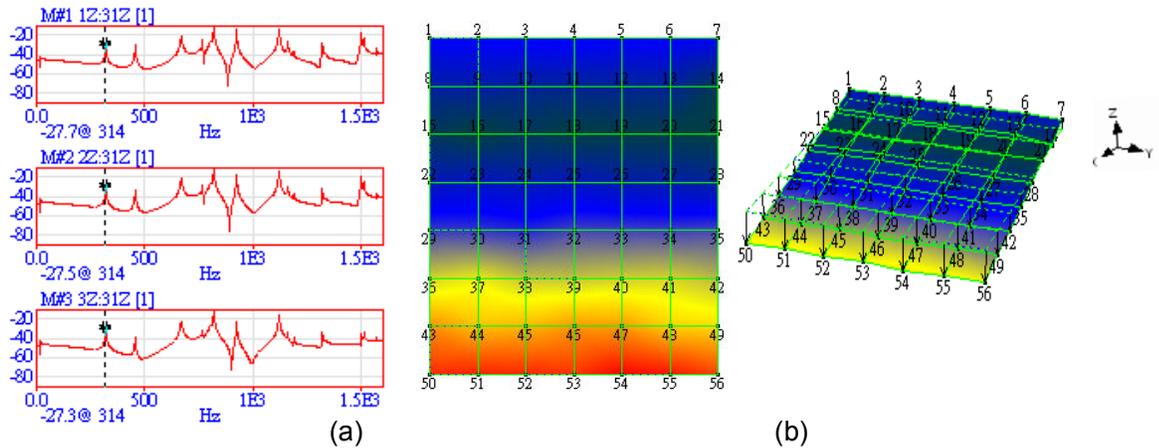


Figure 7. Curve fitting for frequency response function and vibration mode in x direction

Generally, the natural frequency can be obtained by exciter, hammer and environmental vibration measurement method [7]. The isolation block of the calibration system was tested by a hammer and environmental vibration. First, a hammer hit the block in X, Y and Z direction before optical parts not mounted and at the same time an accelerometer measured the vibration-frequency spectrum. Because hammer hit is a wide band power, the block resonance was excited and accelerometer received responding peak at its natural frequency, shown in figure 8. After mounting optical parts on the block, environmental vibration measurement method was used to excite the natural frequency of the test structure. This test was performed at night without disturbance, such as people-walking and air-condition-operation, and the environmental vibration is pretty small and easily affected. Also, environmental vibration is a wide band vibration but tiny signals and 3- axis higher sensitivity accelerometer was used to obtain peaks at natural frequencies, shown in figure 9. From figure 8 and 9, the natural frequency in x direction is 15.25 Hz, 9.5 Hz in y direction and 37.5 Hz in z direction.

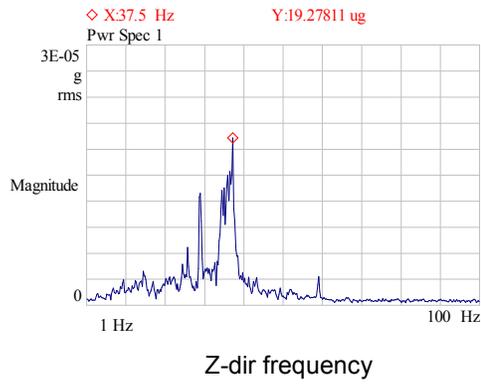
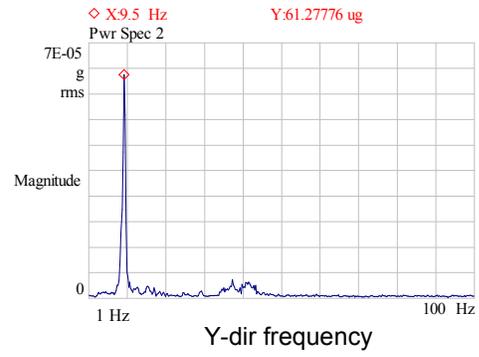
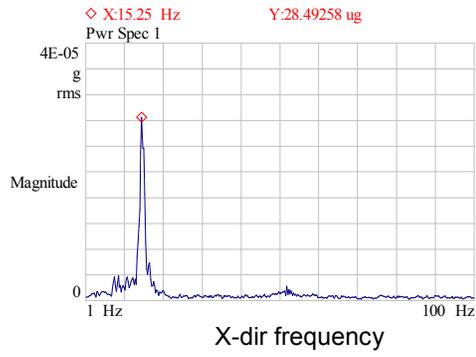


Figure 8. Block's natural frequency measurement by a hammer

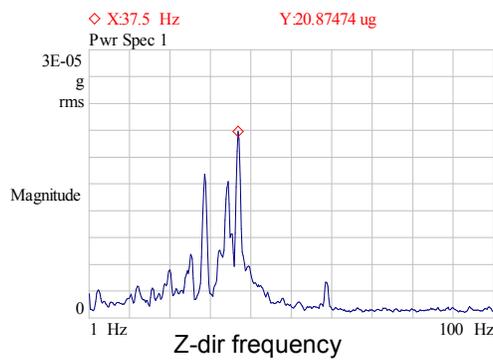
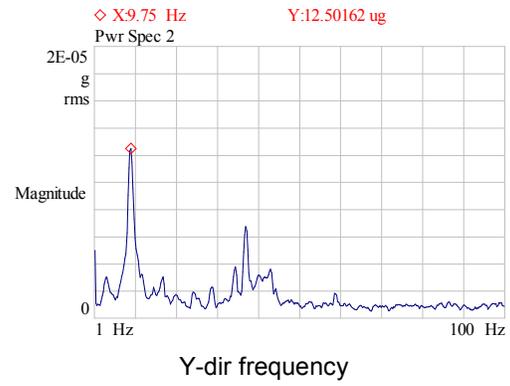
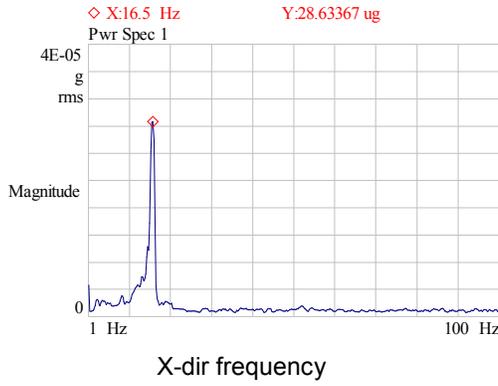


Figure 9. Block's natural frequency measurement by environmental vibration

5. Reaction force and vibration transmissibility test for the 2000-times mass block

For verifying the reaction force of this 2000-times mass block, APS exciter of the system will generate accelerations under different frequencies. These accelerations were measured by the standard accelerometer, QA-3000, of the system and also a 3-axis high sensitivity accelerometer, put on the base of the optical parts, measures reaction accelerations induced by the exciter. Results of calculating the accelerations between them are shown in table 1 and figure 10. From figure 11, the acceleration ratios in x, y and z direction are over 2000 times except 12 Hz, 14 Hz, 15 Hz, 16 Hz, 20 Hz, 60 Hz, and 70 Hz in x direction. Generally speaking, the isolation performance is good for this block.

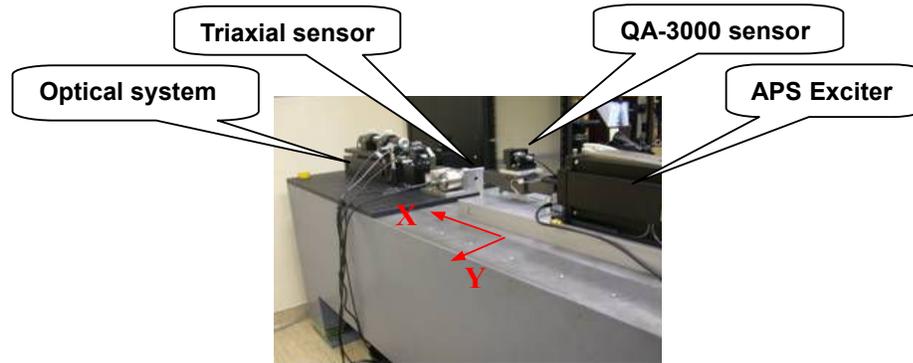


Figure 10. Reaction accelerations test for 2000-times mass iron block

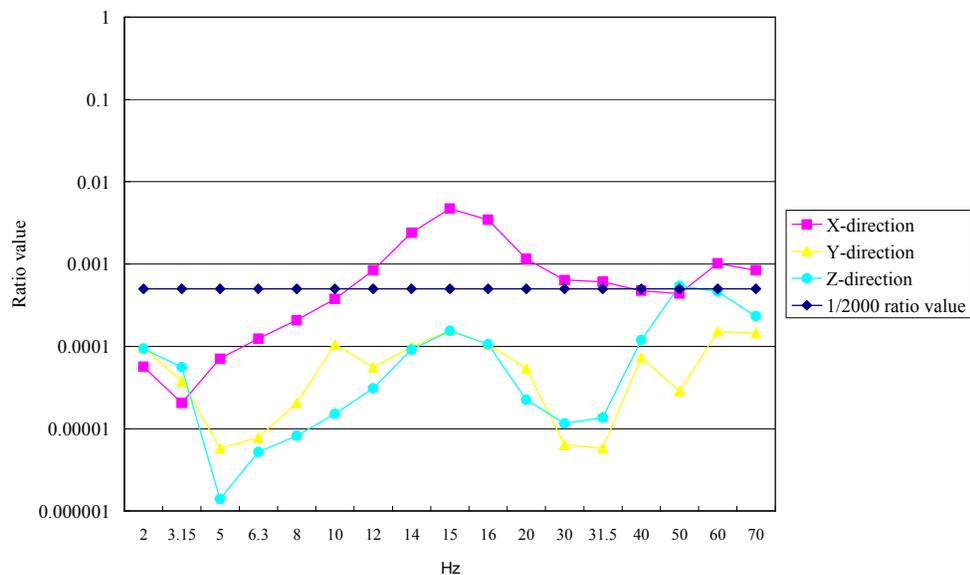


Figure 11. Ratios of reaction force for 2000-times mass iron isolation block

For understanding outside vibration disturbance after mounting isolator rubber on the calibration system, vibration transmissibility test is performed. Mounting accelerometers on the floor and isolation block respectively and hitting the ground, measure the acceleration from each accelerometer and then calculate its transmissibility. If value below 1, the acceleration on the block is lower than the floor; otherwise isolation not found. In figure 12 for test results, it has isolation function over 21 Hz in x direction, 14 Hz in y direction except 35 Hz to 42 Hz and 52 Hz in z direction.

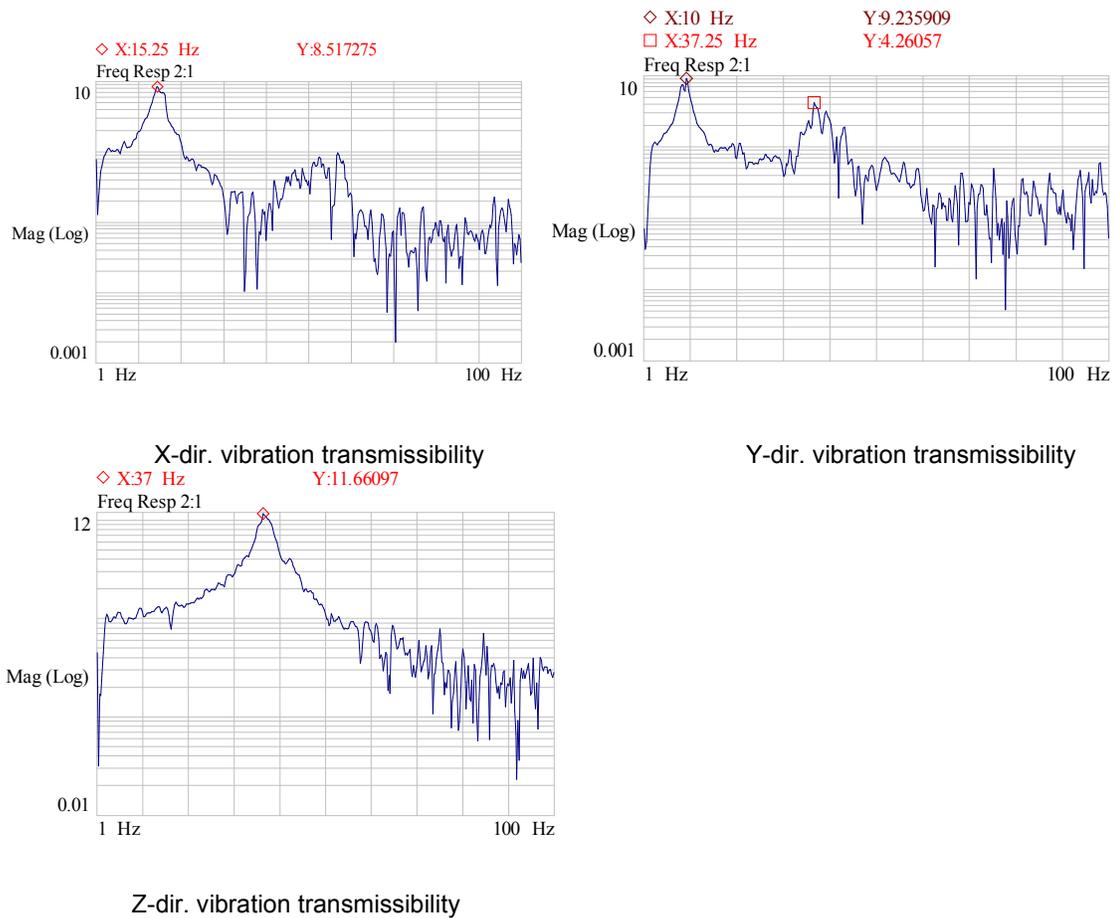


Figure 12 Vibration transmissibility

6. Conclusion

6.1 Isolation design of the low-frequency calibration system at National Measurement Laboratory, Taiwan: Exciter and optical parts are mounted on the same isolation iron block, which weighs 4000 kg and the first mode frequency occurs at 314 Hz, higher than operation frequency, 70 Hz, for this calibration

system. Therefore, this block satisfies the calibration requirements.

6.2 An isolator rubber is used to prevent vibration from the environment and its natural frequency in x direction is 15.25 Hz, 9.5 Hz in y direction and 37.5 Hz in z direction. Isolation performance, from the transmissibility test, is 21 Hz in x direction, 14 Hz in y direction and 52 Hz in z direction.

6.3 Consider resonance effect around 15 Hz in x direction because there is no 2000-times factor for this 2000-times mass isolation block.

6.4 There is no measurement on the optical parts with the accelerometer and it might be a magnification effect on them. A non-contact sensor will be used for this goal in the future.

6.5 A long-term data acquisition should be carried out to check its effect on the uncertainties of this isolation iron block.

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