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Ground Simulation of Wide Frequency Band Angular Vibration for Lander's Optic Sensors

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***Abstract*—To guide a lander of Moon or Mars exploration spacecraft during the stage of descent onto a desired place, optic sensors have been chosen to take the task, which include optic cameras and laser distance meters. However, such optic sensors are sensitive to vibrations, especially angular vibrations, from the lander. To reduce the risk of abnormal function and ensure the performance of optic sensors, ground simulations are necessary. More importantly, the simulations can be used as a method for examining the sensor performance and finding possible improvement on the sensor design. In the present paper, we proposed an angular vibration simulation method during the landing. This simulation method has been realized into product and applied to optic sensor tests for the moon lander. This simulator can generate random angular vibration in a frequency range from 0 to 2000Hz, the control precision is ±1dB, and the linear translational speed can be set to the required descent speed. The operation and data processing methods of this developed simulator are the same as a normal shake table. The analysis and design methods are studied in the present paper, and test results are also provided.**

***Index Terms*—Angular Vibration, Optic sensor, Ground Simulation.**

Ⅰ. INTRODUCTION

During space exploration and earth observation, the vibration environment is inevitable for an image sensor, as a result, the image quality might be affected, especially by the angular vibration. Therefore, angular vibration test on the ground is an important approach to decrease the mission risk to the minimum. Meanwhile, taking as a part of an image sensor design process, the angular vibration test is also a cost effective way for reducing the times of expensive whole system test, especially whole spacecraft test.

Comparing with translational vibration, the facility of angular vibration test is rather limited, and the highest angular vibration excitation frequency is 1000Hz according to open reported literatures [1], which is probably not enough to simulating angular vibration environments, whose upper frequency usually as high as 2000Hz.

China is going to send a lander onto the moon very soon. During the stage of descent, optic sensors, i.e. a set of optic camers, have been chosen to guide that lander to an desired place, with the assistance of a set of laser distance meters. However, such optic sensors are sensitive to vibrations, especially angular vibrations, from the lander. To reduce the risk of abnormal function and ensure the performance of optic sensors, ground vibration simulations are necessary. More importantly, the simulations can be used as a method for examining the sensor performance and finding possible improvement on the sensor design.

In this paper, a wide frequency band angular vibration excitation method is proposed, which is based on frequency response function estimation and target spectrum transformation, avoiding the problem of joint clearance. Subsequently, this method has been realized into product, and the test results are also provided.

Ⅱ. ANGULAR VIBRATION EXCITATION AND CONTROL METHOD

In this section, the wide frequency band angular vibration excitation method is introduced in detail, including the vibration transfer structure which turns translational vibration into angular vibration, the angular vibration measure method and the angular vibration control method.

A. Vibration Transfer Structure

Comparing with angular vibration excitation, translational vibration excitation is more common and cost effective, especially to wide frequency band. Therefore, the motivation of vibration transfer structure is to utilize this, where the input is translational vibration and the output is angular vibration. The design diagram is in Fig.1.

This vibration transfer structure could be simplified into a single degree of freedom problem due to the symmetric feature. Thus, when the desired angular vibration frequency is lower than the structure natural frequency, the frequency response function from input excitation force to output angular displacement is plotted as Fig.2.

As it shown in Fig.2, when the desired angular vibration frequency is distinct lower than the natural frequency of the vibration transfer structure, the angular vibration displacement is nearly under the division of statics, in which the FRF from input translational force to output angular displacement is constant d/k, as Fig.3.

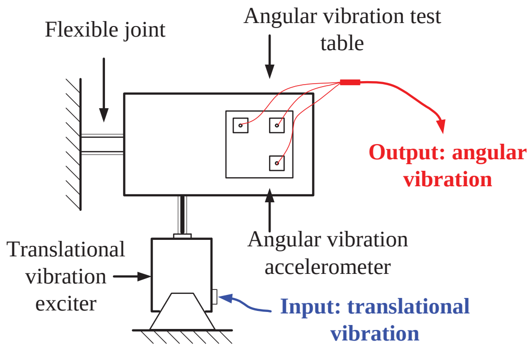

Fig. 1. Vibration transfer structure design diagram.

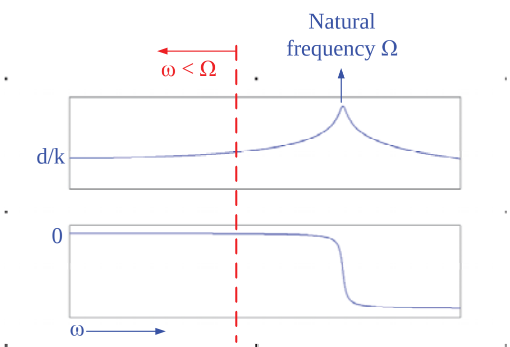

Fig. 2. FRF picture from excitation force to angular displacement in low frequency.

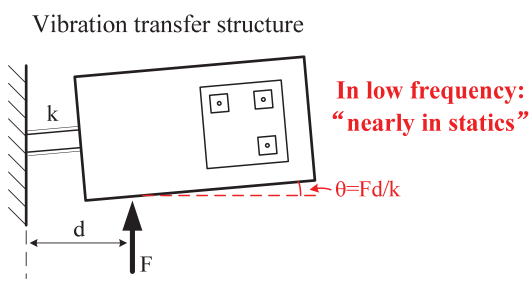

Fig. 3. Vibration transfer principle in low frequency.

When the desired angular vibration frequency is obvious higher than the structure natural frequency, the frequency response function from input excitation force to angular acceleration is plotted as Fig.4.

As it shown in Fig.4, the vibration transfer structure is nearly in free-free boundary condition when the desired angular vibration frequency is distinct and higher than the vibration transfer structure natural frequency. This means that the flexible joint almost does not influence the dynamic response in high frequency. Therefore, the principle of vibration transfer in high frequency is just the same as free-free boundary condition, shown in Fig.5.

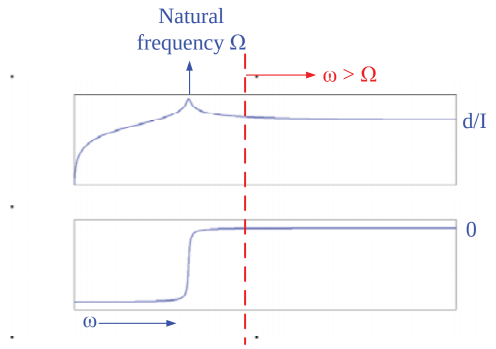

Fig. 4. FRF picture from excitation force to angular acceleration in high frequency.

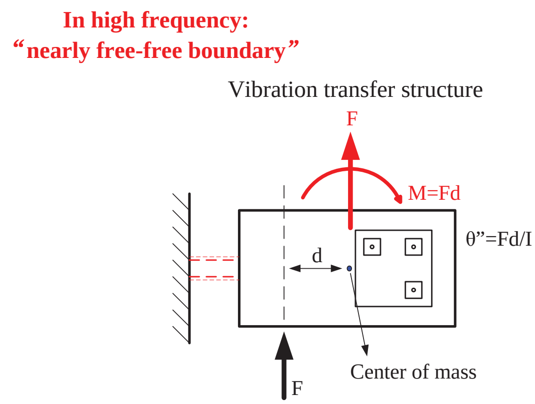

Fig. 5. Vibration transfer principle in high frequency.

The principles of vibration transfer structure are discussed in detail when the desired angular vibration frequency is obvious lower or higher than the simplified single DOF system's natural frequency. The previous discussion does not focus on specific frequency response functions but a new concept in which the angular vibration could be obviously excited by the input translational force, during either low or high frequency band. When the desired angular vibration frequency is close to the natural frequency of the vibration transfer structure, the vibration transfer principle is just the mixture of low and high frequency, and the angular vibration could be obvious excited too, which can be validate by both FEM calculation and experiment measurement.

In the previously proposed vibration transfer structure, wide frequency band angular vibration could be generated through translation force excitation. Before an angular vibration test, the frequency response function should be estimated, therefore, the input translational force could be calculated with the estimated frequency response function and the angular vibration target spectrum.

B. Angular Vibration Measurement Method

The angular vibration measurement is necessary in an angular vibration test. Unfortunately, unlike translational vibration acceleration measurement, the measurement approaches of wide frequency band angular vibration are rather rare. Consequently, a wide frequency band angular vibration measure method is proposed here base on traditional translational vibration accelerometer.

If the body frame is OXYZ, distribute four measurement points on each axis and origin by distance r, as Fig.6.

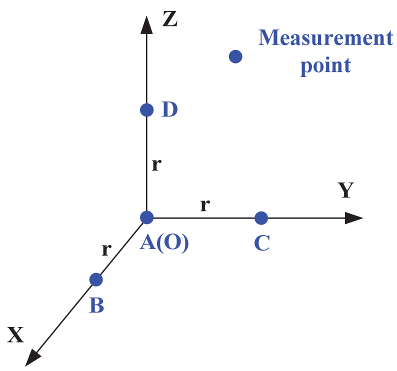

Fig. 6. Wide frequency band angular vibration measurement method.

According to the acceleration composing principle [2], there is

$$\begin{bmatrix} a_{BX} \\ a_{BY} \\ a_{BZ} \end{bmatrix} = \begin{bmatrix} a_{AX} \\ a_{AY} \\ a_{AZ} \end{bmatrix} + \begin{bmatrix} \varepsilon_X \\ \varepsilon_Y \\ \varepsilon_Z \end{bmatrix} \times \begin{bmatrix} r \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} \omega_X \\ \omega_Y \\ \omega_Z \end{bmatrix} \times \left(\begin{bmatrix} \omega_X \\ \omega_Y \\ \omega_Z \end{bmatrix} \times \begin{bmatrix} r \\ 0 \\ 0 \end{bmatrix} \right) \quad (1)$$

$$\begin{bmatrix} a_{CX} \\ a_{CY} \\ a_{CZ} \end{bmatrix} = \begin{bmatrix} a_{AX} \\ a_{AY} \\ a_{AZ} \end{bmatrix} + \begin{bmatrix} \varepsilon_X \\ \varepsilon_Y \\ \varepsilon_Z \end{bmatrix} \times \begin{bmatrix} 0 \\ r \\ 0 \end{bmatrix} + \begin{bmatrix} \omega_X \\ \omega_Y \\ \omega_Z \end{bmatrix} \times \left(\begin{bmatrix} \omega_X \\ \omega_Y \\ \omega_Z \end{bmatrix} \times \begin{bmatrix} 0 \\ r \\ 0 \end{bmatrix} \right) \quad (2)$$

$$\begin{bmatrix} a_{DX} \\ a_{DY} \\ a_{DZ} \end{bmatrix} = \begin{bmatrix} a_{AX} \\ a_{AY} \\ a_{AZ} \end{bmatrix} + \begin{bmatrix} \varepsilon_X \\ \varepsilon_Y \\ \varepsilon_Z \end{bmatrix} \times \begin{bmatrix} 0 \\ 0 \\ r \end{bmatrix} + \begin{bmatrix} \omega_X \\ \omega_Y \\ \omega_Z \end{bmatrix} \times \left(\begin{bmatrix} \omega_X \\ \omega_Y \\ \omega_Z \end{bmatrix} \times \begin{bmatrix} 0 \\ 0 \\ r \end{bmatrix} \right) \quad (3)$$

a_{AX} represents the acceleration of A point along X axis direction, and ε_X represents the angular acceleration along X axis. By simplifying Eq. 1, 2 and 3, we can obtain that

$$a_{BX} = a_{AX} - \omega_Y^2 r - \omega_Z^2 r \quad (4)$$
$$a_{BY} = a_{AY} + \varepsilon_Z r + \omega_X \omega_Y r \quad (5)$$
$$a_{BZ} = a_{AZ} - \varepsilon_Y r + \omega_X \omega_Z r \quad (6)$$
$$a_{CX} = a_{AX} - \varepsilon_Z r + \omega_X \omega_Y r \quad (7)$$
$$a_{CY} = a_{AY} - \omega_Z^2 r - \omega_X^2 r \quad (8)$$
$$a_{CZ} = a_{AZ} + \varepsilon_X r + \omega_Y \omega_Z r \quad (9)$$
$$a_{DX} = a_{AX} + \varepsilon_Y r + \omega_X \omega_Z r \quad (10)$$
$$a_{DY} = a_{AY} - \varepsilon_X r + \omega_Y \omega_Z r \quad (11)$$
$$a_{DZ} = a_{AZ} - \omega_X^2 r - \omega_Y^2 r \quad (12)$$

Observing Eq. 4 - 12, we can obtain an angular vibration measurement method as described by Eq. 13, which is

$$\begin{cases} \varepsilon_X = \dfrac{1}{2r}(a_{CZ} - a_{AZ} - a_{DY} + a_{AY}) \\ \varepsilon_Y = \dfrac{1}{2r}(a_{DX} - a_{AX} - a_{BZ} + a_{AZ}) \\ \varepsilon_Z = \dfrac{1}{2r}(a_{BY} - a_{AY} - a_{CX} + a_{AX}) \end{cases} \quad (13)$$

Because a_{AX}, a_{AY}, a_{AZ}, a_{BX}, a_{BY}, a_{BZ}, a_{CX}, a_{CY}, a_{CZ}, a_{DX}, a_{DY} and a_{DZ} could be measured by traditional translational accelerometer, the angular vibration acceleration could be calculated from the measurement results in Eq. 13.

C. Angular Vibration Control Method

The diagram of angular vibration control system is shown in Fig.7 as follows.

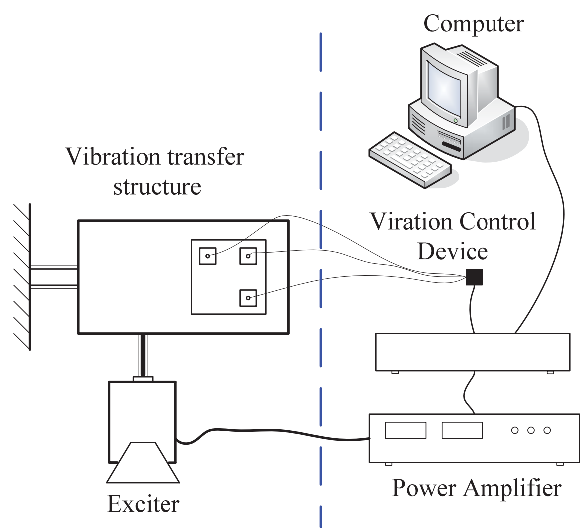

Fig. 7. Diagram of angular vibration control system.

As it shown in Fig.7, the angular vibration control system includes exciter, vibration transfer structure, computer, vibration control device and power amplifier. Before an angular vibration test, the frequency response function from exciter input force to angular vibration acceleration is identified by the computer and vibration control device, therefore the exciter input could be calculated by the angular vibration target spectrum. During an angular vibration test, the system is in closed loop to ensure the angular vibration control precision.

III. SYSTEM REALIZATION

The vibration transfer structure proposed before has been calculated, designed, manufactured, assembled and tested, shown as Fig.8.

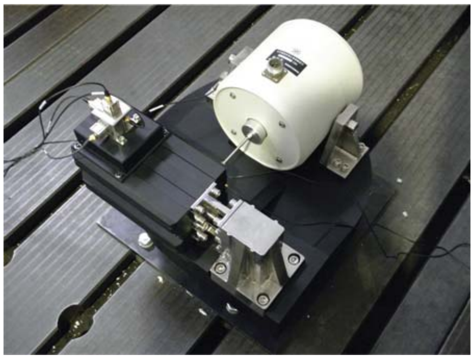

Fig. 8. A photo of the vibration transfer structure.

The angular vibration measure method has also been obtained in Section Ⅱ(B), however, in practical, the angular vibration displacement is rather small, so there is

$$\begin{aligned} &\varepsilon_X, \varepsilon_Y, \varepsilon_Z \gg \omega_X, \omega_Y, \omega_Z \\ &\omega_X, \omega_Y, \omega_Z \ll 1 \end{aligned} \tag{14}$$

According to Eq. 4 - 12 and Eq.14, the simplified angular vibration measure method is

$$\begin{aligned} \varepsilon_X &\doteq \frac{a_{CZ} - a_{AZ}}{r} \\ \varepsilon_Y &\doteq \frac{a_{AZ} - a_{BZ}}{r} \\ \varepsilon_z &\doteq \frac{a_{BY} - a_{AY}}{r} \doteq \frac{a_{AX} - a_{CX}}{r} \end{aligned} \tag{15}$$

By utilizing four translational high sensitive 3-axis accelerometers, an angular vibration measurement sensor has also been obtained as Fig.9.

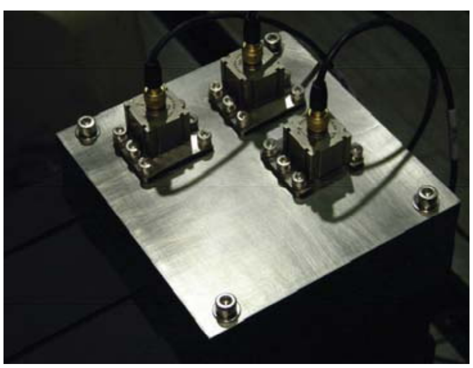

Fig. 9. A photo of the angular vibration measurement sensor.

Based on works already done before, the angular vibration control system has also been built, which is shown in Fig.10. Then, the whole angular vibration control system has been tested, which shows an anticipating performance. The test results of wide frequency band angular vibration control is given in Section Ⅴ.

Fig. 10. A photo of the angular vibration control system.

Ⅳ. Coupled Ground Simulation of Translation, Rotation and Angular Vibration

When a lander descends on the Moon, Mars or a planetoid, the coupling of angular vibration, translation and rotation is inevitable. Therefore, in order to simulate the real environment where a navigation image sensor works, we put the angular vibration control system on a motion table which could move both in translation and rotation. The motion of the table is also controlled by the computer, which could be programmed to the desired path. The photo of the whole system is shown in Fig.11.

Fig. 11. A photo of the whole system.

Ⅴ. Test Results

According to the angular vibration environment calculation results of the moon lander navigation image sensor, we have set the target power spectral density, and generated the desired target spectrum in the developed angular vibration control system. The test results of angular vibration ground simulation along X, Y and Z axis are shown in Fig.12, Fig.13 and Fig.14.

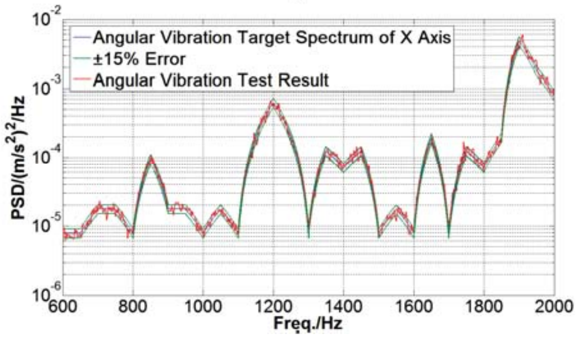

Fig. 12. Angular vibration simulation result in X axis.

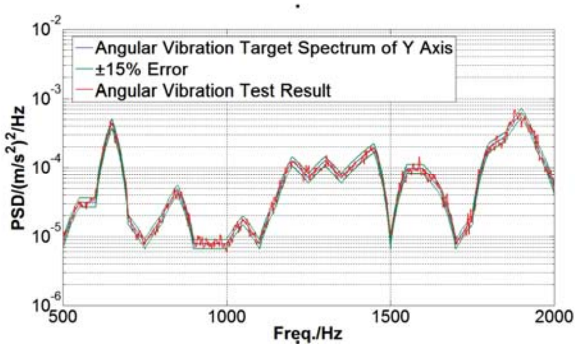

Fig. 13. Angular vibration simulation result in Y axis.

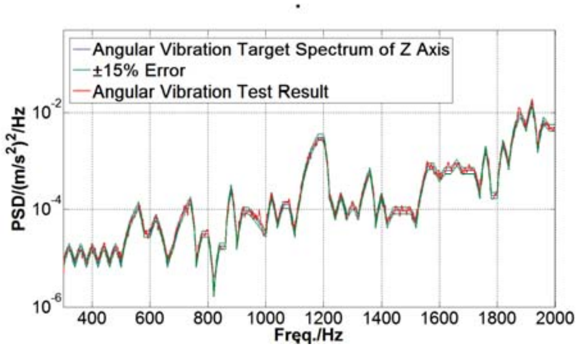

Fig. 14. Angular vibration simulation result in Z axis.

As it shown in Fig.12, Fig.13 and Fig.14, the developed angular vibration control system could simulate wide frequency band angular vibration up to 2000Hz with good precision. The test results show that the design purpose of angular vibration control system has been achieved. The GUI of angular vibration control system is also provided as Fig.15.

Ⅵ. Conclusions

In this paper, a wide frequency band angular vibration simulation method is proposed, and has been realized into product. Test results show that the frequency band of angular vibration simulation could cover 0 - 2000Hz with good accuracy. This angular vibration simulation system provides a new approach to validate the image quality of image sensors working in angular vibration environment, which is very important in eliminating the mission risks.

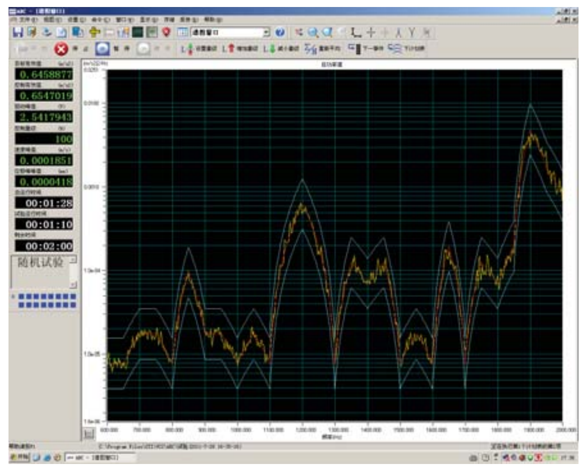

Fig. 15. GUI of angular vibration control system.

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[2] J. F. Li, X. Zhang, G. X. Ren, and Y. F. Gao, "Classical Mechanics," Tsinghua University Press, 2001.