Micro-vibration Test of High Resolution Spacecraft

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Abstract. The accuracy of the high resolution earth observation spacecraft has remarkably increased in recent years. The micro-vibration induced by moving machine, such as moment wheels, may cause severe disturbance to the sensitive payload onboard the spacecraft. It is crucial to perform ground micro-vibration test to verify the observation performance of the spacecraft on orbit. This paper focuses on the system level micro-vibration test method of high resolution spacecraft. The key requirements of the micro-vibration test are firstly presented, and then the test system development is introduced. Finally, the micro-vibration application technique is given to demonstrate the whole process of the micro-vibration test. It is concluded that the test method and the test system are effective for the verification of the high resolution spacecraft.

1. Introduction
The vibration induced by movement mechanism onboard the spacecraft, such as moment wheels, control moment gyros, etc, transmits via bus structure of the spacecraft to the sensitive payload, and perturbs the pointing axis of the sensitive payload. The vibration is one of the factors affect the performance of the spacecraft[1]. Driven by the remarkably improvement of the observation accuracy of modern spacecraft, the issue of accurate ground micro-vibration testing has grown of importance. The micro-vibration test is necessary to predict and verify the on-orbit observation performance by measuring and analysing the response and the transmission of the micro-vibration induced by the disturbance sources. The micro-vibration are of very low level vibration compared with the dynamic environment during launch. The test method and the test system are different than the testing of usual launch dynamic environment[2]. In the micro-vibration test of SDO (Solar Dynamics Observatory), the spacecraft was suspended by air bags to give flight-like boundary condition, and the acceleration response at the interface location of the payload induced by moment wheels was measured and compared with analysis results[3]. On ground and in orbit micro-vibration was measured for SPOT4 satellite. In the test, the disturbance force and moment of the moment wheels mounted on the spacecraft structure were measured, and the micro-vibration frequency response function of the whole spacecraft was tested[4]. The laser communication satellite OICETS was suspended by using low frequency suspension devices, and 40 accelerometers with sensitivity of 1 mG (1 G=9.8m/s²) and dynamic range of 50 dB were used in the micro-vibration test. The influence of micro-vibration to the tracking performance was evaluated[5]. A micro-vibration test fixture with a large bearing capacity and a low stiffness was established for the spacecraft micro-vibration test[6]. This paper focuses on the system-level micro-vibration test method of high resolution spacecraft. The key requirements of the micro-vibration test are firstly presented, and then the test system development is introduced. Finally, the micro-vibration application technique is given to demonstrate
the whole process of the micro-vibration test. It is concluded that the test method and the test system are effective for the verification of the pointing stability performance of the high resolution spacecraft.

2. Test requirements
For the purposes of this paper, spacecraft micro-vibration are small-amplitude mechanical vibrations due to dynamic interactions, usually in the range of micro-g's to milli-g's, which typically occur at frequencies from a few Hz up to a few hundred Hz[7]. According to the basic characteristics of the micro-vibration and the task of the micro-vibration test, the micro-vibration test is quite different than the launch dynamic environment test. There are mainly three key aspects of requirements for the micro vibration test. The first is the multi-parameter measurement requirement, that is, the acceleration measurement and the angular vibration measurement. The angular vibration measurement is dedicated for the evaluation of the pointing stability performance of the sensitive payload in the micro-vibration test. And the second aspect is the high precision measurement for the above parameters since the micro-vibration is of very low acceleration level compared to the dynamic environment during launch. To measure acceleration response of the micro-vibration, the sensitivity of the accelerometer is required to be 1000mV/g at least. For angular vibration measurement, 1/10 pixel of the resolution should be distinguished for the popular 1.0 meter level of observation in general, the angular sensor resolution is required to be better than 0.01″ in the test. And the third aspect is the free boundary reproduction requirement. Because the spacecraft flies without any constraint on orbit, due to the lack of gravity of the space. However, external constraint have to be applied to suspend the spacecraft weight on ground, due to the gravity of the earth. The effect induced by this difference should be reduced as little as possible after the constraint is applied in the test. And this leads to the requirement of free boundary reproduction. In general, the suspension frequency should be lower than 1/10 of the natural frequency of the spacecraft.

3. Test system development
3.1. Configuration of the test system
The basic configuration of the test system is shown in figure 2. There are measuring system and free boundary reproduction equipment basically. The spacecraft is mounted on the free boundary reproduction equipment. The measuring system including sensors and data acquisition/processing are connected to the spacecraft.

3.2. Measuring system
The measuring system mainly includes accelerometers, angular displacement sensors, and data acquisition /processing computer. The accelerometers(A) are installed on the structure of the spacecraft. They are used for measuring the micro-vibration response of the spacecraft. The sensitivity is 1000mV/g. The accelerometers(B) are sticked on the floor of the test hall to monitor the background environment. And its sensitivity is 10000mV/g. Commercial products are used for the accelerometers, as shown in figure 3.

![Figure 1. The key requirements of micro-vibration test.](image-url)
The angular displacement sensors are installed on the mirrors of the optical payload to measure the jitter of the optical axis of the payload. There are several technologies for the angular vibration sensor, such as laser gyroscope technology, optical fibre gyroscope, and magnetofluid gyroscope. And finally, the laser gyroscope technology are selected to develop the angular sensors based on the maturity of the technology. The sensors are shown in figure 4. And the resolution reaches 0.004 arc-sec which is better than the requirement.

3.3. Free boundary reproduction

The free boundary reproduction equipment as shown in figure 5 is dedicated to suspend the spacecraft with heavy load-bearing, low frequency, high stability, and high reliability. The equipment provides suspension in 6 degrees of freedom. Finite element analysis was carried out during the development as is shown in figure 6. The six suspension frequencies are designed between 0.45Hz to 2.08Hz. Based on the design and analysis, the free boundary reproduction equipment is manufactured.

4. Micro-vibration test application

After the test system is developed, it is applied to the micro-vibration test for more than ten high accuracy spacecrafts. Test purpose, items, and implementation method are discussed in this section.

4.1. Micro-vibration test application
For system level micro-vibration test of spacecraft, the final test purpose is to verify the spacecraft mission performance in micro-vibration environment, by acquiring micro-vibration response of sensitive payload through response measurements. And also to verify the transfer path design by acquiring the transfer characteristics from disturbance source to the sensitive payload, and to update analysis model by identifying modal parameters of spacecraft.

4.2. Test items
In general, the test items include suspension frequencies measurement, modal survey test, transfer function measurement, and micro-vibration response measurement. The suspension frequencies measurement acquires the suspension frequencies of the free boundary reproduction equipment with spacecraft attached, and proves the boundary condition appropriate for the test. The modal survey test identifies the elastic modes of the spacecraft, and supplies data for finite element model update. The transfer function measurement acquires the micro-vibration transfer characteristics and the frequency response characteristics of the sensitive payload by applying external excitation, and check the linearity of the structure under different levels of excitation, and also the frequency response data are used for finite element model update and structure design improvement. The micro-vibration response measurement acquires the micro-vibration response of the sensitive payload and the structure during the disturbance sources working onboard the spacecraft. The response data are used to evaluate the pointing stability performance and the quality of the imaging.

4.3. Test implementation

4.3.1. Suspension frequencies measurement
The suspension frequencies measurement is performed firstly in the test. After external force or torque released, the free oscillation response of the system of spacecraft and free boundary reproduction equipment is measured by acceleration sensor and laser displacement meter. The suspension frequencies, are extracted through analyzing the measured data by FFT.

4.3.2. Modal survey test
The structure is excited by random or steady sine force inputted at certain points of the structure. The excitation points are selected to make sure the desired modes can be excited. The modal frequencies, modal shapes, and modal damping are extracted by PolyMAX method. Usually, modes lower than 200Hz of the structure are identified in the test. The first orders of elastic modes of a certain spacecraft is identified as 40.7Hz. Comparing with the suspension frequencies, the first order of natural frequency of the spacecraft is ten times higher than the suspension frequencies.

4.3.3. Transfer function measurement
The structure is excited by random force inputted at the points close to the disturbance sources. In this measurement different levels of force of 2N, 5N, and 10N are applied to the structure. The main resonant frequencies of the sensitive position are identified through the frequency response transfer function, as shown in figure 7. The results are consistent with the modal test results. And also, the linearity of the structure at different levels of force excitation is checked by comparing the transfer function curves. It is seen that the structure if of good linearity under low level excitation.
4.3.4. Micro-vibration response measurement
The micro-vibration response measurement is carried out as the last item in the test flow. The power of the real disturbance sources onboard the spacecraft, such as the control moment gyros, are turned on. The acceleration response of the structure and the angular displacement response of the sensitive payload excited by the disturbance sources are acquired. The time history of the measured acceleration response at different positions are shown in figure 8. And the transfer characteristic from the disturbance source to the payload is analyzed by figure 9. It is seen that the level of the micro-vibration is high at the disturbance source mounting position, and it is remarkably attenuated through the structure transmission.
The angular displacement response is also acquired in this measurement. By introducing the measured angular displacement data to the optical analysis model, the image offset can be calculated, and the image quality and the pointing stability performance are determined. So that the applicability of the spacecraft in micro-vibration environment is verified.

5. Conclusion
The ground micro-vibration test is necessary for high accuracy observation spacecraft. This paper discussed the key requirements for the test, developed the test system satisfying the test requirements, and established the test implementation method with consideration of engineering application. The test method and system were applied for more than 10 high resolution observation spacecraft with validation of on-orbit flight. It is proved that the test method and the test system are effective for the verification of the high resolution observation spacecraft.

6. References
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