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# THE APPLICATION STUDY OF FORCE LIMITED METHOD IN VIBRATION TESTS

YUE Zhi-yong, ZHANG Jun-gang, FENG Yao-qi

Beijing Institute of Spacecraft Environment Engineering
Beijing 100094, China
yuezy2004@yahoo.com.cn

**Abstract**

Based on a force limited vibration test in the vertical direction of a satellite centertube, this paper introduces the equipment of the force limited vibration test, including the fixture and FMD, force signal acquisition and analysis technique, force transducer calibrating technique, etc. This paper compares the result of the force limited method with the acceleration controlled method, and indicates the influence on control precision and test results of the force limited method. By FEM simulation, this paper analyzes the reason for the lower resonance frequency of the centertube in the force limited vibration test, and discusses the question and solutions relating to the fixture and FMD. This paper was very valuable in the development of force limited method.

## 1. INTRODUCTION

Spacecrafts must be subjected to the dynamics environments of sound, vibration, impact etc in the courses of launch and return. Although the time of dynamics environments is not very long, their significance can not be ignored. Dynamics environment test shall be sufficiently performed in order to ensure that the satellite and its subsystems can withstand dynamics environments. In the traditional acceleration controlled vibration test, the experimental results will be consistent with that of the actual flight if the joint boundary condition of the test item is consistent with that of actual flight and the test condition (accelerating control curves) is consistent with the joint surface response of the test item at flight. But compared with the actual flight, the mechanic impedance of the test fixture is greater in the vibration test so as that the bending and torsion degrees of freedom of the joint surface on the test item are limited and that the inherent frequency of the test item is increased. In addition, the test condition in the vibration test is acceleration envelope. The two reasons enable the vibration test for the test item to easily produce the over-test phenomenon.

As early as the 1950's, many engineers of aerospace mechanics recognized that ignoring the low mechanical impedance of lightweight mounting structures, would lead to unrealistically severe vibration tests of aerospace equipment[1]. In order to solve the product over-test problem, people have found out various methods. Presently the control method of response amplitude limited is typically used. The control methods of response amplitude limited consist of the acceleration controlled method and the force limited method. Firstly the acceleration and force on the key points of test item in the actual flight shall be estimated and then the acceleration and force are measured and controlled on these keys points in the vibration test so as that the measured acceleration and force are limited within a range.

The acceleration controlled method mainly limited the acceleration of the joint interface of the satellite. At present it is a method most widely used in the vibration test for the spacecraft. But this method is typically considered as more complexity and the limited condition is not easy to be defined. Also reference acceleration spectrum of high-magnitude test is executed with the active sunken processing comparing to low-magnitude test data. When the sunken processing is used to solve the over-test problem in the vibration test, the experience of the test persons is highly required for the formulation of the sunken condition because the resonance frequency of test item in high-magnitude test excurses forward comparing to that in the low-magnitude test and the product strongly shows nonlinear characteristics in the high-magnitude vibration test. If the sunken condition is formulated incorrectly, the over-test or even insufficient-test problem still appears.

Force limited method considers two situations of the acceleration and force on the joint surface of the satellite. It is a double controlled method of acceleration and force. In the force limited method, acceleration is a main controlled factor. The acceleration condition will be automatically sunken to solve both the over-test and insufficient-test problems when the satellite input force surpasses the given condition at the satellite resonance. In the force limited method test, force measurement and control technology are critical. Therefore high requirements are proposed for the force limited conditions, namely determination of force spectrum, force measurement device (FMD), collection and processing of force signals, double control method of acceleration and force. Force limited control method started to gradually obtain the application in American NASA and European Space Agency from 90's of previous century [2].

In order to apply the force limited control technology into the vibration test of Chinese spacecrafts, Beijing Institute of Spacecraft Environment Engineering has already developed the research on force limited control technology and has yielded a certain result [3,4]. The paper introduces a vibration test course of vertical force limited method for a centertube, and analyses the test result. With the comparison with the test fixture used in the acceleration controlled test, the difference of the fixtures is the main reason for the lower resonance frequency in the force limited method test. With the finite elements model analysis, the optimized ways for fixture and FMD of force limited test are proposed and research keys and direction of force limited control technology in the future are analyzed.

## 2. INTRODUCTION TO THE FORCE LIMITED TEST FIXTURE

Force sensor: single-direction force sensor, see Figure 1. Because the product is mainly subjected to vertical force, the electric charge signals derived from the 4 single-direction force sensor simply need to be physically added and the derived total force signals are controlled.

The fixtures for force limited test: based on the characteristics of centertube, an existing fixture and a newly made stainless steel ring are used as FMD of the force limited test and simultaneously served as test fixture, see Figure 2. 4 singly-direction force sensors are corresponding to 4-points support.

Fig.1 Force sensor (Kistler 9061A)

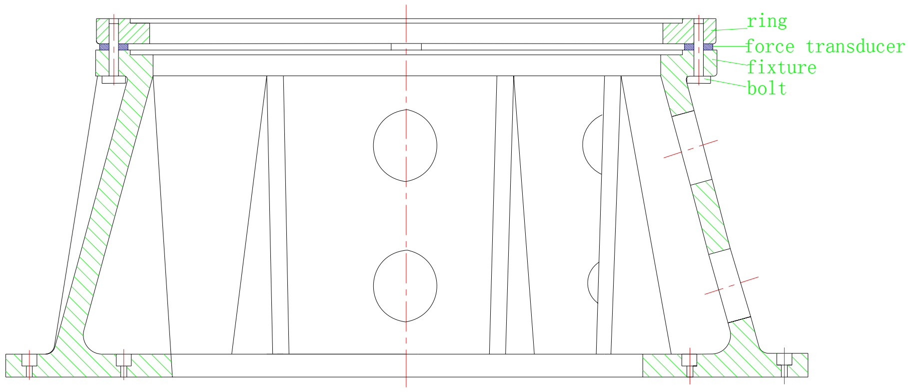


Fig.2 FMD used in the force limited vibration test of a satellite centertube

## 3. PREPARATION BEFORE FORCE LIMITED TEST

In the preparation stage of force limited test, the force sensor is mounted under preload between two plates. The pre-tightened bolts influence on the measurement result shall be calculated. The joint bolts are carried on the safety analysis. The sensitivity coefficient of the sensors shall be calibrated in order to derive more accurate signals.

### 3.1 Mounting rules of preload for the force sensors

The preload for the force sensors shall conform to two rules: 1, the initial tightened force is 10% - 50% of full range of the force sensors. 2, the initial tightened force shall be bigger than the maximum force measured in practice.

### 3.2 Analysis of pre-tightened bolts influence on the measured force

In the force limited vibration test, the forces derived from the force sensors are not total received forces due to the influence of pre-tightened bolts. Supposed that force sensor fixture is demonstrated in Figure 3, the dynamic force of test item receiving in the vibration test is equal to the sum of the dynamic force received by the force sensors and dynamic force received by the pre-tightened bolts. The analysis of receiving forces is demonstrated in Figure 4, in which the force sensors are equivalent to spring $k_1$ and the bolts (and environmental factors) are equivalent to spring $k_2$. Supposed that the quantity of the dynamic force received by the test item is N, the forces received by the force sensors and the bolts are $N_1$ and $N_2$ respectively.

The error of measurement is:

$$\frac{N-N_1}{N}=\frac{N_1\dfrac{k_2}{k_1}}{N_1\dfrac{k_1+k_2}{k_1}}=\frac{k_2}{k_1+k_2} \tag{1}$$

Formula (1) shows: When the bolts rigidity is constant, the bigger the equivalent rigidity of force sensors are, the higher the force measurement accuracy is.

In formula (1), the equivalent rigidity $k_1$ of the force sensor using in this test is equal to14KN/um, and the equivalent rigidity $k_2$ is equal to EA/L. E is bolt elastic modulus. A is section area of bolt. L is effective length of the bolt.

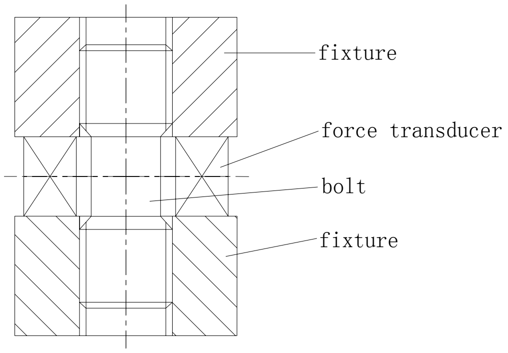


Fig.3 Force sensor fixture

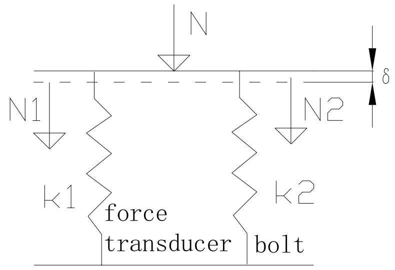


Fig.4 Mechanical analysis

### 3.3 Safety calibration method of joint bolts

Bolts safety shall be calibrated prior to the test according to the design standard for the fixture, including bolts rigidity, pre-tightened force, intensity, etc.

*3.3.1 Calibration method of bolts rigidity*

In the FMD equipment, in order to satisfy the safety requirement of vertical vibration test (Namely the inherent frequency of the bolts and load system shall be greater than the test maximum frequency). The rigidity of bolts connected to the force sensors shall satisfy:

$$n\frac{\pi d^2}{4L} \geq (2\pi f_{\max})^2 \frac{m_0}{E} \tag{2}$$

In formula (2), n--number of bolts; d--diameter of bolts; $f_{max}$--test maximum frequency; $m_0$--total mass of ring and satellite.

*3.3.2 Calibration method of pre-tightened force of bolts*

Pre-tightened force F of bolts shall ensure no gap occurs between the contact surfaces and shall be greater than 1.1 times of the biggest separating force $F_s$, namely $F>1.1F_s$. In the vertical vibration test, the biggest separating force of the location at which the force sensors are fastened with the joint bolts is:

$$F_s = \frac{m_0 a Q}{n} \tag{3}$$

In formula (3), a--input maximum acceleration, Q--quality factor at the resonance.

### 3.4 Sensitivity calibration method of force sensors

Measurement accuracy of force sensors is affected greatly by the environmental factors, such as pre-tightened bolts influence on the measurement accuracy. In addition, the mounting quality of the force sensors also affects greatly the measurement accuracy, such as: roughness degree of the surface between the fixture and force sensors, insulation state of the force sensors, plane degree of installing multi-sensors, etc. The sensitivity of the sensors shall be re-calibrated prior to force limited test and after mounting the sensors in order to reduce the environmental factors influence on the measurement.

The methods of calibrating the sensitivity of force sensors consist of static force calibration method and dynamic force calibration method. The static force calibration method is that the force load is imposed directly on the fixture and simultaneous the force load charge signals are measured. The force sensors are calibrated according to the ratio of signals and force load. The dynamic force calibration method is that the counterweight is fixed on the fixture and then the sinusoidal vibration test method at constant frequency with low frequency is performed. The sensitivity of the force sensors is calibrated according to the measurement result. The advantage of this method is the measurement accuracy is higher, and the shortcoming of this method is that there are some difficulties and dedicated counterweight need to be made.

The dynamic force calibration method is used in this force limited test with centertube. The counterweight approximately equal to the weight of the product is used to perform the calibration. The sensitivity value of the force sensors gotten in the high magnitude vibration test is slightly bigger than that gotten in the low magnitude test and is more accurate because of the higher signal-noise ratio. The error is about 5%.

## 4. ANALYSIS OF FORCE LIMITED TEST WITH CENTERTUBE

The experimental content is the vertical sinusoidal vibration test. The test steps include: 0.1g test(acceleration control method); 0.3g test(acceleration controlled method); the first 0.48g test, the force limited test condition is made from the maximum measured force in the 0.3g test ( force limited method); the second 0.48g test, the force limited test condition is made from the maximum measured force in the 0.1g test ( force limited method).

### 4.1 Analysis of test result

There are two differences between the force limited test and acceleration controlled test.

The first is that the control accuracy of the force limited test is far higher than that of acceleration controlled test near the resonance frequency. This can relieve the over-test problem. For example, the control system curves in Figure 5 and Figure 6 are respectively derived from acceleration controlled test and force limited test. The ultra-differences of acceleration amplitude curve in Figure 5 reaches: (0.1963-0.1)/0.1=96%, the frequency ultra-difference range is approximately 15Hz (49 ~ 64Hz). The ultra-differences of force amplitude curve in Figure 6 reaches (45.5-38.99)/38.99=16.7%, and the frequency ultra-differences range is approximately 13Hz (46 ~ 59Hz). Namely the frequency ultra-difference range is changed a little, but the amplitude ultra-differences are obviously improved, and the control accuracy is obviously enhanced. Thus may relieve the over-test problem. Because the acceleration control accuracy fluctuates greatly near the resonance frequency of the centertube, if inappropriately control, the oscillatory situation occurs. But the force curve is relatively gentler than the acceleration curve, it is easier to be controlled. There are two reasons for the force curve easily controlled: 1, the acceleration signal at the interface of the satellite and rocket is smaller, and typically the peak control model is adopted, therefore the environmental noise near the interface is more sensitive, and the signal-noise ratio of acceleration signal is lower. But the force signal at the interface is bigger, therefore the environmental noise is not sensitive, the signal-noise ratio of the force signal is higher. 2, near the resonance frequency of the test item, the acceleration signal is greatly subjected to the dynamic absorber effect (it is the main reason for fluctuation of the acceleration curve), but the force signal is slightly subjected to the dynamic absorber effect.

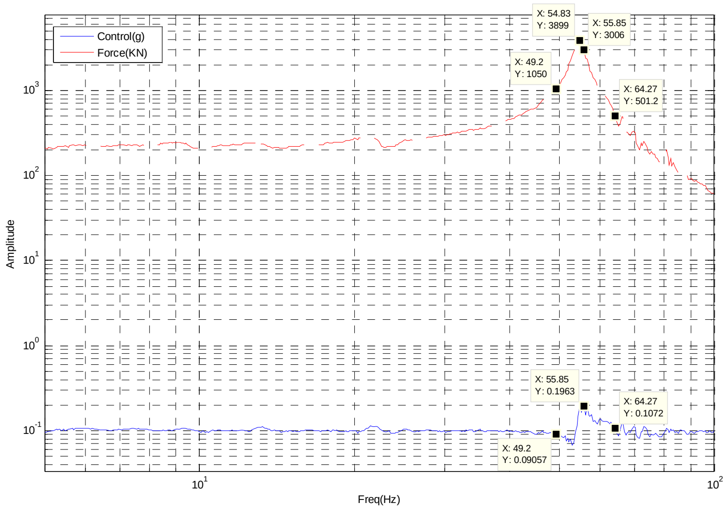


Fig.5 0.1g test (acceleration controlled method )

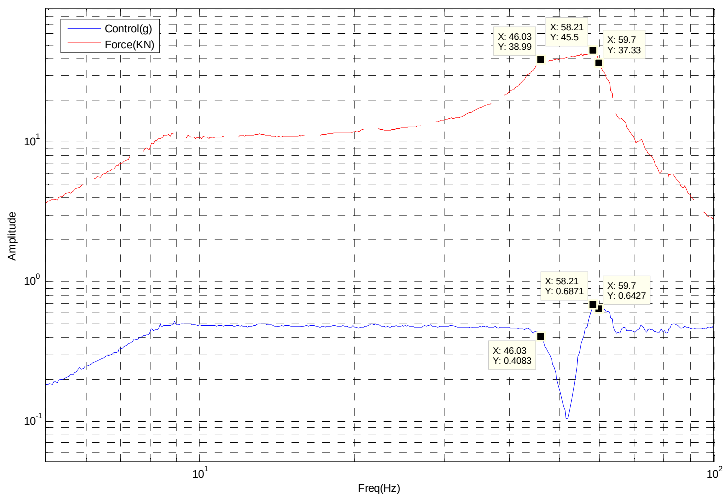


Fig.6 the second 0.48g test (force limited method, force limited to 38.99KN)

The second is that the first frequency of the product is decreased by 7Hz. Under the 0.1g input condition, Figure 7 is the control curves respectively derived from acceleration controlled method (using acceleration controlled test fixture) and force limited method (using force limited test fixture). Comparing with the results of the acceleration controlled test, the first resonance frequency of the test item in the force limited test generates approximately 7Hz forward excursion.

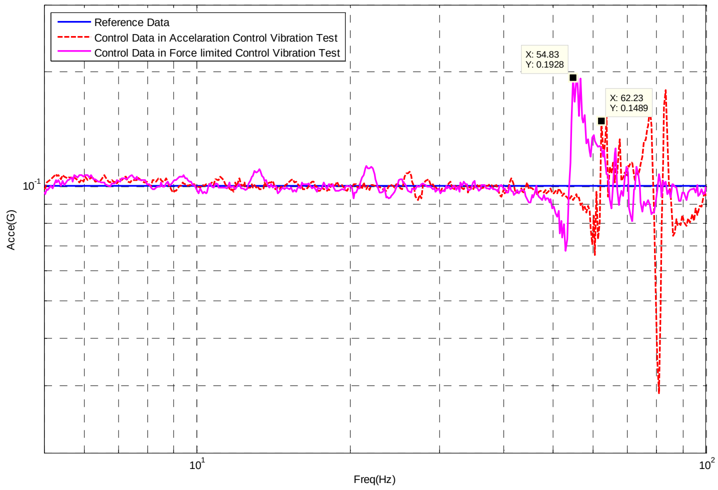


Fig.7 Comparison of the control data on 0.1g test

### 4.2 Reasons analysis for forward excursion of test item resonance frequency

Because of the use of 4-points support mode, the first frequency of the fixture used in the force limited test is far lower than the first frequency (above 300Hz) of the fixture used in the acceleration controlled test.

FEM analysis for the fixture of force limited test is performed. The finite elements model is shown in Figure 8.

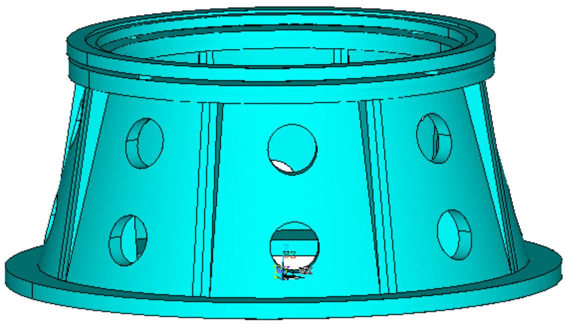

Fig.8 FEM modal of the fixture in the force limited vibration test

The lower three frequencies are: 138Hz, 166Hz, 166Hz, and the first frequency is smaller that 300Hz, and the vibration modal of the fixture is all the local distortion of the ring. This is a main reason why the resonance frequency is forward excursed in the force limited test.

## 5. OPTIMIZED TECHNOLOGY FOR THE FIXTURE AND FMD

The fixture rigidity can be increased with the number of force sensors increased [5]. The FEA software Ansys is used in order to sufficiently research various factors affecting the frequency of the fixture. The lower three frequencies of the fixture are as shown in Table 1.

It is demonstrated from Table 1: The first frequency of the fixture is better when the cast aluminum materials is used as the ring, but the influence is not remarkable (smaller than 25%). The increase of the number of the force sensors can increase the first frequency of the fixture. The increase of the thickness of ring is not sensitive to the first frequency of the fixture. Even the increase of the thickness of ring possibly drops down the first frequency of the fixture.

Table 1 Comparison of frequencies of the fixture

| Materials of the ring | Number of sensors | Thickness of the ring(mm) | Frequencies of the fixture (Hz) | | |
|---|---|---|---|---|---|
| Stainless steel | 4 | 40 | 138 | 166 | 166 |
| | | 80 | 160 | 247 | 247 |
| | 8 | 40 | 427 | 427 | 532 |
| | | 80 | 381 | 381 | 477 |
| Cast aluminium | 4 | 40 | 164 | 181 | 181 |
| | | 80 | 192 | 272 | 273 |
| | 8 | 40 | 492 | 492 | 583 |
| | | 80 | 466 | 466 | 560 |

## 6. CONCLUSIONS

With the foregoing analysis, the conclusion can be drawn:

1. Near the resonance frequency of the test item, the control accuracy of the force limited method is far better than that of the acceleration controlled method. It can relieve the over-test problem.
2. Fixture and FMD shall be optimized in order to enable the result of the force limited method consistent with that of the traditional acceleration controlled method.
3. The smaller the ring’s thickness is, the better the ring is, at the condition of the test fixture rigidity and intensity satisfying the requirement. The ring may be made from steel, copper or aluminum with smaller density.
4. In order to increase the accuracy of the force limited test, the environmental factors affecting the sensitivity of the force sensors in FMD should be studied, and the calibration technology of the sensitivity of the force sensors should be enhanced.

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