Experimental Analysis on Combined Vibration and Acoustics Test of a Satellite

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Abstract: Random vibration tests and acoustics tests are typical environmental testing approaches for verifying the dynamic environmental adaptability of a satellite, which should be selectively carried out on the ground before launch. Existing test criteria suggests that large spacecraft should be excited in a reverberation chamber, while a shaker should be used for a small spacecraft. With the development of experimental technique of environment simulation, the combined vibration and acoustics (vibro-acoustic) test are increasingly investigated for reproducing a more realistic environment and avoiding an over test or an under test. However, few studies have been published on coupling effect of combined vibration and acoustic test of a full scale prototype satellite. This paper discusses the equivalence between random vibration and acoustics excitation for satellite ground testing. The experiment results have shown advantages of the combined test in reproducing flight environment. And the coupling effect and distributions of high frequency response attenuation during the combined vertical vibro-acoustic test is observed and analyzed in detail.

1. Introduction
As we all know that the realistic launch environment should be reconstructed in ground experimental verifications of spacecraft. In fact, satellites would be generally subjected to vibration and acoustic loads simultaneously during launch and ascent.

In the early stage of space development, satellites were designed to be small and compact. Single random vibration test was known to be adequate. With the development of space technology, more spacecraft with a large surface area, such as solar wings or antenna arrays, are increasingly designed for long-time tasks. To investigate the equivalence between random vibration tests and acoustic tests on an assembled satellite, some assessment methods\[1-6\] based on experimental results and simulations have been proposed. In the recent years, the combined vibro-acoustic testing technique has been drawing attentions in dynamic environment simulation. The combined vibro-acoustic tests for subsystems or even an assembled system were performed \[7-9\].

It is known that the dynamic environment testing level of a satellite is generally determined by the envelope lines of spacecraft-vehicle coupling analysis in a separate environment. However, this approach ignores the influence of the combined vibro-acoustic coupling effect in reality. Frendi and Robinson\[10\] showed that the coupling effect is important for plate response predication at high excitation levels. And they also indicated that the acoustic coupling may attenuate plate response at high frequency bandwidth. Consequently, it seems to be inaccurate to deduce the component testing levels based on complex environment decomposition, which may lead to an overestimation or an underestimation, and even result in an inappropriate strength and stiffness design.
In this paper, a combined vertical vibro-acoustic test for a prototype satellite is executed.

2. Combined vibro-acoustic test of a prototype satellite

2.1. Equipment and tested satellite
A full scale, dynamically equivalent, prototype satellite is designed for vibration and acoustic qualification test before the launching the satellite. The size of the prototype satellite in Z-direction is about 2560mm, and the mass is about 990kg.

![Figure 1](image)

*Figure 1* Coordinates system of the prototype satellite and sensor placement

The combined vibro-acoustic test system consists of a reverberation chamber subsystem and an electromagnetic shaker subsystem, in which each subsystem has a controller to achieve the reference test level. During the tests, the satellite was mounted on a special fixture by using four M12 screws. There are five acoustic modulators in reverberation chamber with the ability to provide 156dB acoustic pressure level. To acquire the acceleration responses on the satellite, a total of thirty-eight three-directional acceleration sensors are mounted on the structure, spreading over the propelling module, instrument capsule, payload capsule, solar wings and antenna of the tested satellite. Some representative measurement points, as shown in Fig.1.

2.2. Control spectrum
The loading levels of random vibration test and acoustic test for vertical direction are taken from China Long March series launching condition. In consideration of subsequent use, half-acceptance level tests were adopted in this work. Table 1 and Table 2 show the control spectrums of the separate random vibration and acoustics test. In the combined vibro-acoustic test, these two kinds of loads are simultaneously acting on the prototype satellite.

| Frequency range (Hz) | 20–200 | 200–800 | 800–1000 | 1000–2000 | Total RMS |
|----------------------|--------|---------|----------|-----------|-----------|
| Magnitude            | +6dB/Oct | 0.01g2/Hz | -6dB/Oct | -6dB/Oct | 3.38grms  |
| Tolerance (dB)       | ±1.5  | ±3.0    | ±1.0     |           |           |

*Table 1* The control acceleration spectrum of half-acceptance level random test in vertical direction

| Frequency range (Hz) | 20–200 | 200–800 | 800–1000 | 1000–2000 | Total RMS |
|----------------------|--------|---------|----------|-----------|-----------|
| Magnitude            | +6dB/Oct | 0.01g2/Hz | -6dB/Oct | -6dB/Oct | 3.38grms  |
| Tolerance (dB)       | ±1.5  | ±3.0    | ±1.0     |           |           |

*Table 2* The control sound spectrum of half-acceptance level acoustic test
| Central frequencies (Hz) | 31.5 | 63  | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 | OSPL |
|-------------------------|------|-----|-----|-----|-----|------|------|------|------|------|
| Magnitude (dB)          | 121  | 126 | 131 | 135 | 130 | 126  | 125  | 119  | 138.5|      |
| Tolerance (dB)          | -2~+4| -5~+4| -5~+4| -1~+3|      |      |      |      |      |      |

2.3. Loading and data acquiring method
The loading method of the combined vibro-acoustic test is similar with single vibration or acoustic test. In this work, four vibration accelerators are mounted on the interface between the satellite and the fixture for average peak value control strategy. For the acoustic test, four sound sensors were symmetrically located about 0.5m away from the satellite with a height of 1200mm which is close to satellite COG.

It should be noted that reverberation would influence the random vibration self-check before loop control start. Therefore, random vibration self-check should be carried out firstly and up to -12dB of the full vibration level, then wait for the acoustic control system till it starting up to -12dB of the full acoustic level, and then random vibration and acoustic excitation would be acting simultaneously to full test level (0dB).

Acceleration responses of random vibration and acoustic tests are acquired in steady state by using statistical average method. According to empirical knowledge, the response acquisition approach of random vibration test is essentially identical to that of acoustic test. The only difference lies in the frequency ranges. To conveniently compare the responses, the same frequency range in the interval of 20Hz to 2000Hz is shown and discussed.

![Control PSDs of random-only test and combined test](image)

The acceleration control PSDs of the single random test and the combined test are shown in Fig.2. It can be seen that the RMS (root mean square) values of both curves are approximately equal to each other, which indicates that the random acceleration control PSD of the combined vibro-acoustic test has not been strongly affected by acoustic excitation. As shown in Fig.3, the sound control spectrums of the acoustic-only test and the combined test are also compared, in which negligible differences appear at each center frequencies.
3. Test results and analysis
The main difference between random-only and acoustic-only test is input energy transition and acting position. In the acoustic test, the satellite was located at the center of high level reverberation chamber, and a number of modulators with horns provided acoustic environment around it. While for a random vibration test, the interface frame of the satellite is connected on a shaker that provides mechanical excitation from the joint interface. It means that random vibration excitation is transmitted from shakers to the satellite, which essentially is point or surface excitation. And acoustic loads are directly acting on the surface of the satellite, considered as field excitation from all the directions. From the view of structural responses, acoustic excitation has higher impact on plate-like structures than random vibration.

The response RMS values resulted from random vibration are mostly greater than that of acoustic test. For a typical measurement point PMA2, the RMS of random response is 5.083grms, and that of acoustics test is 3.1grms. As shown in Fig.4, the responses of PMA2 are enhanced by shaker excitation in the whole frequency bandwidth. It can be seen that the combined vibro-acoustics test response is similar with that of single random vibration test, and basically envelopes the response of acoustics test. Significant disparity appears between single acoustic and random vibration test for PMA9.

The response curves of antenna subsystem during the three individual tests are compared in Fig.5, two resonate peaks in low frequency range appear in the curves of random excitation and combined vibro-acoustic excitation, and none for acoustic test. It means that the antenna is excited adequately by mechanical random excitation. Above 300 Hz, the response of the combined test and the single acoustic test are in good agreement. The solar wings exposed outside the main structure frame is far away from source of mechanical vibration. It can be obviously seen from Fig.6 that the response at the center of solar wing from the combined vibro-acoustic test is almost identical to that of single random vibration test below 150Hz, and close to that of the acoustic-only test above 150Hz. It can be concluded that the combined vibro-acoustic test can give a less conservative test, compared with single vibration and acoustic test, for plate-like structures exposed out of the main structure.
4. Conclusion
This paper focuses on a combined vertical vibro-acoustic test of a prototype satellite. The coupling effect of combined test in high frequency response attenuation and its distributions on a prototype satellite are experimentally investigated. Some appealing results can be summarized.

In most representative measuring points, the responses are enhanced by random vibration in low frequency range, while dominated by reverberation field loads in high frequency range. Compared with single random vibration or acoustic test, the combined vibro-acoustic test not only makes up the deficiency of acoustic test in low frequency, also improves the attenuation of vibration transmission far away from excitation source, which might be close to true flight environment intuitively.

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