Vibration responses of a satellite subjected to acoustic excitation at launch stage

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Abstract. Acoustic-vibration prediction at early stage of satellite development can contribute to their structural and layout design. In this paper, numerical models of a practical satellite subjected to acoustic excitation at launch stage were established. Then, the effect of acoustic condition was further analyzed. The results demonstrate that it is difficult to predict all-frequency-band acoustic response of complex satellites by an individual method, so a combined method was proposed in this paper. The damping loss factor model of panels with equipment was introduced to resolve the issue of on-board equipment modelling in the statistical energy analysis model. The service modules are extremely sensitive to acoustic excitation of about 354~2828Hz, which should be highlighted when carrying a rocket with a high sound pressure level at this frequency band.

1. Introduction

Satellites experience complicated dynamic environment at launch stage, including acoustic condition with high sound pressure level sound pressure level (SPL). This acoustic condition would introduce a wide-frequency-band excitation from 10Hz to 10000Hz, and even cause unexpected damage, such as structural fatigue and equipment failure [1]. Accurate acoustic-vibration (hereinafter referred to as acoustic) response prediction is beneficial to the structural, layout and ground pre-test design at the early stage of satellite development, and it has become a key technique of satellite projects [2].

The acoustic performance of satellites is dramatically complex at launch stage with determined-dominated performance at low frequency and random-dominated performance at high frequency, which indicates that single method is hard to predict all-frequency-band acoustic response [3, 4]. There have been some researches on the acoustic response of satellites. Morshed et al. [5] established theoretical and numerical models for the prediction of external sound pressure loading on composite structures representing launch vehicles, and results show that the scattered sound pressure field plays a major role in determining the total circumferential sound pressure field at the surface of the cylinder and cannot be ignored for the launch case. Stevens [6] investigated several materials and methods used to optimize the structural properties of spacecraft assemblies and adopted the FE method to design the configuration of the entire satellite. Aidan Bettridge [7] also studied the design of a Cube Sat and applied the FE method on the analysis of acoustic vibration and random vibration of the cabin plate. Ez-Deen et al. [8] focused on the correlation between acoustic and vibration of a plate from a certain satellite by both experimental and FE methods. Results show that the displacement, velocity, acceleration and stress at low frequency are higher than those at high frequency, and those in the...
The center of the plate are higher than those at the edges. Renji et al. [9] used the statistical energy analysis (SEA) method to investigate vibration energy transfer in a system of three plates separated by a small distance and connected at a few discrete points, similar to the solar array assembly of satellites. Results show that the measured responses of the inner plates are higher than the responses estimated based on the coupling loss factors obtained, which is probably due to the sound radiated from the outer plates not being taken into account for the calculation. Cap et al. [10] compared the response of a satellite to acoustic radiation using SEA and experimental methods. The results show the acoustic response of the solar array was accurately predicted over the entire frequency range of interest (100-2500Hz), while other locations exhibit relatively poor agreement at the frequency below 500 Hz due to the relatively low modal density.

The former investigations above indicate that the FE method is more effective to predict the acoustic response of satellites, while there are some deviations for the SEA method. But compared with the fast-computing SEA method, the FE method needs to calculate the modes of the satellites over the frequency band of interest and refine the meshes to ensure calculating accuracy, which results in a large amount of computation and time.

To improve modeling accuracy and reduce calculation time, a combined method of the FE and SEA methods was proposed in this paper. Acoustic models of a practical satellite in all the frequency bands were firstly established in order to form common acoustic prediction method of satellites. Then, the effect of acoustic condition was studied in terms of different launch vehicles. This paper can be a guideline for acoustic response analysis and prediction of satellites during the development.

2. Numerical method

FE, hybrid FE/SEA and SEA methods are preferred to low, middle and high frequency bands respectively, which are divided according to structural modes in bands (N), namely low frequency when $N \leq 1$, middle frequency band when $1 \leq N \leq 5$ and high frequency band when $N \geq 5$ [11]. Acoustic models of a practical satellite were established to explore the acoustic responses at launch stage. The analysis frequency band is from 20Hz to 5000Hz as an octave type which is based on engineering experience. In order to determine a frequency ($f_1$) to divide the band into high and low segments, a SEA model of the satellite was firstly built as shown in Figure 1, and modes in every octave band were obtained from the model as shown in Figure 2. It can be found that modes of the most components in the band after 500Hz are over 5 except the base and middle panels, and that of solar array is basically over 5 in all the bands. 500Hz was selected as $f_1$, as there are no important equipment on the base and middle panels. Therefore, the hybrid FE/SEA method was used from 20 to 500Hz, in which only solar arrays were modeled by SEA while other components by FE method. And all the components were simulated by SEA model from 500 to 5000Hz.

![Figure 1. SEA model of a satellite](image1)

![Figure 2. Modes in bands of satellite components in terms of frequency](image2)
2.1. Hybrid FE/SEA model

Hybrid FE/SEA model of the satellite from 20Hz to 500Hz was established. The modal superposition method was used in FE method, and the modes below 600Hz were calculated by finite element software with the on-board equipment simulated by non-structural mass. Then, the modal results were imported into acoustic-vibration analysis software to introduce sound field.

Semi-infinite field and diffuse acoustic field were used to model structural acoustic-vibration radiation and sound pressure excitation, respectively. Since the hard-boundary sound pressure is 3dB higher than the pressure of reverberant field [12], SPL in test (namely AC1 in Table 1) was added with 3dB to the surfaces of the satellite.

In addition, the damping loss factor (DLF), couple loss factor and mode density are included in the model. The coupling loss factor and modal density are automatically calculated by acoustic-vibration analysis software. Based on many experimental data, it was found that DLF is negative to the area-to-mass ratio and frequency of components. A DLF model of components was introduced as follows:

$$\eta_j' = \frac{\alpha_j}{f_j} \left( M_j \cdot \frac{\beta_j}{S_j} \right)^{\gamma_j}$$

Where $\eta_j'$, $M_j$ and $S_j$ denotes the DLF, mass and area of $j$-th component respectively. $\alpha_j$, $\beta_j$ and $\gamma_j$ is correction factors of $j$-th mounted panel. These parameters were obtained based on experiments.

| Center frequency at octave band (Hz) | AC1 (dB) | AC2 (dB) |
|-------------------------------------|----------|----------|
| 31.5                                | 127.7    | 121.7    |
| 63                                  | 132.7    | 126.7    |
| 125                                 | 137.7    | 136.7    |
| 250                                 | 141.7    | 138.7    |
| 500                                 | 136.7    | 141.7    |
| 1000                                | 132.7    | 138.7    |
| 2000                                | 131.7    | 133.7    |
| 4000                                | 130.7    | 126.7    |
| 8000                                | 125.7    | 123.7    |
| Global SPL                          | 145.2    | 145.8    |

Note: Reference sound pressure is $2 \times 10^{-5}$Pa, and *AC* denotes acoustic condition.

2.2. SEA model

SEA model of the satellite from 500Hz to 5000Hz is shown in Figure 1. Semi-infinite field and diffuse acoustic field were used to simulate structural acoustic-vibration radiation and sound pressure excitation respectively, and acoustic condition, the coupling loss factor and modal density are the same as hybrid FE/SEA model. Note that the on-board equipment cannot be simulated by non-structural mass in SEA model like in FE model. The equipment and the mounted panel can be regarded as a coupled structure composed of multiple subsystems, and the corresponding power flow balance equation is as follows:

$$\omega E_1 \eta_i + \omega E_i \left( \eta_{i1} + \eta_{i2} + ... + \eta_{i6} \right) - \omega (E_2 \eta_{i2} + E_3 \eta_{i3} + ... + E_6 \eta_{i6}) = P_1$$

Where $\omega$ denotes the center frequency in the analysis band, $E_1$ is the average energy of the panel, $E_2$, $E_3$, ...$E_i$ are the average energy of every equipment respectively, $\eta_i$ is the DLF of the panel, and $\eta_{i1}$,$\eta_{i2}$,$\eta_{i3}$...$\eta_{i6}$ is the coupling loss factor with the energy from the panel to the equipment, and $P_1$ is the input power of the panel.

The external loads are only exerted on the panels, so the energy flows from the panel to the equipment, thus the value of $E_2 \eta_{i2}, E_3 \eta_{i3}, ... E_6 \eta_{i6}$ is small and can be ignored. Then the equivalent DLF of the panel with equipment is:

$$\eta_{eq} = \eta_i + \eta_{i1} + \eta_{i3} + ... + \eta_{i6}$$
Therefore, the on-board equipment can be simulated by increasing DLF of the panel. A DLF model of the panel mounted with equipment was introduced based on the DLF model of components mentioned above, as follows:

\[
\eta_{j}^{\text{eqv}} = \frac{\alpha_{j}}{f_{j}^{\beta}} \left( \frac{M_{j} + M_{j}^{l}}{S_{j}} \right)^{\beta_{j}}
\]

(4)

Where \( M_{j}^{l} \) is the mass of the equipment mounted on the \( j \)-th panel.

3. Model verification

The acoustic test of the satellite was carried out in a reverberant room. The satellite was placed on a supporting trolley and floated with a shock absorber during the test. The sound field was controlled by the average response of 4 microphones.

The prediction error of acoustic model compared with experimental data is illustrated in Figure 3, in which error is equal to \( 20 \times \log_{10}(\text{experimental result/numerical result}) \). It can be seen that GRMSs of CMs and solar arrays in the low frequency band (<500Hz) and high frequency band (500Hz–5000Hz) are close, while GRMSs of service modules (SMs), earth panel, base panel and antennas in the high frequency band are 1.2–3.7 times than those in the low frequency band, especially for SMs (3.7 times), which indicates that SMs are most sensitive to the high-frequency acoustic excitation in components of the satellite. In addition, numerical and experimental results in 20–500Hz and 500–5000Hz are very close, which verify the effectiveness of the hybrid FE/SEA and SEA models.

![Figure 3. The prediction error of acoustic model compared with experimental data](image)

4. Effect of acoustic condition

A kind of satellites may be launched by different vehicles, so the effect of acoustic condition on satellite response was investigated in this section. Acoustic conditions of two commonly used launch vehicles were considered as shown in Table 1.

The deviations of acoustic responses of these two acoustic conditions were calculated by \( 20 \times \log_{10}(\text{response in AC}_2 / \text{response in AC}_1) \) as shown in Figure 4. It can be found that GMRSs of all the components increase by at least 1.7dB though Global SPL of AC2 is only 0.6dB higher than that of AC1. This is because SPL of AC2 is more than that of AC1 from 354–2828Hz which is sensitive frequency for components of the satellite, especially for SMs. And there are some important equipment such as batteries mounted on the SMs, thus the anti-noise capability of the equipment on the SMs should be paid attention to when carrying a rocket with a high SPL at about 354–2828Hz.
5. Conclusion
In this paper, acoustic models of a practical satellite were established and studied and the effect of acoustic condition was discussed. A serial of conclusions obtained as follows:

It is hard to predict all-frequency-band acoustic response of complex satellites by an individual method, so a combined method was proposed in this paper. Division frequency ($f_1$) is determined according to whether modes of highlighted components are over 5 when $f>f_1$. Hybrid FE/SEA method is recommended when $f\leq f_1$ with only solar arrays by SEA method and other components by FE method, and all the components are preferred by SEA method when $f>f_1$.

Based on SEA theory, it is proved that on-board equipment can be simulated by increasing DLF of the mounted panel and a DLF model with equipment was introduced, which solve the problem of on-board equipment modeling in the SEA model.

The SMs are extremely sensitive to acoustic excitation of about 354~2828Hz, thus anti-noise ability of the equipment on the SMs should be paid attention to when launched by a rocket with a high SPL at this frequency band.

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