Simulations and Ground Experiments of Interior Noise for Space Station Module

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Abstract. China Space Station (CSS) module is currently under construction. Considering astronauts will be working and living on orbit for several months, a comfortable acoustic environment in manned space station must be provided. This paper investigates the interior noise effects for CSS using two typical vibro-acoustic analysis methods, that is, coupled finite element/finite element method (FE/FEM) and statistical energy analysis (SEA) method. The simulation models are validated through ground experiments by the noise test for space station simulation module. The combination of the above two methods can well predict the acoustic levels for both low and high frequencies. A ground experiment scheme for interior noise of space station module is also proposed on the basis of its noise characteristics. Sound power equivalent method is utilized to simulate a single noise source and multi-input multi-output (MIMO) closed-loop control method is employed for multiple noise sources. It is shown that the sound field simulation results are in perfect agreement with the simulation requirements of noise sources.

1. Introduction
Interior noise is one of the important environmental factors of manned space station where astronauts work and live on orbit. The noise can affect the normal life of astronauts, e.g., disturbing language communication, distracting, and affecting sleep, and in severe cases, may also cause astronauts' hearing loss and other physiological damage [1]. Therefore, it is a key issue to control the levels of interior noise for the space station. Many devices in the space station need to work simultaneously to ensure the normal operation of the space station, which forms a long-term stable noise environment. Boeing and NASA have established several acoustic test laboratories for acoustic assessment and noise control in International Space Station (ISS) [2]. These test facilities contain reverberation chambers and anechoic chambers, which are expensive and cannot be implemented in a short time. China Space Station (CSS) module is currently under construction. The acoustic noise levels inside CSS module must be controlled and kept to within an appropriate range. In order to meet the requirements of interior acoustic environment in the module, it is important to conduct research on the analysis, prediction and control of noise levels during the design and manufacturing of CSS module.

In this article, we investigate the interior acoustics for CSS. Two typical vibro-acoustic analysis methods, coupled finite element/finite element method (FE/FEM) and statistical energy analysis (SEA) method, are applied for the acoustic simulation of the space station module. The accuracy of the acoustic simulation models is verified by the ground test in the simulation module. A ground experiment scheme for interior noise of CSS module is also proposed. Sound power equivalent method and multi-input multi-output (MIMO) closed-loop control method are employed for single and...
multiple noise sources on the basis of its noise characteristics, respectively. The interior sound field simulation results well satisfy the simulation requirements of noise sources.

2. The space station simulation module and noise sources

2.1. The space station simulation module
CSS module is composed of several cylindrical segments of different size. The interior of module is separated into different function areas, such as areas for equipment installation, work and sleep areas for astronauts etc. The materials with good acoustic characteristics used inside CSS module are required. Some special noise absorbing materials are needed to be developed for important areas such as sleep areas. A space station simulation module is shown in figure 1. The module is constructed for the interior acoustic research of CSS module. It is a cylinder cabin which the interior is divided by bulkheads and racks. The melamine foam is placed on the bulkheads and panels for sound absorption and noise reduction. A loudspeaker is installed in a single compartment at the bottom of the section. Therefore, the noise radiation of the equipment can be simulated.

![Figure 1. Space station simulation module of CSS.](image)

2.2. Noise sources simulation
CSS module is still under construction, and many devices are still under development at this stage. Therefore, it is direct and flexible to carry out the system acoustic testing of the module by using simulated noise sources. Sound Pressure Level (SPL) of noise source is directly related to distance and spatial locations. Considering the installation location of equipment is different in the space station, the sound power of the noise source must be taken into account. Thus, sound power equivalent method is utilized to single noise simulation on the basis of its noise characteristics. The sound power measurement in the semi-anechoic chamber is referred to reproduce the sound field through loudspeakers according to the measured sound spectrum of the noise sources [3], and then the driving voltages of speakers are recorded, as illustrated in figure 2. When in-cabin noise simulation is performed, the corresponding noise spectrum can be emitted from the loudspeakers by loading their recorded driving voltages.

![Figure 2. Sound power measurement of loudspeaker.](image)

The Control Moment Gyroscope (CMG) is one of the main noise sources of the space station. The SPL test results are close to 80 dBA. The CMG noise should be reduced to meet the cabin noise
requirements. In the space station simulation cabin, loudspeakers are utilized to simulate the radiated noise of the CMG as the input excitation of the space station cabin noise simulation [4].

3. Acoustic modelling of space station module
Many acoustic modelling methods can effectively solve interior noise simulation problem, such as ray tracing method, acoustic FE method, and SEA method [5]. These methods are suitable for different frequency ranges and each has some limitations. The appropriate modelling approach should be adopted to carry out the acoustic prediction and analysis for different frequency ranges of different acoustic problems. Considering that the noise in the space station is radiated by structural vibration from different sources, the acoustic-vibration coupling effect need to be noticed. In this paper, we investigate the interior noise effects for the space station module using two typical vibro-acoustic analysis methods, FE/FEM and SEA.

3.1. Low frequency modeling
By using FE/FEM, the acoustic analysis model for low frequencies is established, as shown in figure 3. The upper frequency limit of acoustic FE/FEM model is related to the length of finite elements. In general, the acoustic wavelength corresponding to the maximum analysis frequency should include at least 6 finite elements and the finite element size is no more than 0.1 m. In our model, 80% elements permit calculations of maximum frequency up to 573.3Hz. The acoustic levels analysis for low frequencies by means of FE/FEM model includes 5 low octave frequency bands (31.5, 63, 125, 250, and 500 Hz).

![Figure 3. Coupled FE/FEM model of the space station module.](image)

3.2. High frequency modeling
By using SEA method, the acoustic analysis model for high frequencies is built, as shown in figure 4. The space station module structures are divided into bulkhead structures and honeycomb sandwich structures. Bulkhead structures are modelled by subsystems of isotropic plates or shells; honeycomb plates are represented by composite sandwich plates, in which the honeycomb core is simplified as orthotropic plates; and the air inside the module is represented by subsystems of sound enclosures. Acoustic package in VA One is utilized to model the melamine material in the cabin, which is set as sound-absorbing layers on the structural surface. The SEA model for the space station module consists of nearly 100 subsystems. The number of modes for all subsystems is much more than 5 within 1000Hz octave frequency band, satisfying the modelling requirement of SEA method. The acoustic levels analysis for high frequencies by means of SEA model includes 4 high octave frequency bands (1000, 2000, 4000, and 8000 Hz).
4. Results of simulations and experiments

The speaker in the cabin of space station module is used to simulate the noise source (CMG) following the actual noise spectrum. The noise level of audible frequency range at specified locations in the module are measured simultaneously. The testing acoustic noise levels are obtained through the experiment of CMG simulation source operating in the space station module. Using our models for low and high frequencies, the same noise source (CMG) operation condition on the space station module is simulated in order to carry out the computation and analysis of predicted Sound Pressure Level (SPL). Similarly, the simulated acoustic noise levels at identical locations of the module are obtained. The simulation and testing acoustic noise spectrums for some areas in the space station module are shown in figure 5.

![Figure 4. SEA model of the space station module.](image)

![Figure 5. Comparison between simulations and experiments.](image)

The correlation between the simulation and experimental results are quite encouraging since their overall characteristics are similar, despite the complexity of the module under investigation. The simulation and testing Overall Sound Pressure Level (OASPL) error at each measuring location is within 2 dB. The agreement between the measured and calculated acoustic responses verifies the FE/FEM and SEA simulation models that consider acoustic-vibration coupling effect. Note that the simulation results in the medium band can well meet the testing results, while bigger errors are shown in the lower and higher frequency bands. Additional testing data indicate that these errors may be
introduced by background noises in low frequency band and structural gap-induced leak noises in high frequency band.

5. Acoustic environment simulation of space station module

5.1. Multiple noise sources simulation

The acoustic levels at specified locations in the space station can be simulated by multiple noise sources using multi-input multi-output (MIMO) closed-loop control method. MIMO control method is a useful approach to separate and clearly identify repeated roots and frequency-proximate modes which is based on the linear time invariant system theory. With more than one reference sources, multiple columns of the frequency response matrix can be measured simultaneously. Thus, the relationship is obtained between the excitation and response of the MIMO vibration system in the frequency domain. MIMO control method provides much higher efficiency and accuracy for the system FRF measurements. When using MIMO control method, the driving source signals are guaranteed to be uncorrelated with one another. By using MIMO control method, the drive spectrum is corrected in processing according to the response spectrum to achieve real-time closed-loop control [6]. The same space station module is adopted for acoustic environment simulation. Figure 6 shows four noise level positions are selected in the centreline of the aisle as the target points for MIMO control. Figure 7 shows four simulated noise sources are installed for acoustic and vibration disturbance.

![Figure 6. Measurement locations in the space station module.](image)

![Figure 7. Installation of simulated acoustic sources.](image)

5.2. Result of acoustic environment simulation

The acoustic noise level at the target positions in the simulation are shown in figure 8. Reference is the target reference spectrum, C1～C4 are the actual target points Control effect. It can be seen that the SPL error at each frequency point in the 1/3 octave band is less than ±3 dB, and the OASPL level error is within ±2 dB. The agreement between the measured and reference acoustic noise level verify the MIMO control method approach.
6. Conclusion

This paper investigates the interior noise effects for CSS using two typical vibro-acoustic analysis methods, coupled finite element/finite element method (FE/FEM) and statistical energy analysis (SEA) method. The simulation models are validated through ground experiments by the noise test for space station simulation module. The combination of the above two methods can well predict the acoustic levels for both low and high frequencies, with the error of overall levels less than 2 dB. A ground experiment scheme for interior noise of space station module is also proposed on the basis of its noise characteristics. Sound power equivalent method is utilized to simulate a single noise source and multi-input multi-output (MIMO) closed-loop control method is employed for multiple noise sources. It is shown that the 1/3 octave error of sound field simulation is less than 3 dB, in perfect agreement with the simulation requirements of noise sources.

7. References

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