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# INFLUENCE OF FILL EFFECT ON PAYLOAD IN A LARGE LAUNCH VEHICLE FAIRING

Zheng Ling

*State Key Laboratory of Mechanical Transmission, College of Automotive Engineering, Chongqing University, Chongqing 400044*
*email: zling@cqu.edu.cn*

Xiang Shuhong

*Beijing Institute of Spacecraft Environment Engineering, Beijing*

This paper focused on the phenomenon of local SPL (Sound Pressure Level) increase caused by the payload filled in the launch vehicle fairing (fill effect). Equivalent models of the fairing and payloads are established using the sandwich plate theory. The interior acoustic characteristic of the fairing is simulated through FE-BEM (Finite Element-Boundary Element Method) and SEA (Statistical Energy Analysis) method, and the fill effects of two payloads with different volume ratio are analyzed contrastively. Furthermore, the mechanism and distribution characteristic of the fill effect are studied from the point of mode frequencies shift. The simulation and test results show that the fill effect is associated with acoustic mode frequencies shift caused by sound-vibration coupling. The shift ratio is greater at low frequencies than high frequencies, which makes the fill effect more obvious. Fill effect will increase with the fill factor because the payload fill factor can influence shift ratio. Numerical computation method based on FE-BEM and SEA provide an effective way to predict the fill effect of payloads.

## 1. Introduction

During a rocket launch, the acoustic field in the fairing becomes very severe due to the high-speed jet noise and aerodynamic noise of rocket engine. In spacecraft system acoustic tests, local pressure is increased in the narrow gap between payload and fairing. It is called the fill effect.

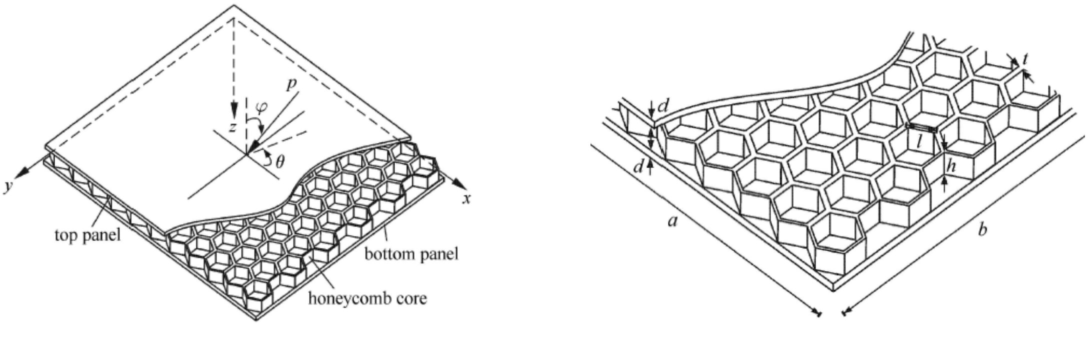
Early in 1980’s, a series of researches have been examined by NASA on the problem of fill effect. The effects on SPL in the fairing resulted by payloads filling of four different shapes, sizes and volumes were tested. A theoretical model was proposed and the industry standard NASA-STD-7001A was developed by NASA [1]. However, this prediction is not accurate at low frequency. After that, SEA (Statistical Energy Approach) and FEM (Finite Element Method) and BEM (Boundary Element Method) are proposed to clarify the mechanism and evaluate this pressure increase [2,3]. It is found that the main reason of the phenomenon is dominated by the acoustic cavity on the appropriate boundary condition rather than structure vibration. Besides, it is verified that the payload geometry could play a significant role in determining the acoustic pressure inside the fairing [4, 5].

In this paper, the interior acoustic characteristic of the fairing is simulated through FE/BEM (Finite Element/Boundary Element Method) and SEA (Statistical Energy Analysis) method, and the fill effects of two payloads with different volume ratio are analyzed to provide theoretical basis for further modification on NASA-STD-7001A. Some conclusions are summarized.

# 2. NUMERICAL ANALYSIS MODELS

## 2.1 Equivalent Treatment of Honeycomb Structure Fairing

Honeycomb sandwich structures are usually composed of the upper and lower skin layer and the intermediate honeycomb core, as shown in Fig. 1 (a). Such structures have been widely used in aerospace due to its high specific strength, stiffness ratio and many other advantages. The fairing and payloads in this paper are composed of regular hexagon aluminium honeycomb sandwich structures. It is necessary to deal with honeycomb structure by equivalent theory due to a large amount of hive in structure and improve computation efficiency.




(a) Global view (b) Partial enlarged view

Figure 1: Honeycomb sandwich structure

The currently used equivalent theories are three type: sandwich panel theory [6, 7], equivalent plate theory [8, 9] and honeycomb plate theory [10]. Only the honeycomb core is equivalent to a homogeneous layer with the first method, while the entire structure is treated with the latter two. Based on the equivalent plate theory, the honeycomb sandwich structure is equivalent to an isotropic plate of different thickness. But it is equivalent to an orthotropic plate of the same size using honeycomb plate theory. Sandwich panel theory is adopted here, which is considered to have higher accuracy and lower computing cost.

For honeycomb sandwich panels with regular hexagon honeycomb core, the elastic constants of the equivalent layer and original material satisfy the following relation [11],

$$E_{cx} = E_{cy} = \frac{4}{\sqrt{3}} E_c (1 - 3\frac{t^2}{l^2})\frac{t^3}{l^3} \quad (1), \qquad E_{cz} = \frac{8\sqrt{3}}{9} E_c \frac{t}{l}. \quad (2), \qquad G_{cxy} = \frac{4\sqrt{3}}{5} E_c (1 - \frac{12}{5}\frac{t^2}{l^2})\frac{t^3}{l^3}. \quad (3)$$

$$G_{cxz} = \frac{\sqrt{3}}{3} G_c \frac{t}{l}. \quad (4), \qquad G_{cyz} = \frac{2\sqrt{3}}{3} G_c \frac{t}{l}. \quad (5), \qquad \rho = 1.54 \rho_c \frac{t}{l}. \quad (6)$$

where: $\rho_c$, $E_c$, $G_c$ are core material density, elastic modulus and shear modulus respectively. $E_c$ represents the elastic modulus of honeycomb core, and subscript *x/y/z* mean three axial directions. *z* direction perpendicular to the honeycomb core layer plane, and the shear modulus subscript has the same meaning. *"l"* is the length of the core layer and *"t"* the thickness of the hexagon. The equivalent core layer parameters are shown in Table 1.

Table 1: Equivalent parameters of the core in sandwich solar panel

| Equivalent parameters | Value | Equivalent parameters | Value |
|---|---|---|---|
| $E_{cx} = E_{cy}$ | 0.15 MP | $G_{cxy}$ | 0.09 MP |
| $E_{cz}$ | 1000 MP | $G_{cyz}$ | 153 MP |
| $\rho$ | 37.7 kg/m³ | $G_{cxz}$ | 306 MP |

## 2.2 FE/BE Analysis Model

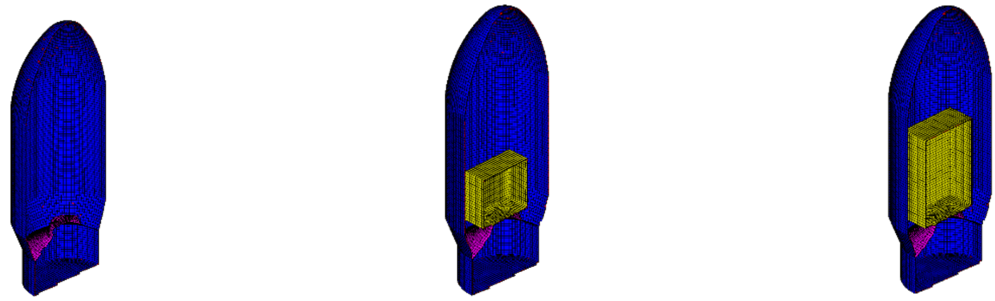
### 2.2.1 Indirect BE Analysis Method

The FEM is usually applied for the prediction of the structural response, while the BEM can be used for the prediction of the acoustic response. For coupled vibro-acoustic problems, both FEM and BEM are necessary.

BEM includes direct and indirect BEM [12], the model of the fluid in direct BEM must be closed cavity and can only be on one side of the element. While in indirect BEM, the fluid can be closed or not, and both sides are allowed. Since the interior and exterior sound field can be considered simultaneously in indirect BEM, indirect boundary element method is used here to establish the coupled model.

### 2.2.2 FE/BE Model

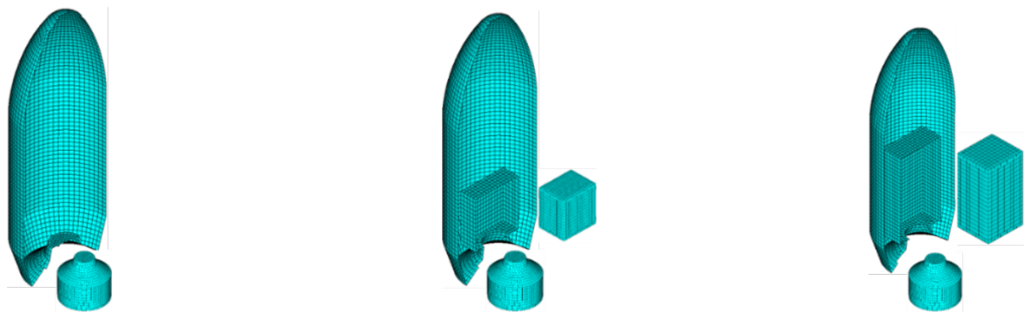
Acoustic-structural coupling models are established using LMS Virtual Lab for the numerical computation of fill effect at low frequencies. Fig. 2 shows the finite element models of different fairing /payload combinations. The grid type is hexahedral, the size of which is controlled in 100mm considering the calculation accuracy and efficiency. As required, the satellite brackets and adapter brackets (Hereinafter referred to as the brackets) are included in the empty fairing. The fill factor (the ratio of the payload volume to the empty fairing volume with the same length at the cylindrical section) of the large and small payload are 35.77% and 28.0575% respectively. The involved frequency range is 31.5Hz~250Hz (band-center frequency).



(a)Empty fairing (b) Fairing with small payload (c) Fairing with large payload

Figure 2: FE models of fairing/payload combinations

Fig. 3 shows the acoustic boundary element models, the grid type of which is quadrilateral in two-dimensional. To ensure that there is 6 elements in the minimum wavelength of the calculating frequency range, the grid size is limited to 200mm. The air cavity in the empty fairing is divided into two parts: one is formed by the fairing and brackets and the other is formed by the brackets and instrument cabin. While the air cavity in the filled fairing comprises three parts: one is formed by the fairing, payload and brackets; another is formed by the brackets and instrument cabin; and the last one is inside the payload.



(a)Empty fairing (b) Fairing with small payload (c) Fairing with large payload

Figure 3: Acoustic boundary element models

Distributed plane wave is applied as acoustic excitation to build the required reverberant field. In Virtual Lab, a distributed plane wave reverberant field is presented in Fig. 4, the input SPLs are experimental measurements.

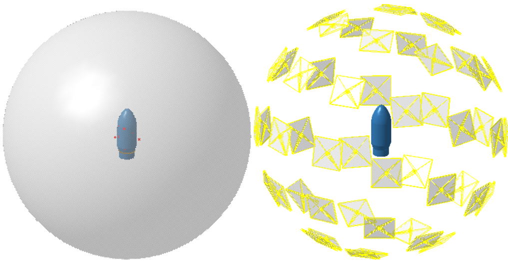


Figure 4: Spatial distribution of distributed plane waves

## 2.3 SEA Analysis Model

SEA analysis models are established with VA One for the numerical calculation of fill effect at medium and high frequencies. Firstly, finite element models of the fairing and payloads are built according to structure parameters, then the fairing, payload and brackets are divided into several statistical energy subsystems in the way SEA method deals with it to finish the calculation models. The SEA model of the fairing filled with the large payload is presented in Fig. 5 and Fig. 6 shows the point, line and surface connections of fairing/payload combination. The involved frequency range is 250Hz~8000Hz (band-center frequency).

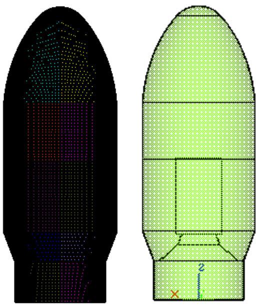


Figure5: FE model and SEA model

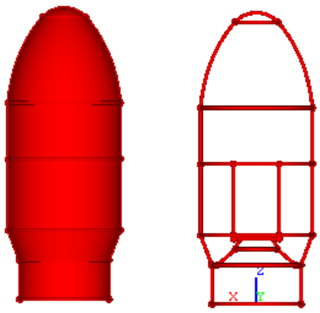


Figure 6: Point, line and surface connections of pay load/fairing combination

When using SEA method, it is demanded to set up the structure loss factor. However, the internal loss factor mechanism is so complex that there is no way to be achieved by theoretical methods. To combine with vibro-acoustic environment test, it is set up with empirical values here as 0.1 for the structures and 0.01 for the air cavity.

The sound source excitation is imposed to the subsystems through diffuse sound field, as shown in Fig. 7.

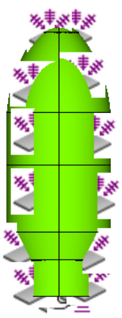


Figure 7: Schematic of imposed acoustic load

Figure 8: Test acoustic chamber and payload fairing

# 3. ACOUSTIC TEST AND LOAD CONDITION

Acoustic tests are carried out in this paper, and the fill effects of two payloads are measured. These tests are carried out at a reverberant acoustic chamber with a volume of 4000m3, as shown in Fig. 8. The frequency range measured is 31.5Hz~8000Hz (band-center frequency). The sound pressure is measured with microphones located interior and exterior the fairing, including 19 measuring ones and 4 control ones. Fig. 9 displays the location of these microphones. The two excitation conditions are given in table 2.

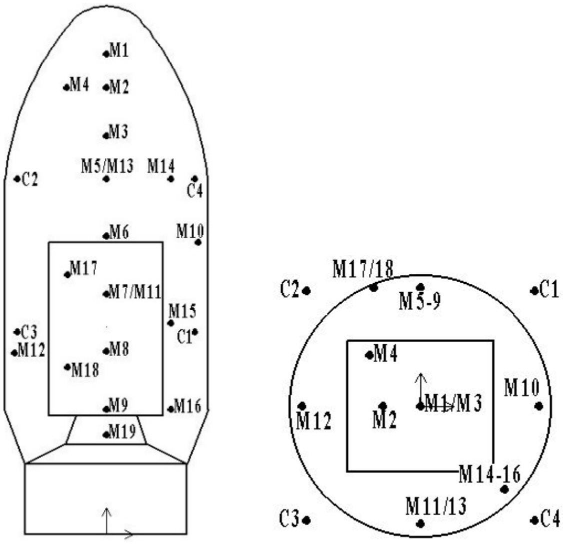



Figure 9: Microphone locations

Table 2: Reverberation chamber incentives SPL (octave)

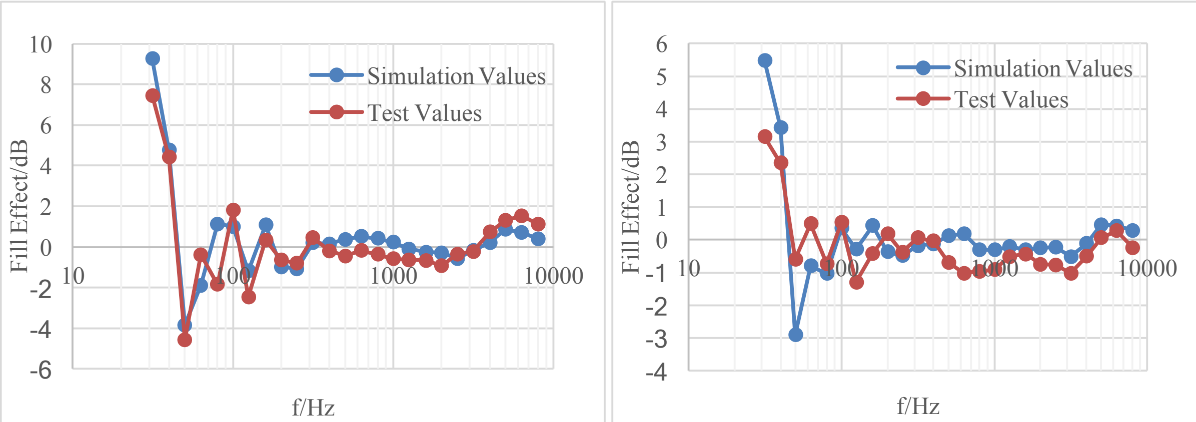
| Frequency/Hz | Sound pressure level/dB | | Frequency/Hz | Sound pressure level/dB | |
|---|---|---|---|---|---|
| | 141.5 | 146.5 | | 141.5 | 146.5 |
| 31.5 | 120.5 | 125.5 | 630 | 128.4 | 133.4 |
| 40 | 123.6 | 128.6 | 800 | 125.3 | 130.3 |
| 50 | 123.5 | 128.5 | 1000 | 123.4 | 128.4 |
| 63 | 126.5 | 131.5 | 1250 | 124.3 | 129.3 |
| 80 | 129.6 | 134.6 | 1600 | 124.1 | 129.1 |
| 100 | 133 | 138 | 2000 | 123.2 | 128.2 |
| 125 | 134.2 | 139.2 | 2500 | 121.1 | 126.1 |
| 160 | 128.8 | 133.8 | 3150 | 120.6 | 125.6 |
| 200 | 127.3 | 132.3 | 4000 | 118.9 | 123.9 |
| 250 | 128.3 | 133.3 | 5000 | 117.5 | 122.5 |
| 315 | 129.3 | 134.3 | 6300 | 117.6 | 122.6 |
| 400 | 129.2 | 134.2 | 8000 | 118.2 | 123.2 |
| 500 | 131.3 | 136.3 | | | |

# 4. RESULTS ANALYSIS AND DISCUSSION

## 4.1 Simulation and Test Results Comparison

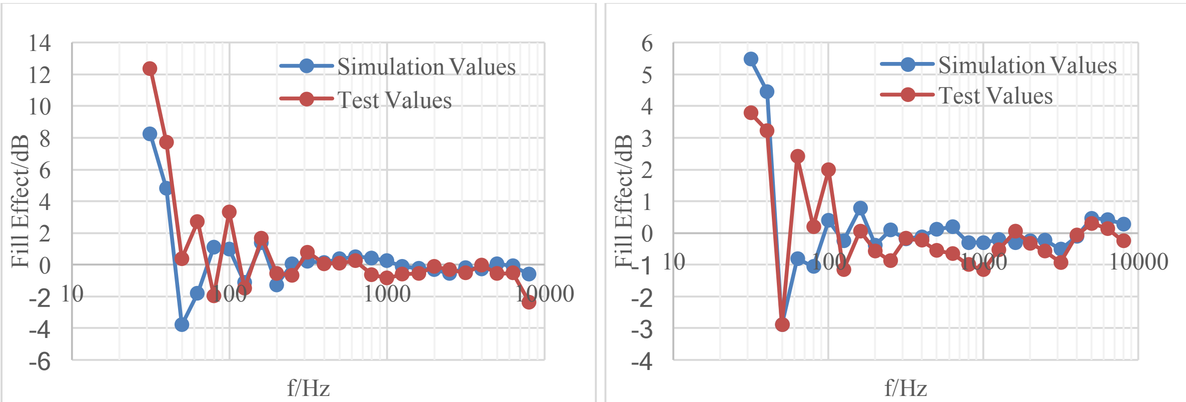
During a rocket launch, the main problem concerned is the sound field environment around the payload. So the way to figure out fill effect here is to minus the SPL in the empty fairing on basis of the SPL in the fairing filled with payload, all the SPLs are averages of the cavity as high as the payload. The differences obtained are fill effects. They are shown in Fig. 10 and Fig. 11. It is seen that the simulation data agrees with the experimental data well. On the other hand, it is illustrated that

SPL changes inside the fairing due to payload filling are extremely obvious, especially at lower frequencies, which will impose additional acoustic loads to the fairing, the payload or other devices and accelerate structural damages.




(a) Fill effect comparison of large payload (b) Fill effect comparison of small payload

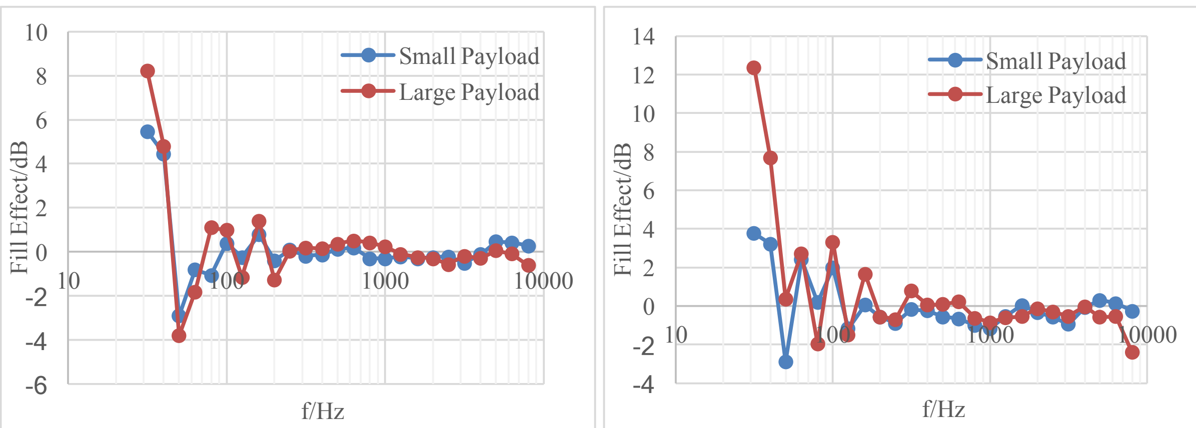
Figure 10: Fill effect comparison of total SPL 146.5dB




(a) Fill effect comparison of large payload (b) Fill effect comparison of small payload

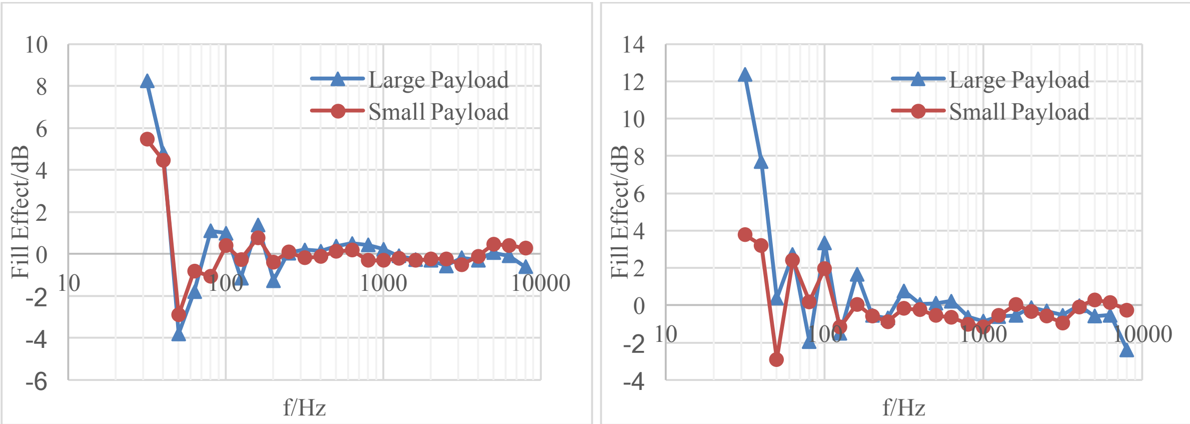
Figure 11: Fill effect comparison of total SPL 141.5dB

It is demonstrated in NASA standard that different payload fill factor causes different fill effects. The fill effect comparison of the two payloads are summarized in Fig. 12 and 13, as we can see, the values of the large payload with a bigger fill factor are almost larger. The fill effect difference from simulation result is 4dB, while it is up to 8dB from test result. That shows the difference caused by the payload fill factor change is significant, which is possibly a factor that we must take into account and use different criteria in structure design of various payloads.




(a) Comparison of simulation values (b) Comparison of test values

Figure 12: Fill effect comparison of total SPL 146.5dB




(a) Comparison of simulation values (b) Comparison of test values

Figure 13: Fill effect comparison of total SPL 141.5dB

### 4.2 Analysis of Acoustic Natural Frequency Shifts

To study the mechanism and characteristics of fill effect, the coupled acoustic modes of the clearance gap cavity between the fairing and payload are analyzed. Table 3 presents the first ten natural frequencies of the gap cavity under different conditions. It is seen that new modes appear between the second (22.4669Hz) and the third mode (42.2256Hz) of the empty fairing duo to the payload fills in. Meanwhile, the original 3st~5th modes(42.2256Hz,48.7379Hz,48.7493Hz) are also changed to low frequency due to payload filling. That's why the fill effect curves of two payloads have a negative valley at 50Hz.

Table 3: First ten natural frequencies of the gap cavity under different conditions

| Number \ Payloads | No Payload | Small Payload | Large Payload |
|---|---|---|---|
| 1 | 0.0001 | 0.0001 | 0 |
| 2 | 22.4669 | 21.995 | 20.772 |
| 3 | 42.2256 | 39.076 | 36.773 |
| 4 | 48.7379 | 40.668 | 38.601 |
| 5 | 48.7493 | 41.385 | 41.380 |
| 6 | 56.5653 | 54.341 | 52.261 |
| 7 | 56.5770 | 54.500 | 52.651 |
| 8 | 60.0886 | 59.644 | 57.330 |
| 9 | 70.4134 | 67.118 | 64.408 |
| 10 | 70.4464 | 67.551 | 65.363 |

## 5. CONCLUSIONS

In this paper, the numerical analysis models for a large fairing with a payload are established using FE-BEM and SEA method to obtain the fill effect of payloads. The fill effects of payloads with different fill factors are studied and analyzed. Numerical and test results show that the fill effect is more obvious at low frequencies than that at high frequencies. Meanwhile, acoustic natural frequency shift happens at low frequency around 50 Hz. This shift causes a negative valley of the fill effect curves of the fairing with a small or a large payload. Because different fill factor results in different frequency shift ratio, the fill effect is more obvious with a large payload than a small payload.

## ACKNOWLEDGEMENTS

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