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Piecewise Bilinear Characteristics of Acoustic Mode In Dual Pulse Solid Rocket Motor Combustion Chamber

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ABSTRACT

Based on the telemetry data of flight tests, the axial abnormal oscillation with frequency doubling characteristics occurred at the end of the first pulse motor's operation while it was normal during the second pulse. With detailed analysis, it was concluded that there was a resonance, the spacecraft structure and the combustion chamber's acoustic cavity spectra are qualitatively similar, exhibiting a unique peak at the resonance frequency. In order to study the acoustic modal characteristics of the dual pulse solid rocket motor comprehensively, a standard model for estimating the acoustic mode of the motor was established by means of simulation and experiment at room temperature. Moreover, based on the law of grain motion and the state frozen method, 3D model of the acoustic cavity was rebuilt accurately, which was provided to the analysis. According to the model above, the acoustic mode's piecewise bilinear characteristics during motor's operation was proposed completed. With the comparison, it was known that there was a good agreement between simulation and flight test at the end of first pulse operation, which proved that the model established was correct. Consequently, it is considered that the results in this paper can characterize the real change process of the acoustic modes during the motor's whole operation.

Keywords: Dual pulse solid rocket motor; Combustion chamber; Acoustic mode; Piecewise bilinear

1. INTRODUCTION

Recently, in order to improve the spacecraft's control performance, viability and propulsive range, dual pulse solid rocket motor has gradually become the main power device of spacecraft(1). Usually, the motor consists of two burning chambers, separated by a bulkhead, designated as pulse separation device which achieves the restarting operation and provides intermittent thrust. Actually, the pulse separation device protects the propellant grain in the second pulse chamber against high temperature and pressure impact during the first pulse operation. At initiation of the second pulse, pulse separation device reliably opens for gas flow through the empty first pulse chamber and the nozzle to atmosphere.

Based on the telemetry data of flight tests, the axial abnormal high frequency oscillation occurred at the end of first pulse operation while it was normal during the second pulse. One of remarkable feature of the data was the large number of resonant peaks observed. As many as 20 peaks can be seen in one configuration over the 200Hz to 5kHz frequency range. In fact, the structural mode of spacecraft remained basically unchanged at the above moments, but the acoustic cavity of the motor combustion chamber changed greatly due to the complex structure of motor. Although several possible causes for the observed vibrations were suggested, it seemed that the most likely cause was combustion-driven acoustic wave in the motor. As shown in Figure1, the resonance between the spacecraft structure and the combustion chamber's acoustic cavity has occurred at a frequency of 225Hz. To date, the vibrations are not known to have prevented completion of the spacecraft's mission but there is concern that minor changes in one or more parameters which occasionally occur during a motor's production history may increase the vibration level and consequently interfere with some vital function such as

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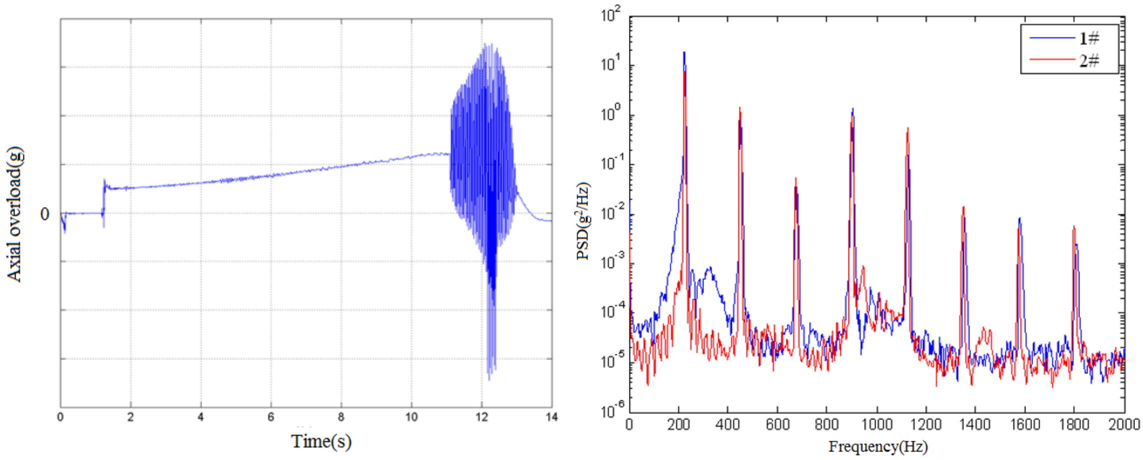
guidance or thrust termination. Compared with traditional one pulse motor, dual pulse motor has more complex acoustic structure, which makes it difficult to study its dynamic characteristic. However, because of the complex situation, little insight had been gained concerning the mechanisms involved.



(a)Time evolution of the Axial overload (b) Frequency domain of the response signal

Figure-1 Vibration data of flight test

Therefore, a series of investigations was initiated to the acoustic characteristics of the interior of the motor by some scholars. Browning carried out acoustic tests on the Minuteman II Stage III motor and obtained the sound pressure distribution in the combustion chamber(2). Mathes carried out the acoustic modal analysis of the 1/4 full scale model of the Poseidon second stage motor, and the experimental data were in good agreement with the numerical simulation (3). Francois determined the acoustic mode of the test motor and estimated the stability range of the motor (4). Anthoine obtained the first three order acoustic modes of the 1/15 scale model of Ariane-5 MPS P230 booster combustion chamber through experiments(6).French took the standard stability prediction program SSP to estimate the tangential acoustic modes of motor(6). Nicoud proposed a numerical method for determining the thermoacoustic modes of combustors, which was verified by two specific cases (7). Zhang Xiangyu grained the acoustic modes of solid rocket motor by simulation and made some comparison between the simulation and the flight test (8). Zhou Xinxin used acoustic resonance simulation method to investigate the acoustic response of combustion chamber acoustic cavity (9). Most attention was pay on the acoustic mode of traditional solid rocket motors under subscale or cold-flow condition, but not including the acoustic modal characteristics during the motor’s operation. So far, there were few research on the acoustic mode of dual pulse solid rocket motor during working process.

In this paper, numerical simulation under the state of the end of first pulse and second pulse operation were carried out. The experiment was designed to determine the frequencies and structural characteristic of standing acoustic wave in the motor. The first three axial acoustic natural frequencies and mode shapes were obtained by the test under room temperature, which proved the finite element model established was correct. Therefore, it was employed as standard procedure for analysis. Then, combined with the law of grain motion and the "state frozen" method, the evolution law of the motor acoustic cavity with time was presented, which leading to the accurate 3D model of the motor at specific moments. By taking advantage of the model established above, the piecewise bilinear characteristics of acoustic mode in dual pulse solid rocket motor was proposed, which has great significance on the cooperative design of motor and spacecraft.

2. Theoretical Background

2.1 Physical hypothesis

In order to solve the wave equation in the combustion chamber of solid rocket motor conveniently, the mass conservation, momentum conservation, energy conservation and equation of state in the combustion chamber are linearized. The simple harmonic sound field in the combustion chamber can be described by Helmholtz equation as follows (10):

$$\nabla^2 P + (\omega^2 / a_0^2) P = \tag{1}$$

Here, ∇^2 is Laplace operator; P is sound pressure; ω is angular frequency; a_0 is sound velocity. Assuming that the acoustic space consists of a finite number of elements, the gas vibration equation in a closed cavity can be obtained based on Equation (1).

$$\left([\boldsymbol{K}] - \omega^2 [\boldsymbol{M}]\right)\{P\} = 0 \tag{2}$$

Here, $[\boldsymbol{K}] = \sum_{e=1}^{m} [\boldsymbol{K}]^e$; $[\boldsymbol{M}] = \sum_{e=1}^{m} [\boldsymbol{M}]^e$; m is the total number of gas elements, $[\boldsymbol{K}]^e$、$[\boldsymbol{M}]^e$ are the stiffness and mass matrices of the system respectively, they are all real symmetric matrices of n×n. The necessary and sufficient conditions for the solution of Equation (1) are as follows, and it gives the natural frequencies of each order of the enclosed cavity.

$$\left\|[\boldsymbol{K}] - \omega^2 [\boldsymbol{M}]\right\| = 0 \tag{3}$$

The actual pressure oscillation in solid rocket motor combustor may be the result of combination of one or more modes, or the superposition effect of high-order harmonic oscillation. These factors lead to complex waveforms, and the main acoustic mode often controls the development trend of oscillating combustion in combustor. For a typical cylindrical combustor chamber with radius R and length L, the axial acoustic frequency is:

$$f_{\text{acoustic}} = \frac{na}{2L} = \frac{n \cdot \sqrt{\gamma R_g T}}{2L} \tag{4}$$

Here, n is the acoustic mode number; γ is the specific heat ratio; R_g is the average gas constant; T is the gas temperature; L is the length of the acoustic cavity.

3. Numerical simulation

3.1 Physical hypothesis

Considering the limitation of the test facility, the simulation analysis was carried out under the static conditions. The physical hypothesis was shown as follow:

1) Grain is a surface dense material without considering its damping effect.

2) The structural stiffness of motor case is relatively large, and the acoustic-solid coupling problem is neglected.

3) The influence of gas flow in combustion chamber is not considered.

3.2 Finite element model

The fluid property density and sound velocity in the acoustic chamber are defined as follows: $\rho = 1.225\,\mathrm{kg/m^3}, a = 340\,\mathrm{m/s}$.The three-dimensional model of the motor under first pulse and second pulse condition was established by using tetrahedral mesh, as shown in Figure 1 and 2. The mesh size is controlled within 50 mm, which ensures the calculation accuracy. The three-dimensional model of the chamber of one pulse combustor consists of 93 012 units while the model of the chamber of second pulse consists of 121 404 units (11).

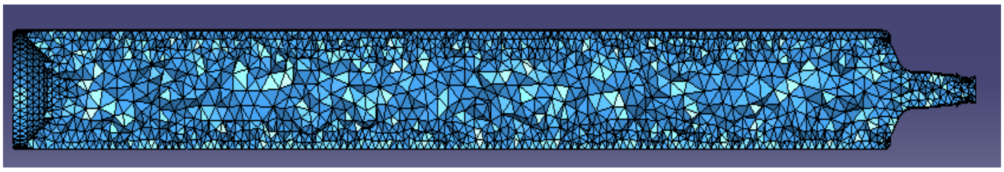


Figure 1–The chamber acoustic field model of first pulse motor

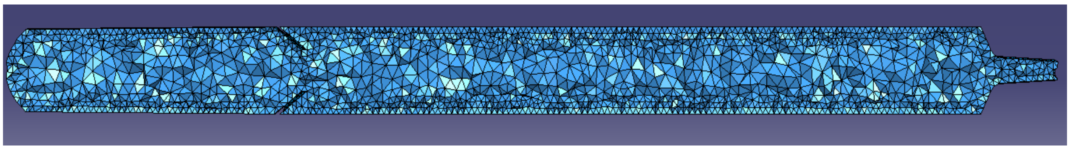


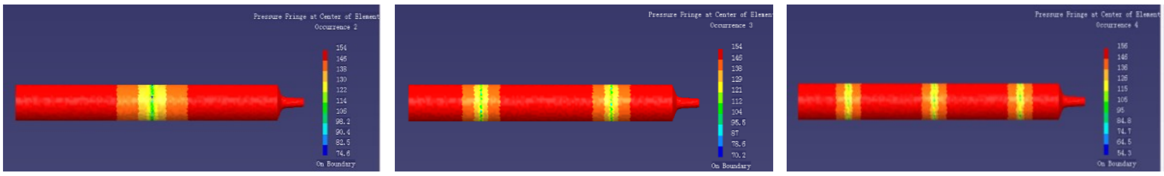
Figure 2–The chamber acoustic field model of second pulse motor

3.3 Simulation results

Based on LMS.virtullab, the estimated natural frequencies and mode shapes of the motor under different conditions were obtained, as shown in Table1 and Figure 3 and 4.

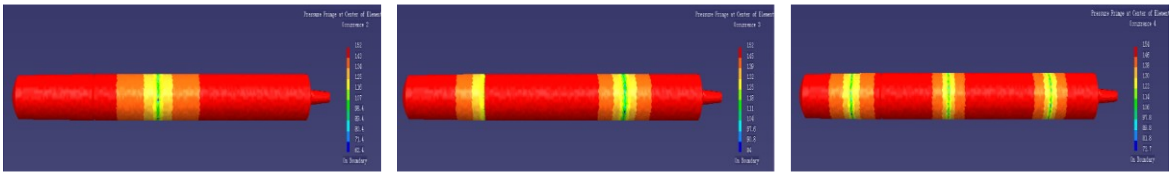
Table 1–Results of the stimulation

State	Order	Result, Hz
First pulse	1	69.13
	2	138.17
	3	206.99
Second pulse	1	47.49
	2	92.13
	3	145.20



(a)first order (b)second order (c)third order

Figure 3–Mode shapes of the first pulse motor



(a)first order (b)second order (c)third order

Figure 4–Mode shapes of the second pulse motor

4. Test

4.1 Test instrument

Figure 5 shows the test instrument which consists of horn, microphone, electric horn and conduit. The electric loudspeaker horn is first extended from the nozzle into the combustion chamber as an excitation source to generate sound field. The signal generator generates random white noise electric signals. After power amplifier treatment, the electric signal is input into the electric loudspeaker horn to produce sound field, which stimulates the acoustic oscillation in the combustion chamber. Axial wave structural characteristics were determined by moving a microphone along the model axis. The microphone could be used to measure on the model centerline to measure the pressure distribution in a line parallel to the axis of symmetry, give a longitudinal pressure distribution near the model wall. The instrumentation system provided means for detecting the position of the moving probe and for continuously recording the acoustic pressure as a function of position in the motor. At the same time, the sound field level in the chamber is controlled by the power amplifier regulator. The fluctuating pressure signal received by the microphone is transformed and amplified by the microphone power supply and then input into the data acquisition system. After spectrum analysis of the power spectral density of the data acquisition system, the combustion chamber acoustic modal frequency can be obtained.

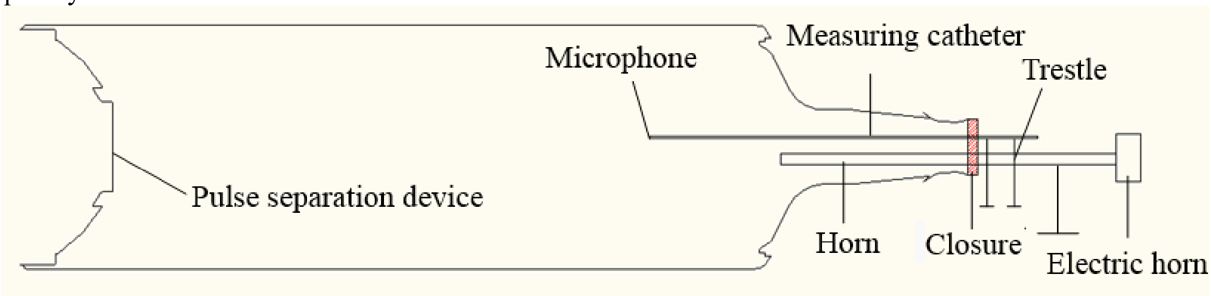
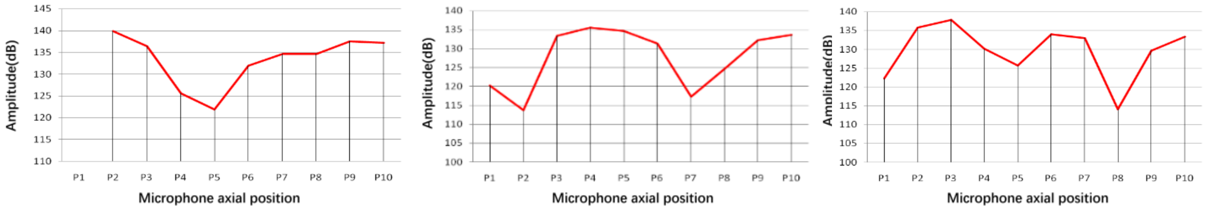


Figure 5–Schematic diagram of the test facility

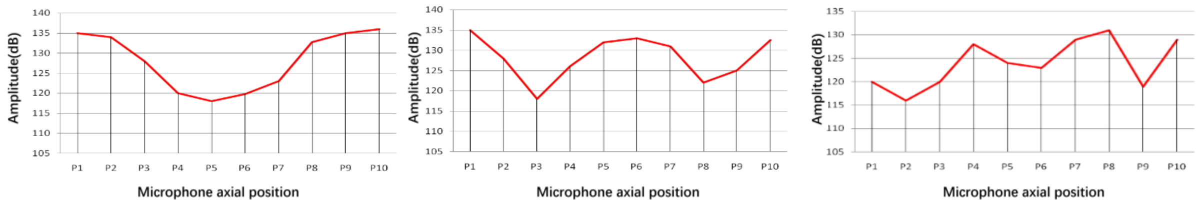
4.2 Test results

By fitting the response amplitudes of each measuring point, the first three order axial acoustic modes were obtained, as shown in Figures 8 and 9. Comparison of simulation-based and experimentally determined frequencies was made in Table 3.



(a)first order (b)second order (c)third order

Figure 8–Mode shapes of the first pulse motor



(a)first order (b)second order (c)third order

Figure 9–Mode shapes of the second pulse motor

Table 3–Summary of the above results

State	Order	Test, Hz	Simulation, Hz	Error,%
First pulse	1	70.0	69.13	1.24
	2	140.0	138.17	1.31
	3	209.5	206.99	1.20
Second pulse	1	48.5	47.49	2.08
	2	93.0	92.13	0.94
	3	147.0	145.20	1.23

From table 2,it was clear that the test results showed good agreement with the corresponding ones obtained from the FEM, the error between them was only 0.94%~2.08%, which proved the FEM model established was reliable.

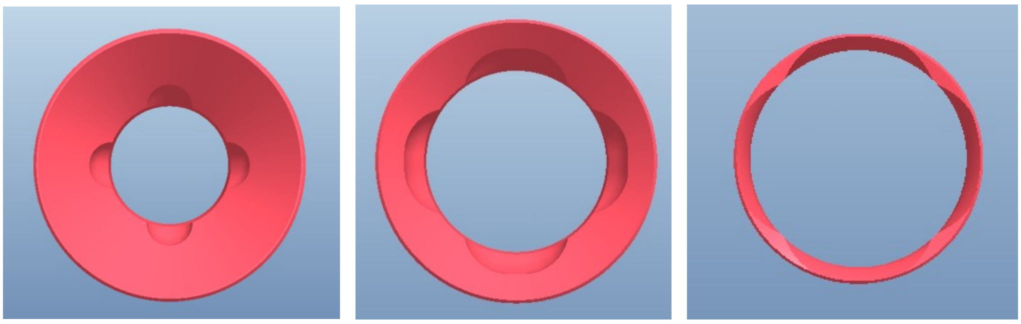
5. Modal analysis of motor's operation

5.1 Acoustic Mode Determination

According to the classical acoustics theory (12), it's well known that the acoustics mode of combustion chamber is only related to motor's geometric variables and gas property. Based on the acoustic modal test of motor at room temperature, the simulation model adopted in this paper is so reliable that it is capable of estimating the acoustic modal characteristics during the motor's operation.

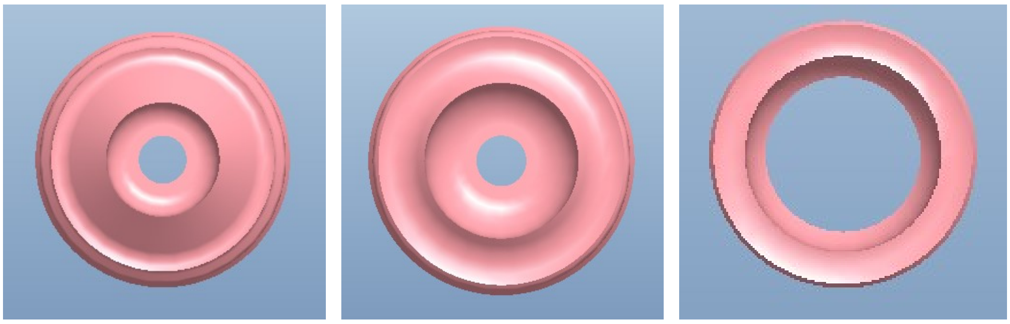
On the basis of test results, it was obvious that the acoustic modal frequency was generally large. That means, its response period was far shorter than the solid propellant burning's. Based on the above analysis, some characteristic moments during working process were chosen by the "state frozen" method which was generally considered from the time-varying system point of view as an operational method, so the 3D model of the motor at specific time were rebuilt respectively(13).

Due to the steady cavity volume variation during the working process, 5 characteristic time points, each interval of 2 seconds, were selected respectively. Then, instantaneous propellant grain shapes of the motor were obtained by the specialized software which could accurately calculate the scale change of grain during the working process, so the 3D model of the motor at specific time were rebuilt, as depicted in Figure 9.Finally, the complete 3D model of the motor during working process was established, regarded as the basement for analysis.



(2s) (6s) (10s)

First pulse's operation



(2s) (4s) (6s)

Second pulse's operation

Figure 9–Time evolution of the motor's grain scale

For the sake of simplicity, combined with the frequency doubling characteristics of the acoustic modes, it is more effectively to study the change of the fundamental frequency of the acoustic modes to illustrate the change of the acoustic modes during motor's operation. Therefore, according to the above 3D model at specific time, combined with the important attributes such as gas property, the standard model is used to analysis the acoustic frequencies. However, the classical method neglects the natural frequency variation caused by the structure change during its operation so that there is a certain error for the actual frequency prediction of the motor. In order to emphasize the accuracy of this method, it was given in Figure 10, compared with the classical case.

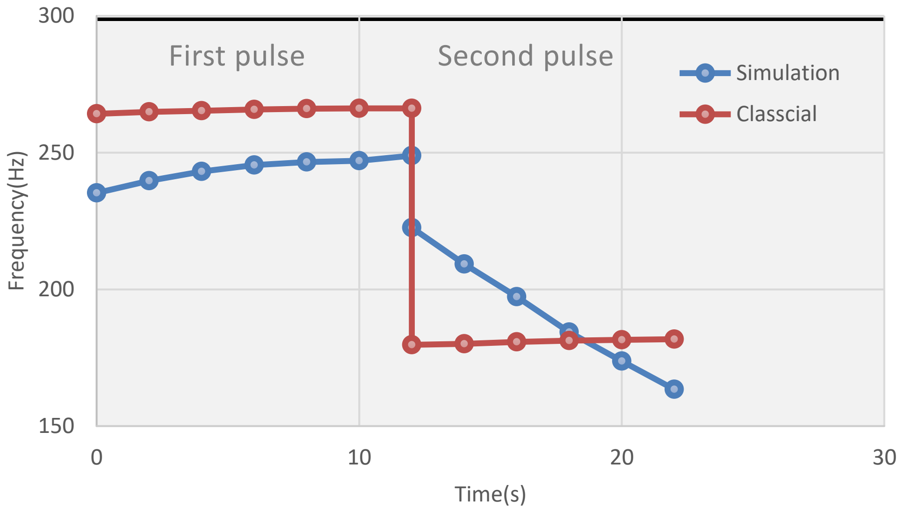


Figure 10–Time evolution of the frequency

5.2 Results and discussions

As indicated by figure 10, the axial acoustic modes of the motor shows piecewise linearity during the motor's operation. The main reason is that the opening of the pulse separation device makes the acoustic cavity of first pulse chamber and second pulse chamber interconnected so that the axial internal geometry of the combustor increase significantly, resulting in the frequency drop at the beginning of the second pulse motor's operation. Besides, it can be seen that the error between simulation and test is less than 10% whereas the error between classical method and test is about 20%. This might be explained by the fact that the simulation model is an accurate configuration of motor's acoustic cavity based on the law of grain motion. As a result, there is a great difference between the method presented in this paper and classical one, whose change in the acoustic frequency almost keeps a constant trend.

It is well known that when the solid rocket motor is working, all the burning surface moves along its normal direction at the same speed, leading to the increase of inner diameter of the grain. At the beginning of the first pulse motor's operation, the initial inner diameter of the grain is close to that of the nozzle. During the motor's operation, the configuration of acoustic cavity changed from the original slender tube to the cylindrical cavity, so the equivalent length of acoustic cavity decreased gradually, which results in the slow increase of the fundamental frequency of acoustic mode.

During the period of second pulse, this is no longer the case. Actually, it was interesting to note that the fundamental frequency decreases monotonously with time while the degree of variation is greater than that of first pulse. These results suggest a link between the pulse separation device and acoustic cavity. In fact, at the beginning of the second pulse motor's operation, the sudden change section effect of the pulse separation device produces a large acoustic load affecting the refraction and reflection of the acoustic wave in the combustion chamber, which reduces the efficiency of acoustic wave transmission and increases the path. It can be considered that the equivalent length of the acoustic cavity increases gradually, so the fundamental frequency of the acoustic mode decreases monotonously.

According to the standard model, the results of acoustic frequencies during operation are obtained. The error between simulation and flight test at the end of first pulse is less than 10%. According to the existing physical parameter errors and the influence of distributed combustion on the gas temperature, it is considered that the present model is actuate and reliable to estimate the acoustic modal characteristics during dual pulse motor's operation.

6. CONCLUSIONS

In this paper, the acoustic investigation is a follow-on to phenomena seen in the motor, which provide a valuable guide. In the present case, the acoustic modes of the dual pulse solid rocket motor were investigated by numerical simulation and experiment. Comparison of experimental results with simulation indicates that the simulation does a reasonably good job of predicting the acoustic characteristics of a cavity with complicated geometry under the end of first pulse and second pulse motor's operation. Furthermore, a procedure capable of tracking the actual modal characteristics variation during motor's operation was presented. The procedure took advantage of the law of grain motion and "state frozen" method, then the 3D model of the motor during its operation was rebuilt accurately, which was provided to the modal analysis, consequently, the standard model was established.

Based on the standard model, the piecewise linear characteristics of motor's acoustic modes were grained and in deep analysis. Combined with the flight test, it is certainly that the method presented shows a greatly improved prediction accurate about the axial acoustic modes determination in dual pulse solid rocket motor combustion chamber. The result of such analysis provide a useful guide for study of motor instability as well as the cooperative design of motor and spacecraft.

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