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Nonlinear Combustion Instability Analysis of Solid Rocket Motor Based on Experimental Data

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Abstract : Combustion instability in solid rocket motors is a long-term open problem since the first rockets were used. Based on the numerous previous studies, it is known that the limit cycle amplitude is one of the key characteristics of the nonlinear combustion instability in solid rocket motors. Flandro's extended energy balance corollary, aims to predict the limit cycle amplitude of complex, nonlinear pressure oscillations for rockets or air−breathing engines, and leads to a precise assessment of nonlinear combustion instability in solid rocket motors. However, based on the comparison with experimental data, it is revealed that the Flandro's method cannot accurately describe such a complex oscillatory pressure. Thus in this work we make modifications of the nonlinear term in the nonlinear wave equations which represents the interaction of different modes. Through this modified method, a numerical simulation of the cylindrical solid rocket has been carried out, and the simulated result consists well with the experimental data. It means that the added coefficient makes the nonlinear wave growth equations describe the experimental data better.

Key Words : Nonlinear combustion instability, Solid rocket motor, Limit cycle, Numerical simulation, Experimental data

1. Introduction

Combustion instability in solid rocket motors (SRMs) is a long-term open problem since the first rockets were used [1]. It is one of the major problems that trouble the designers and that obstruct the development of SRMs. This phenomenon has cost the SRM industry lots of money and work time due to its serious impact on the state of the SRM [2].Thus this problem attracts significant attentions and becomes a subject of intensive studies. Many approaches and theoretical models have been developed and applied to explain and predict the phenomenon of combustion instability [3]. This phenomenon has cost the SRM industry lots of money and work time due to its serious impact on the state of the SRM. Based on the numerous previous studies, it is known that the limit cycle amplitude is one of the key characteristics of the nonlinear combustion instability in solid rocket motors [4]. It is assumed that the pressure oscillation in the chamber is a superposition of all harmonics with varying amplitude [5]. As the pressure oscillation grows from the small disturbance or triggering amplitude to the finite amplitude, the energy coming from unsteady combustion cascades from low to high modal components [6].

Flandro's extended energy balance corollary aims to predict the limit cycle amplitude of complex, nonlinear pressure oscillations for rockets or air−breathing engines. It is generally accepted that

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Flandro's method leads to a precise assessment of nonlinear combustion instability in solid rocket motors [7-10]. However, based on the comparison with experimental data, it is revealed that the Flandro's method cannot accurately describe such a complex oscillatory pressure.

This paper is focused on making modification of Flandro's method to make it be more suitable to experimental data. Through this modified method, a numerical simulation of the cylindrical solid rocket has been carried out, and the simulated result is compared with the experimental data.

propulsion system for the domestic lunar orbiter[1-2].

2. Numerical method

As described in previous papers of Flandro, the modeling of combustion instability can be broken down into a set differential equations [11-15].

$$\frac{d}{dt}R_m = R_m\alpha_m - A\omega_m\sum_{n=1}^{\infty}\sum_{l=1}^{\infty}R_lR_nE_{mnl} \qquad (1)$$

Where Rm is the amplitude of a given mode, and αm is the linear stability for a given mode, m, which itself is the summation of many individual mechanisms.

The nonlinear wave growth equations in this method can be evaluated by using fourth order Runge-Kutta [16]. The advantage of this method is that the complicated interaction between modes and mechanisms could be solved in 1-D model which takes minutes instead of days as the CFD simulation does. It is often observed from experimental data of the solid rocket motor that the low modes of oscillation have larger amplitudes than the high modes. Furthermore, the mechanism of the wave steepening could be well depicted by this method.

However there are also some cases that this method cannot hold. A cylindrical solid rocket motor experiences the typical nonlinear instability characteristics of triggering, the limit cycle amplitude and mean pressure shift (DC shift). By applying Fast Fourier Transform (FFT) analysis to the experimental data, it can be found that the pressure oscillation is a superposition of more than 15 harmonic modes, and the second mode and third mode of acoustic waves both have larger amplitude than the first mode. Fig.1 is the FFT result of the experimental data, and it just depicts the first six modes. It shows that the third mode has the largest amplitude followed by the second mode while the first mode has the smallest one. Then we applied the Flandro's method to generate the simulations to describe this phenomenon. After adjusting the linear coefficient of each mode for several times, as shown in Fig.2, the difference still exists. When it reaches the limit cycle, the amplitudes of the first three modes have only three kinds of relationships. Fig.2 shows the relationship between the amplitudes of the first three modes. They are R1>R2>R3, R2>R1=R3=0, and R1>R3>R2. The first and the third relations are first mode driving while the second one is second mode driving.

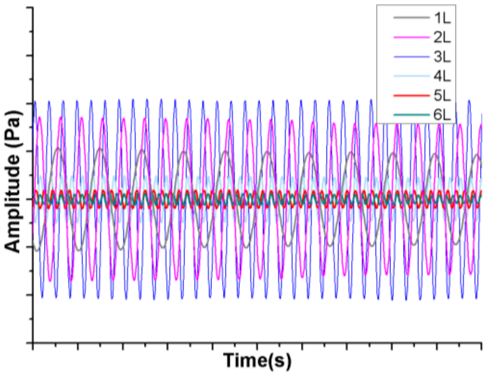
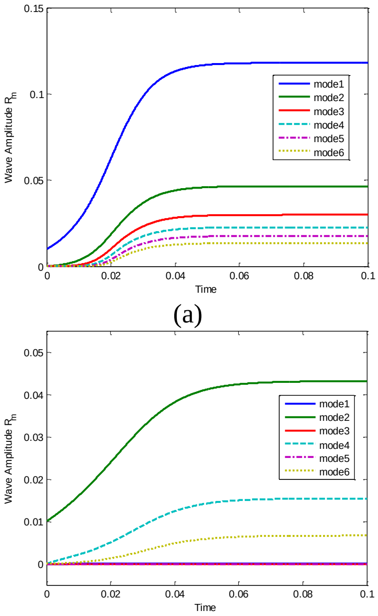
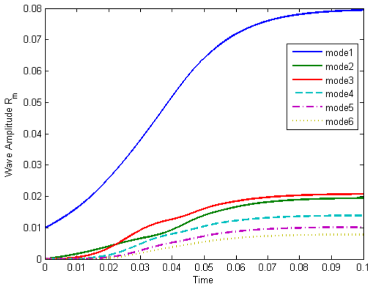


Fig.1 The FFT result of the experimental data



(a)

(b)



(c)

Fig.2 The relationship between the amplitudes of the first three modes ((a) R1>R2>R3, (b) R2>R1=R3=0, and (c) R1>R3>R2)

The main reason of this difference is Flandro's method cannot exactly describe the energy distribution in the realistic situation. As it is in vain to just adjust the linear coefficient, we try to make modifications of the nonlinear terms in the nonlinear wave equations which can show the interaction of different modes. The nonlinear term gives the physics of energy cascading from low modes to high modes. A feedback with an appropriate coefficient is added to the second and third mode nonlinear wave growth equations which mean that there is more energy transferred to the second mode and the third mode. Thus, a coefficient is introduced in the termR_1R_1 in the second mode equation. Then the second mode equation is given below.

$$\frac{d}{dt}R_2 = R_2\alpha_2 - A\omega_1(-16R_1^2 + 4R_1R_3 + 4R_2R_4\cdots) \quad (2)$$

3. Results and Discussions

Through the modified method a numerical simulation of the solid rocket motor is carried out, the result could fits the experimental data better, as shown in. Fig.3. is the Simulation results through the modified method. Comparing to Fig.1, it agrees better consists with the experimental result. The third mode has the largest amplitude followed by the second mode while the first mode has the smallest one.

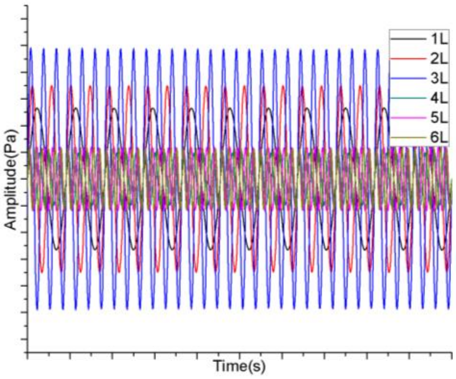


Fig.3 Simulation results through the modified method

When the limit cycle is achieved, the energy transferred out of the first mode is equal to the energy entering it due to the linear excitation, α1. And the most energy out of the first mode is transferred to the second mode and the third mode. However the second mode gets energy not only from the first mode but also from the nonlinear term R_1R_1, which reflects the unsteady combustion, and hence the amplitude of the second mode becomes higher. Subsequently, the amplitude of the third mode increases. Then, we believe that there is some certain nonlinear mechanism existing which could transfer the energy to the second mode. It seems that this mechanism has some correlations with both the frequency and the amplitudes of the first three modes.

4. Conclusions

Combustion instability troubles designers of SRMs. There is a SRM experiencing nonlinear combustion instability and its pressure oscillation cannot be predicted by Flandro's method. We make modification of the nonlinear term in the nonlinear wave equations. The added coefficient makes the nonlinear wave growth equations more suitable for data analysis of the experimental SRM. The calculated results agree well with the experimental data. In order to make the nonlinear wave growth equations suitable for more complex pressure oscillations, a universal expression for the coefficient should be developed.

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