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Effects of gas temperature on nozzle damping experiments on cold-flow rocket motors

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ABSTRACT

In order to explore the impact of gas temperature on the nozzle damping characteristics of solid rocket motor, numerical simulations were carried out by an experimental motor in Naval Ordnance Test Station of China Lake in California. Using the pulse decay method, different cases were numerically studied via Fluent along with UDF (User Defined Functions). Firstly, mesh sensitivity analysis and monitor position-independent analysis were carried out for the computer code validation. Then, the numerical method was further validated by comparing the calculated results and experimental data. Finally, the effects of gas temperature on the nozzle damping characteristics were studied in this paper. The results indicated that the gas temperature had cooperative effects on the nozzle damping and there had great differences between cold flow and hot fire test. By discussion and analysis, it was found that the changing of mainstream velocity and the natural acoustic frequency resulted from gas temperature were the key factors that affected the nozzle damping, while the alteration of the mean pressure had little effect. Thus, the high pressure condition could be replaced by low pressure to reduce the difficulty of the test. Finally, the relation of the coefficients "alpha" between the cold flow and hot fire was got.

1. Introduction

Since World War II, researchers have been working on the presence of undesired oscillations in a combustion chamber. It occurs in all combustion devices, including rockets (liquid, hybrid, and solid), turbojets (combustors and augmenters), ramjets, scramjets, and others. These phenomena can cause mechanical failure, interference with the control and guidance systems. In the serious condition, it can result in motor or mission failure [1,2]. Thanks to forty years of iterative research by Culick [3–9], Yang [6,7,10], Cantrell [11], Hart [11–13], and many others, the underlying linear theory is put forward to predict the tendency for a solid rocket motor whether or not to become unstable. The stability of the motor can be evaluated by the total effect of the driving mechanisms and damping mechanisms [14]. The driving mechanisms that tend to increase the energy of the flow disturbances and thus exert a destabilizing influence upon the motor mainly result from pressure coupled response, vortex shedding, distributed combustion, etc. While the damping mechanisms tending to dissipate the energy of the flow disturbances and thus exert a stabilizing influence on a motor are nozzle damping, particle damping, mean flow/acoustic interactions and structural damping and so on. If the gain factor exceeds the loss factor, the motor turns to be unstable. A pressure disturbance can be enlarged and then the serious combustion instability occurs. Thus, increasing the total damping and eliminating the initial driving sources are the effective methods to suppress combustion instability. As is known to all, the nozzle damping contributes nearly 50% of the acoustic energy loss to the solid rocket motor [15], which is the largest damping mechanism of longitudinal instability. When the acoustic waves contact the nozzle throat section, some of the acoustic energy is transmitted and radiated out of the nozzle. So the evaluation of the nozzle damping characteristics is of great significance in linear prediction of combustion instability.

Researchers have been working on the nozzle damping for more than half a century. The theoretical calculation of the nozzle is a difficult gas dynamical problem, which requires the solution of the mathematically complex system of conservation equations describing the behavior of the flow oscillations in the convergent section of a choked nozzle. Available theoretical treatments for computing the nozzle admittance are complex in nature. To date, solutions have been obtained only for a limited number of cases. Tsien [16] firstly studied the response of a choked nozzle under the influence of axial pressure and velocity perturbations

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superimposed upon the steady mean flow. He provided the analysis of the transfer function of rocket nozzles, however, his studies are restricted to the limiting cases of very high and very low frequency oscillations. Later, Crocco [17,18] extended Tsien's work to include the entire frequency range, and introduced the concept of admittance to study the influence of the nozzle on the flow oscillations. In 1967, he extended his earlier analysis to consider the admittances of choked nozzles with three-dimensional flow oscillations. On the basis of previous studies, B.T. zinn [19,20] analytically investigated the wave energy flux loss through nozzle entrance and discussed the relationship between wave energy flux loss and motor stability. Marble and Candel [21] (1977) offered an analytical relation for admittances of short nozzles. It can be used to describe the stability of a nozzle depending on the Mach number. Stow [22] et al. (2002) investigated the small perturbations of choked flow through a annular nozzle. Moase [23] et al. (2007) extended the research work of Marble and Candel and systematically investigated the linear and nonlinear response of compact chocked nozzles to flow perturbations. Recently, Duran and Moreau [24,25] (2013) presented a method to analytically evaluate the acoustic damping of nozzles.What's more, there are several experimental techniques that could be used to determine the damping capabilities of a nozzle. Such as the direct [26], wave-attenuation [27,28], half-power band width [27], and standing wave methods or modified impedance tube technique [29–31]. All of these methods have been carried out to test the solid rocket motor nozzle damping characteristics via cold flow. In these cold flow tests, air is used as the fluid in the simulated motor at normal temperatures. But in the true working process of solid rocket motors, the gas temperature in the chamber is very high, which can often reach about 3500 K. So there must be exist a big difference between the cold flow test and the real working condition. And the exploration of the impact on the nozzle damping characteristics is of great significance in linear prediction of combustion instability. But the past research work mainly focused on the cold flow test of nozzle damping and the numerical prediction of nozzle admittance. However, the relationship between cold flow experimental test and hot fire test is scarcely reported.

In this paper, the pulse decay method and the commercial program (FLUENT®) were used to study the gas temperature's effect on nozzle damping characteristics in solid rocket motor. Firstly, mesh sensitivity analysis and monitor position-independent analysis were carried out for the computer code validation. Then, the numerical method was further validated by comparing the calculated results and experimental data. Finally, the effects of gas temperature on the nozzle damping characteristics were studied and discussed in this paper. Both the method and the results can help to familiarize engineers and researchers with the accurate prediction and test of combustion instability phenomenon in solid rocket motors.

2. Theoretical foundation and computational methods

2.1. Problem description

In practice, we often use the coefficient "alpha" α to evaluate the overall stability of solid propellant rocket motors, which describes the rate of growth or decay of a small amplitude oscillation inside the combustor. The value of coefficient "alpha" α determines whether the oscillation will grow or decay with time. If coefficient "alpha" $\alpha > 0$, the amplitude of the small oscillations will increase with time and the motor is unstable. If coefficient "alpha" $\alpha < 0$, the amplitude of the small oscillations will decrease with time and the motor is stable. The coefficient "alpha" α contains the contributions of the various relevant processes, it can be expressed as [14,32,33]

$$\alpha = \alpha_{PC} + \alpha_{VC} + \alpha_{DC} + \alpha_N + \alpha_P + \alpha_{MF} + \alpha_{SD} \tag{1}$$

In Eq. (1), α_{PC}, α_{VC} and α_{DC} are the driving terms due to pressure coupling, velocity coupling and distributed combustion, respectively. α_N, α_P, α_{MF} and $\alpha_{SD}$are the damping terms due to nozzle damping, particle damping, mean flow interactions and structural damping, respectively.

Moreover, the change of acoustic pressure amplitude in a motor can be expressed as an exponential according to linear stability theory that has been successfully used to the prediction of solid propellant rocket motors [32–35]. So The pressure at the head end can be represented in the following way [36]:

$$p(t) = p_0 \sin(\omega.\ t)e^{-\alpha t} \tag{2}$$

where, ω denotes the radian frequency, $\omega = 2\pi f$. α is the attenuation constant after pulse. p_0 is the initial pressure amplitude.

In this text, it is supposed that there is no other source of acoustic energy exists in the chamber, and the acoustic energy consumption of energy due to viscous is ignored. Therefore, the acoustic energy is not affected by other factors than the nozzle itself, and at this time the nozzle is the only factor that can affect the growth or decay of an oscillation inside the combustor, the temporal behavior of the combustor oscillation may he expressed in the following form:

$$p(t) = p_0 \sin(\omega.\ t)e^{-\alpha_N t} \tag{3}$$

According to Eq. (3), the pressure oscillation decays in accordance with an exponential way. Therefore, the nozzle damping decay coefficient can be obtained by plotting the peak-to-peak amplitude-time curve in a logarithmic-time coordinate system. By fitting the line to the plot and calculating its slope, the appropriate decay constant will be determined.

$$\alpha_N = \frac{\ln p_2 - \ln p_1}{t_2 - t_1} \tag{4}$$

As an example, if p_1 and p_2 are the amplitudes at the times t_1 and t_2 on the straight line portion of the logarithmic decay plot, then the decay coefficient is obtained. A typical example is illustrated in Fig. 1.

In addition, in order to confirm the rationality and effectiveness of the numerical methods, a theoretically evaluated formula is adopted [27–30]. It is concluded by many different cold flow experiments. It is recognized at home and abroad.

$$\alpha_N = -\lambda \frac{a}{L} J \tag{5}$$

where, a is the actual speed of sound in motor chamber, L is closed-closed tube length, J is defined as the ratio of the nozzle

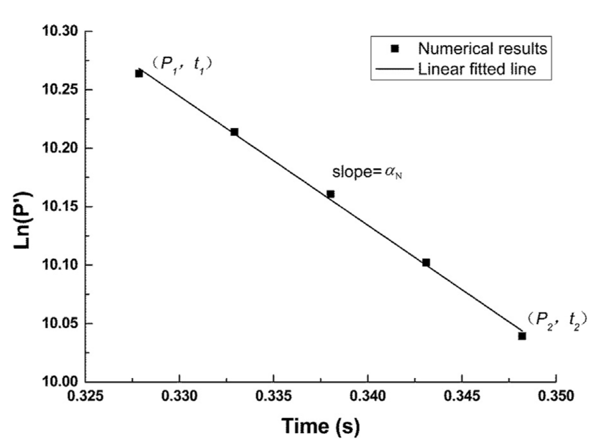

Fig. 1. A typical example of data processing.