Research Article

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Effect of the inner-surface baffles on the tangential acoustic mode in the cylindrical combustor

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Abstract: The combustion instability in a propulsion system is a ubiquitous problem. The radial baffles usually installed on the injector faceplate eliminate the combustion instability (acoustic pressure oscillation) in the propulsion system. In this article, the longitudinal baffles are installed on the inner surface of the combustor wall to control the combustion instabilities. The first-order and second-order tangential modes are induced in the experiments. The effects of the parameters of the baffle on the acoustic pressure oscillation in the cylindrical combustor are investigated. The effect of the combustor nozzle on the tangential modes has been systematically investigated. It is concluded that the eigen-frequency and amplitude of the first-order tangential mode decline with the increase in the longitudinal baffle number and height. For the second-order tangential mode, the eigen-frequency and amplitude monotonically increase until a

maximum value (four baffles), subsequently decrease with the increase in the baffle number and height. The combustor without the nozzle obtains a lower frequency than that with the nozzle, especially for the low baffle height in the combustor.

Keywords: combustion instability, acoustic pressure oscillation, longitudinal baffles, tangential mode, cylindrical combustor

1 Introduction

Performance and stability are two conflicting concerns in the development of new rocket engine combustion. Generally speaking, high-performance engines are prone to encounter combustion instabilities. Culick and Yang [1] thought that the high-frequency combustion instabilities were usually considered as the acoustic pressure oscillations. These undesirable phenomena, especially for the tangential mode of the high-frequency combustion instabilities, may enhance the heat transfer rates or resonance, resulting in the deterioration of the propulsion performance and even severe damage on the injector faceplate and combustor wall of the power-generating devices such as rocket engines, ramjets and turbojet thrust augmentors. To eliminate these undesirable instabilities, some passive control methods such as radial baffles and acoustic cavities were widely applied. However, the acoustic cavities were narrowband absorbers that had to be tuned accurately to separate the acoustic frequencies in the combustor. In contrast, baffles can be easily designed and the narrowband characteristics of the acoustic cavities can be overcome [2]. Investigations show that the combustion instability usually occurs near the injector faceplate [3–5]. Therefore, many researchers have investigated the effect of the radial baffles, which were installed on the injector faceplate (Figure 1), on the acoustic pressure oscillations in propulsion systems [6–8].

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Figure 1: Liquid propellant rocket engine with injector face baffles.

Relevant research studies were first performed by Oberg *et al.* [9]. The results showed that the radial baffles were destabilizing rather than stabilizing. Quinlan *et al.* [10] investigated the effect of the inviscid radial baffles on the acoustic pressure oscillations. Their results also found that the baffles had a destabilizing influence on the acoustic pressure oscillations. Baer and Mitchell [11] developed a linear analysis method to establish the baffle tip energy dissipation model. The model assumed that the symmetric gas flowed on the radial baffles with no flow separation. A general theoretical model for treating both linear and nonlinear acoustic waves in the baffled combustors was developed by Wicker *et al.* [12]. The results clearly showed that the radial baffle length provided a greater impact on the acoustic pressure oscillations than the radial baffle number. Feng *et al.* [13] investigated the acoustic pressure oscillation in the YF-960 rocket engine through the finite-volume method. They considered two different geometric configurations, namely, three and six radial baffles with a circular hub, respectively. All the literature above focused on the theoretical research. Several experimental investigations also gave a valuable insight into the effect of the radial baffles on the acoustic pressure oscillations [14–17]. Earlier experimental investigations were non-reacting. Wieber [18] investigated the influence of the baffle pattern on the acoustic characteristics in a cylindrical combustor with no mean flow. By comparing the acoustic damping in the transverse mode in the unbaffled and baffled combustors, they found that the radial baffles damped much more effectively in the tangential mode than in the longitudinal mode. Torda and Patel [19] investigated the acoustic pressure oscillations in the cylindrical combustor with the radial baffles. Their

experimental results indicated that viscous damping was a possible mechanism of the baffle operation. Laudien *et al.* [20] conducted both cold-flow and hot-flow tests to investigate the effect of the radial baffles on the acoustic pressure oscillation. The results showed that the radial baffle number was very important for suppressing the acoustic pressure oscillation in tangential mode, for instance, an odd baffle number was more effective than an even baffle number. Hannum *et al.* [21] experimentally investigated 17 different baffle configurations for a hydrogen–oxygen engine with 20,000 lbf thrust. Their results indicated that the baffles protected the sensitive combustion zone from the pressure and velocity fluctuation, and a similar experiment was also performed by Vincent *et al.* [22].

In the theoretical and experimental studies cited above, the radial baffles are installed on the injector faceplate in the cylindrical combustor. However, for the RD-0110 engine, the combustion instabilities occur during the engine start-up process. The longitudinal baffles are installed on the combustor wall inner surface to provide the reliability. No general rules have been established to design the inherent stable combustor with the longitudinal baffles. Consequently, it is necessary to investigate the effect of the longitudinal baffles on the acoustic characteristics in the cylindrical combustor. In this article, the longitudinal baffles are installed on the inner surface of the cylindrical combustor wall for cold-flow tests. The effects of the nozzle on the tangential acoustic modes are investigated. The first-order and second-order tangential acoustic modes are experimentally induced in the cylindrical combustor. The effects of the longitudinal baffles on the tangential acoustic modes are experimentally investigated. The effect of the nozzle on the tangential acoustic mode is researched.

2 Experimental model

As shown in Figure 2, an acoustic experimental model using non-reacting flow is built to investigate the tangential acoustic modes in the cylindrical combustor. The model has two parts: the cylindrical combustor (500 mm in length, 250 mm in diameter) and the nozzle (180 mm in length, 250 mm in maximum diameter, 90 mm in minimum diameter), as shown in Figure 3. The baffle length is 350 mm, as shown in Figure 4. The acoustic pressure signals are induced by four loudspeakers installed around the periphery of the faceplate and the acoustic signals are sinusoidal waves, as shown in Figure 3.

Figure 2: Experimental system for acoustic tests.

Figure 3: Longitudinal baffles installed on the combustor wall inner surface.

Figure 4: Longitudinal baffles in the experiments.

Table 1: Parameters

Number	N1	N2	N3	N4	N5	N6	N7
h/mm	20	25	30	35	40	50	60
H/mm	350	350	350	350	350	350	350

Four microphones are uniformly mounted on the cylindrical combustor wall inner surface. The phase difference of the sound pressure signal is 90° , and the sound pressure is 10 Pa. The acoustic pressure signal is received by the microphone sensors near the combustor outlet and collected by the data acquisition system, as shown in Figure 3. The eigen-frequency and amplitude of the tangential acoustic modes are very sensitive to the combustor structure.

The longitudinal baffles are made of stainless steel and attached to the cylindrical combustor model with a rubber O-ring. The parameters of the baffles are shown in Table 1. The air flow is not considered and the inlet and outlet of the combustor are closed in the acoustic test.

3 Tangential mode

In this experiment, the first-order and second-order tangential modes are induced by installing the loudspeaker arrays on the basis of previous research results [23–28]. To preferentially generate the specified tangential mode, the loudspeakers are driven by a phase shift. In

particular, the tangential mode in the cylindrical combustor is obtained by Zhou *et al.* [29].

$$Q = \sum_{\kappa=1}^B e^{i(m+\sigma\frac{B}{2\pi})\frac{2\pi}{B}(\kappa-1)} = \begin{cases} B & m + \sigma\frac{B}{2\pi} = sB \\ 0 & m + \sigma\frac{B}{2\pi} \neq sB \end{cases} \quad (1)$$

$$s = \dots, -1, 0, +1, \dots,$$

where Q is the summation term of a series of exponential functions, B denotes the loudspeaker number, s is an integer and σ is the phase angle of the adjacent loudspeakers.

The relation $m + \sigma\frac{B}{2\pi} = sB$ is satisfied, and the sound pressure can be obtained as [29]

$$p(\vec{x}, t) = -\frac{Be^{i\omega t}}{4\pi} \sum_{s=-\infty}^{\infty} \sum_{n=0}^{\infty} \frac{\phi_{mn}(\kappa_{mn}r)e^{im\varphi}}{\kappa_{mn}} \int_{S(\vec{\xi})} \Delta p \phi_{mn} \times (\kappa_{mn}\vec{r}')e^{-im\varphi'} \left\{ H(Z - \bar{Z}') \left(\frac{m}{r'} - \alpha_1 \frac{\Omega r'}{U} \right) e^{i\alpha_1(Z - \bar{Z}')} \right. \quad (2)$$

$$\left. + H(\bar{Z}' - Z) \left(\frac{m}{r'} - \alpha_2 \frac{\Omega r'}{U} \right) e^{i\alpha_2(Z - \bar{Z}')} \right\} dS(\vec{\xi}),$$

where p is the sound pressure, κ_{mn} denotes the eigenvalues, φ , r and Z denote the source positions in the coordinate system, H is the amplitude of bending vibration, ϕ_{mn} denotes eigenfunctions, Ω is the cascade rotational frequency, U is the mean flow velocity in the axial direction, ω denotes frequency and α is the wavenumber.

$$m = sB - V \quad s = \dots, -1, 0, +1, \dots \quad (3)$$

$$V = B\sigma/2\pi. \quad (4)$$

We take $B = 4$, $s = 0$ and $\sigma = -90^\circ$ to generate the first-order tangential mode ($m = 1$), as shown in Figure 5. We take $B = 4$, $s = 1$ and $\theta = 180^\circ$ to generate the second-order tangential mode ($m = 2$), as shown in Figure 6. Zhou [29] also provided a simple approach with high accuracy for the nonlinear oscillators.

The experimental and theoretical tangential modes are shown in Figures 5 and 6. The phase differences of the acoustic pressure signals of four loudspeakers in the first-order and second-order tangential modes are 90° and 180° , respectively. The theoretical prediction is in consistent with the experimental data. The acoustic pressure oscillations in the cylindrical combustor were dominantly in the first-order and second-order tangential modes.

4 Results and discussion

The acoustic pressure oscillations in the combustor are experimentally investigated in this article. The eigenfrequency and the corresponding acoustic pressure amplitude are obtained by fast Fourier transform, as shown in Figure 7. The acoustic pressure amplitude in the first-order tangential mode is largest, and the corresponding abscissa is the acoustic eigen-frequency. The effect of the first-order tangential mode on the combustion instabilities is the most important.

(a)

(b)

Figure 5: First-order tangential modes in the cylindrical combustor. (a) Experimental first-order tangential mode and (b) theoretical first-order tangential mode.

Figure 6: Second-order tangential mode in cylindrical combustor. (a) Experimental second-order tangential mode and (b) theoretical second-order tangential mode.

Figure 7: Acoustic pressure oscillations in the combustor.

4.1 Effect of the longitudinal baffles on the first-order tangential mode

Figure 8 shows the effect of the longitudinal baffles on the eigen-frequency and amplitude of the acoustic pressure oscillations in the first-order tangential mode. The baffle number and height vary from 3 to 12 and 0 to 60 mm, respectively. As shown in Figure 8, the eigen-frequency and amplitude of the acoustic pressure oscillations in the first-order tangential mode are higher for the unbaffled combustor. When the longitudinal baffles are installed on the combustor wall inner surface, the eigen-frequency and amplitude of the acoustic pressure oscillations in the first-order tangential mode gradually decrease with the increase in the baffle height. In terms of physics,

Figure 8: Effect of the longitudinal baffles on the first-order tangential mode. (a) Effect on the eigen-frequency and (b) effect on the amplitude.

Figure 9: Effect of the longitudinal baffles on the second-order tangential mode. (a) Effect on the eigen-frequency and (b) effect on the amplitude.

as the baffle length increases, the tangential mode gradually becomes longitudinalized within the baffle compartments. The larger height of the baffles is, the stronger the tangential mode becomes longitudinalized. Meanwhile, the baffle number also plays an important role in determining the eigen-frequency and amplitude of the acoustic pressure oscillations in the first-order tangential mode. Those two values decline with the increase in the baffle number.

4.2 Effect of the longitudinal baffles on the second-order tangential mode

The effect of the longitudinal baffles on the second-order tangential mode is shown in Figure 9. The baffle numbers

and heights vary from 3 to 12 and from 30 to 60 mm, respectively. As shown in Figure 9, when three longitudinal baffles are installed on the combustor wall inner surface, all the curves monotonically increase until a maximum is reached, and the curves subsequently decrease with the increase in the baffle number. The largest eigen-frequency and amplitude of the acoustic pressure oscillations in the second-order tangential mode are four longitudinal baffles. In other words, the effect of the four longitudinal baffles on the second-order tangential mode is less. When the baffle numbers are greater than four, the eigen-frequency and amplitude of the acoustic pressure oscillations of the second-order tangential mode decrease with the increase in the baffle heights and numbers.

4.3 Effect of the combustor nozzle on the first-order tangential mode

Figure 10: Effect of the nozzle on the frequency on the first-order tangential mode.

Figure 10 shows the effect of the combustor nozzle on the first-order tangential mode. The effect of the nozzle on the eigen-frequency is obvious, especially for the combustor without the baffles. The combustor without the nozzle obtains a lower frequency than that with the nozzle. When three baffles are installed, the frequency in the first-order tangential mode decreases for with and without the nozzle. However, the effect of the nozzle on the eigen-frequency of the first-order tangential mode gradually diminishes as the baffle height h increases. So the effect of the nozzle on the frequency cannot be ignored, especially for the low baffle height in the combustor.

5 Conclusions

In this article, the effect of the longitudinal baffles that are installed on the combustor wall inner-surface on the eigen-frequency and amplitude of the tangential acoustic modes in a cylindrical combustor with the nozzle is experimentally investigated. Some conclusions can be drawn as follows:

1. The combustor with the baffles can effectively decline the eigen-frequency and amplitude of the first-order tangential acoustic mode. The eigen-frequency and amplitude of the first-order tangential acoustic mode decrease gradually with the increase in the baffle height and number.
2. For the second-order tangential acoustic mode, the eigen-frequency and amplitude monotonically increase first. When the baffle numbers are greater than four, the eigen-frequency and amplitude of the acoustic pressure oscillations of the second-order tangential mode decrease with the increase in the baffle heights and numbers.
3. The combustor without the nozzle obtains a lower frequency than that with the nozzle, especially for the low baffle height in the combustor.

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