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Prediction of stability behaviors of longitudinal and circumferential eigenmodes in a choked thermoacoustic combustor

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ABSTRACT

Many aero-engine and gas turbine combustion systems are in choked configuration. These combustors are more prone to thermoacoustic instability. Thus there is a need to characterize and predict the stability behaviors of the choked systems. In this work, stability analysis of both longitudinal and circumferential eigenmodes in a thermoacoustic system with a choked outlet is performed via two different approaches. One is an analytical method, which describes the choked outlet by using two analytical expressions. The main difference between these expressions is whether a length correction is considered. The other method is a numerical one, which is based on linear Euler equation (LEE). Comparison is then made between the analytical results and the numerical ones. It is found that when longitudinal eigenmodes are considered and the length of the choked nozzle is not small, the analytical expression with a length correction should be used. However, when the flow Mach number is large (>0.1), these analytical expressions can lead to significant errors, especially for the longitudinal eigenmodes at higher frequency. To further validate these methods, they are then applied to predict the stability behavior of circumferential eigenmodes. It is found that the expressions for the choked outlet can be used for the predictions of azimuthal thermoacoustic instabilities. However, non-negligible errors are also brought when the Mach number is large (>0.1).

1. Introduction

In order to reduce NOx emissions from modern gas turbines and aero-engines, lean premixed pre-vaporized (LPP) combustion technology is widely applied by mixing fuel and air more uniformly before combustion. However, combustion/propulsion system with LPP applied is more susceptible to self-sustained combustion oscillations (also known as thermoacoustic instability). The pressure oscillations are so strong that may result in engine structural damages. To enable engines operate safely and stably, intensive research has been conducted in the past few decades to understand the physics of thermoacoustic instability and to develop mitigation methods [1–6]. However, it is difficult to comprehensively understand the fundamental physics of such instability, because the combustion systems involve various and complex processes, such as heat transfer, fluid dynamics, chemical combustion, interaction of flame and acoustic wave, and coupling of acoustic and entropy disturbances at the boundaries [7–12].

CFD methods can be used to simulate thermoacoustic instabilities occurred in combustors [13]. Large eddy simulation (LES) has proven to be a powerful tool. It was reported in Refs. [14,15] that LES was successfully applied to study the stability behaviors of lean premixed swirl-stabilized combustion systems. LES is associated with many advantages. However, it is involved with high computational cost. To reduce computational cost and to predict thermoacoustic stability, new computational methods or theoretical models are needed. Typically, linear prediction methods of thermoacoustic instabilities are used. There are two types of linearized methods. One is low-order model/analytical model (LOM). The other is linearized Euler equation method (LEE). In these linearized methods, eigenfrequencies of the thermoacoustic system are obtained. The real and imaginary parts correspond to the oscillation frequency and the mode growth rate respectively. LOM is associated with low computational cost. However, the accuracy of the eigenvalues depends strongly on the modeling of the heat source and the description of the combustor boundary conditions. In LEE methods, the variations of the flow and cross-sectional area can be taken into account. This enables the boundary condition of a choked end to be calculated directly.

Due to the wide application of choked combustors, it is necessary to know the effect of choked nozzle on the propagation of the

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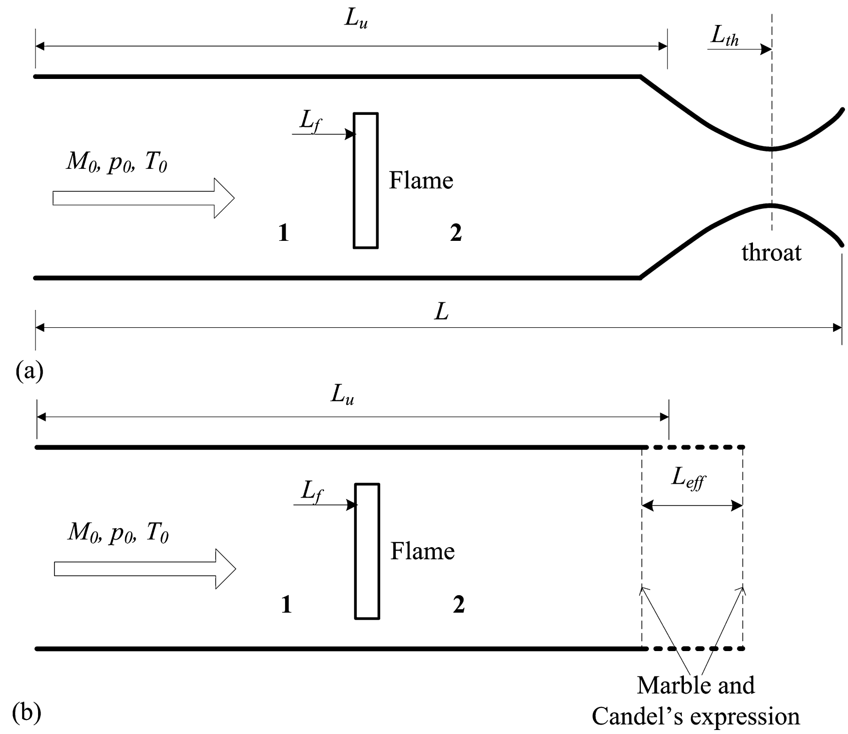

Fig. 1. The numerical configuration of a combustion chamber with a choked nozzle, (a): physical configuration; (b): simplified configuration with simplified boundary conditions.

disturbances, i.e., reflection and/or transmission of acoustic waves and entropy waves. Several groups of researchers have attempted to study this problem in the absence of heat sources. The general idea is to simplify LEE in the domain of a choked nozzle first. Then asymptotic or numerical solutions are obtained. Tsien [16] might be the first one studying the acoustic characteristics of a choked nozzle. By assuming a linear velocity distribution approximate solutions for small and large frequencies were obtained. Candel and Marble [17] then obtained an analytical solution of a choked nozzle. It was assumed that the nozzle is compact and the flow disturbances satisfied the boundary conditions at the throat of the choked nozzle. Candel and Marble's expression has been widely used for predicting the stability behaviors of a combustor with a choked end [18–24]. Stow et al. [25] extended the study of Marble and Candel by making a second order correction and proposing a length correction (also known as effective length) to describe the choked end via conducting asymptotic analysis. They compared the analytical solutions with the numerical ones obtained from LEE method. A good agreement is obtained in terms of the phase prediction. Moreover, this analytical expression for choked nozzle has also been shown to be able to characterize circumferential modes. Recently Goh and Morgans [26] theoretically determined the effective length of the downstream part for the choked nozzle. Duran and Moreau [27] used invariants method and obtained the solutions of the quasi-1D LEE. Good agreement is observed between their results and the numerical ones in terms of both modulus and phase.

Marble and Candel [17] showed that the reflection coefficient of a choked nozzle was a function of mean flow Mach number. It has also been shown that Marble and Candel's expression can provide the same solution as the numerical ones, when the nozzle is acoustically compact [19]. However, if the length of the choked nozzle is not small (not acoustically compacted), the calculated reflection coefficients may be different from that predicted by using this expression with a length correction considered [19]. When the length correction proposed by Stow et al. [25] is used, the phase of the reflection coefficient is found to agree well with the numerical results [25]. But the modulus remains the same as that estimated by using Marble and Candel's expression, which is different from the numerical predictions [25]. Therefore it is expected that errors may be brought by these analytical expressions for the choked outlet when calculating the eigenfrequencies of a thermoacoustic system. In Ref. [25] the expression of a choked outlet is validated by comparing with LEE method. Hence errors brought by the expressions for choked nozzle in calculating eigenfrequency can also be assessed by comparing the results of these two methods. But it has not been systematically investigated. This motivates the present work. Moreover, in Ref. [25] it shows that the expression of choked outlet can be used for circumferential modes. In the present paper the instability of circumferential modes will also be studied and the use of the expression for choked outlet in prediction of circumferential instability will be validated.

In this work, theoretical and LEE studies of the boundary condition effect on thermoacoustic eigenmodes stability in a choked combustor are conducted. The geometry and physical configuration of the choked combustor with a flame confined is described in Section 2. Analytical investigations of both longitudinal and circumferential thermoacoustic eigenmodes are then preformed as described in Section 3. The mean flow effect is considered, and the flame is assumed to be acoustically compact. The predicted eigenfrequencies of the combustor without a length correction are then compared with those in the presence of a length correction. In Section 4, a linearized Euler equation method is developed to investigate the choked combustor. The choked outlet is involved automatically in the numerical solving process.

2. Geometry and physical configuration of the choked combustor

The main configuration of the choked combustor considered in the present paper is shown in Fig. 1(a). Its total length is L. And it consists of a cylindrical duct with a constant cross-sectional area A_p and a length L_u and a choked outlet of length $L - L_u$. An acoustically compact flame is anchored at $x = L_f$. The flow is assumed