Journal of Sound and Vibration 429 (2018) 206–223

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Mode coupling due to the non-uniformly distributed heat release in combustion instabilities

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ARTICLE INFO

Article history:
Received 30 October 2017
Received in revised form 6 May 2018
Accepted 12 May 2018

Handling Editor: L. Huang

Keywords:
Thermoacoustic instability
Combustion instability
Vorticity wave
Low-order model

ABSTRACT

Combustion instabilities in a chamber with circumferentially non-uniform heat release is investigated. A low-order model is developed to predict the combustion instabilities under the effects of a non-uniform heat source. A good agreement was observed between the results of the present model and the previous linear Euler equation method, which indicates that the present model can be used for the prediction of the combustion instabilities with the non-uniform heat source. The analysis shows that mode coupling can be brought by the non-uniformly distributed heat release in azimuthal direction. Results show that the oscillation frequency is less influenced by mode coupling. The growth rate, however, can be significantly affected by the non-uniformity of the heat release. For the instabilities of longitudinal-dominant mode, azimuthal acoustic modes are excited and coupled with the longitudinal mode. If the distribution type of the heat source is $\sin(j\theta)$, the jth azimuthal mode are the strongest one, while other azimuthal modes are weak. Moreover, with the increase of the duct length, the oscillation frequency decreases and get close to the cutoff value of the azimuthal modes. Mode coupling becomes weak for this condition and the effects of the non-uniformity of the heat source on the combustion instabilities are also reduced.

1. Introduction

Thermoacoustic combustion instabilities may occur in the combustors of energy systems such as rocket engines, aero engines and gas turbines. It may lead to large pressure fluctuations and structural damages, even the failure of a combustor. Such instabilities arise from the interactions between the acoustic modes and the unsteady combustion. In an annular combustion chamber of gas turbine, thermoacoustic combustion instabilities may be longitudinal or azimuthal [1]. Longitudinal instabilities are characterized as axial acoustic mode and many works have been done on the interaction between the flame and the longitudinal acoustic waves [2,3]. Azimuthal instabilities occur due to the coupling of the azimuthal acoustic mode and the flames. Typically, in analysis of azimuthal instabilities, the annular geometry is usually assumed to be thin enough that the radial dependence is ignored and the pure azimuthal modes are considered [4,5].

CFD methods can be used for the simulation of the combustion instabilities in a combustor. Large eddy simulation (LES) has been proven to be a powerful tool in simulation of swirl-burner behaviors [6–8] and azimuthal instabilities in combustion system [9]. LES method has many advantages, but it is always involved with high computational cost. To reduce the computational cost, reduced-order models are needed in the analysis of combustion instabilities [10–17]. The simplified low-

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http://dx.doi.org/10.1016/j.jsv.2018.05.021

order model is associated with low computational cost. But it should be noted that the accuracy of the results strongly depends on the modelling of the turbulence combustion process [18–20] and the description of the system boundary conditions [5,21,22].

The prediction of azimuthal instabilities is much more complicated than the longitudinal instabilities. To simplify the problem, zero flow Mach number is assumed and net-work model can be used, in which both the axial and radial directions of the annular chamber can be neglected and only circumferential modes are considered. For example, a simple analytical model was given by Parmentier et al. [4]. The single annular chamber with *N* burners is modeled by using one-dimensional zero Mach number formulations. The flame transfer function of each burner is included in the form of a lumped parameter model. This model can be used for the prediction of the combustion instabilities of the system with different types of burners. If the flow Mach number is not zero, however, the convection mode may be significant. By using a two-dimensional low-order model and a liner Euler equation method, it was found that vorticity waves are generated from the interaction of acoustic waves and the flame, which may have non-negligible effects on the azimuthal instabilities [23].

Typically, a flame transfer function should be included in a low-order model to predict the combustion instability of a system. For longitudinal instabilities, the flame transfer function can be given as a jump condition, in which the flame is assumed to concentrate on a zero thickness plane [10]. However, it has been proved that the axially spatial distribution of the flame model may also have crucial effects on the combustion instabilities. For the longitudinal modes, if the length of the flame is not small enough compared with the acoustic wave length, the axial distribution of the heat release should be considered [24,25]. For example, a flame model with triangular distribution was introduced for the prediction of combustion oscillation in a dry low emission combustor [24]. It was found that the triangular flame model gave a better prediction of the combustion instabilities compared with the simple flame sheet model.

The combustion instabilities with an azimuthally spatial-distributed heat source have also been investigated. It has been proved that the method of mixing different types of burner in one annular chamber can be used to suppress the azimuthal instabilities [4]. Moreover, the combustion instability with an azimuthally non-uniform heat release was studied using a linear Euler Equation method [26,27]. It was shown that the circumferential distribution of heat source also has effects on the longitudinal instabilities. And the generation of vorticity wave was observed. However, the mechanism of such effects has not been well understood. The generation of vortical modes in such a non-uniform heat release problem was also not quantitatively determined yet. The aim of the present paper is to develop a low-order model. The interaction of the longitudinal acoustic modes with the azimuthally non-uniform heat release will be investigated. It will be seen that the coupling of longitudinal and azimuthal modes is caused by the azimuthal non-uniformity of the heat source, which may have significant effects on the instability characteristics of a system. Furthermore, the generation of convection modes will also be studied.

This paper is organized as follows. Section 2 gives the assumptions of the present work. Section 3 presents the basic formulations and the description of the model, and gives the analysis of the mode coupling due to the non-uniformity of the heat source. The last section contains the results and the discussion.

2. Problem description

Fig. 1 shows the configuration of an annular duct, in which a planar flame is contained. The flame sheet separates the upstream and downstream regions. The following assumptions are made in order to simplify the problem: (1) the thickness of the flame in axial direction is neglected; (2) the flame position is fixed and the response of the flame to the flow disturbance is modeled in the unsteady heat release function; (3) the axial and circumferential directions are considered, whereas the radial dependence is ignored; (4) there will be azimuthal modes and longitudinal modes in the duct, however, the present work focus on the longitudinal or longitudinal dominant modes; (5) the axial mean flow is uniform and the azimuthal flow is

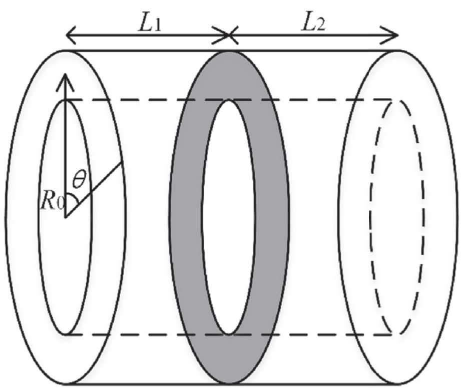

Fig. 1. Annular chamber with planar flame.