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Theoretical and experimental investigation of thermoacoustics transfer function

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HIGHLIGHTS

- Premixed flame–acoustics interaction is theoretically studied.
- Premixed flame is found to respond more strongly to lower-frequency perturbations.
- Linear and nonlinear transfer functions are determined.
- Hammerstei–Wiener model can provide a better agreement.
- Transfer function of a thermoacoustic system is experimentally measured.

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ABSTRACT

The coupling between unsteady heat release and acoustic perturbations can lead to self-sustained thermoacoustic oscillations, also known as combustion instability. When such combustion instability occurs, the pressure oscillations may become so intense that they can cause engine structural damage and costly mission failure. Thus there is a need to understand the coupling physics between acoustic waves and unsteady combustion and to identify a measure to quantify the interaction between the flame and acoustics. The present work studies linear and nonlinear response of a conical premixed laminar flame to oncoming acoustic disturbances. Unsteady heat release from the flame is assumed to be caused by its surface area variations, which results from the fluctuations of the oncoming flow velocity. The classical *G*-equation is used to track the flame front variation in real-time. Second-order finite difference method is then used to expand the flame model. Time evolution of the flame surface distortions is successfully captured. To quantify the dynamic response of the flame to the acoustic disturbances, system identification is then conducted to estimate the linear and nonlinear flame transfer function. Good agreement is obtained. Finally, transfer function of an actuated open–open thermoacoustic system is experimentally measured by injecting a broad-band white noise. The present work opens up new applicable way to measure heat-driven acoustics transfer function in a thermoacoustic system by simply implementing white noise.

1. Introduction

The interaction between unsteady heat release and acoustic disturbances can lead to self-sustained thermoacoustic oscillations, also known as combustion instability [1–5]. Such oscillations are wanted in thermoacoustic engines/prime movers or cooling systems [6–9]. However, they are undesirable in aero-engines, gas turbines, rocket motors and boilers [3–5]. Low emission propulsion/combustion systems are more susceptible to combustion instability. When combustion instability occurs, the flame may be blow out. Such instability can even cause structural vibrations and other operational problems. Therefore it is important to understand the physics and to develop control approaches to mitigate these self-sustained thermoacoustic oscillations in the design of stable combustors. These oscillations are mainly caused by the

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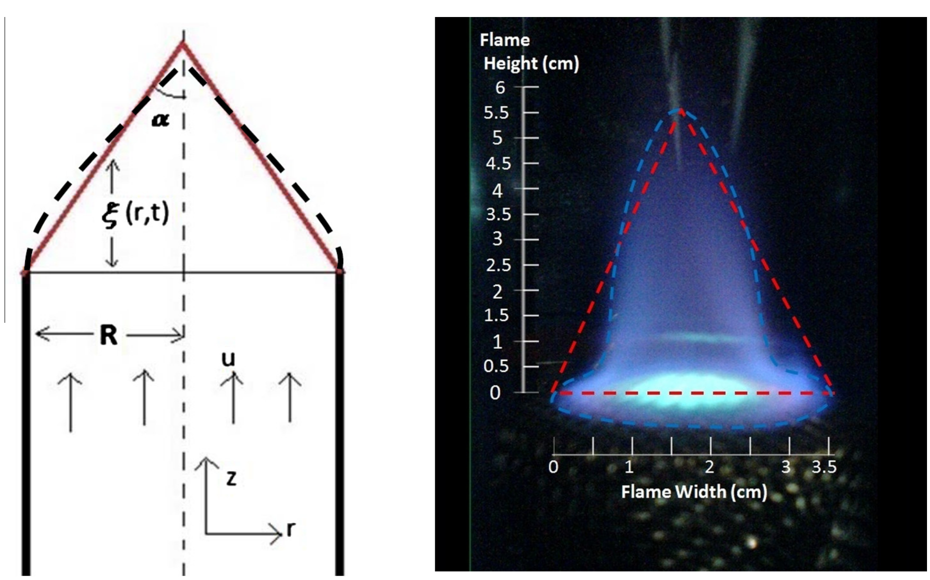
energy transferred from the heat source to sound waves [10–17], which depends upon the nature of coupling between the flame and oncoming flow fluctuations [18,19]. Small amplitude flow disturbances can excite natural modes of combustion chamber and cause them to grow into a nonlinear limit cycle. Rayleigh criterion [20–22] is widely used to check if the unsteady heat release can amplify or dampen the acoustic disturbances. It states that if thermal energy is added during the acoustics compression phase and removed during the rarefaction phase, then the acoustic oscillations will grow and vice versa.

In premixed combustion chambers, small change in flame surface area or burning rate or equivalence ratio can lead to heat release fluctuations, which are efficient sound sources to produce acoustic waves. It has been shown that the unsteady heat release from a premixed laminar flame and acoustic velocity perturbations are related. And the relationship can be described by using a transfer function. The acoustic velocity fluctuation is an input and the heat release fluctuation is an output [20,21]. To determine such transfer function, experimental and theoretical investigations have been conducted. The first theoretical analysis of such transfer function for a premixed laminar flame may be the work reported by Fleifil et al. [21]. The transfer function was defined as the ratio of the unsteady heat release rate to the velocity fluctuation as given as $G(\omega) = (\widehat{Q}(\omega)/\widehat{Q}_0)/(\hat{u}(\omega)/\hat{u}_0)$. Here, $\widehat{Q}(\omega)$ and $\hat{u}(\omega)$ are Fourier transform of unsteady heat release $Q'(t)$ and oncoming flow velocity $u'(t)$ respectively. Q_0 and u_0 are the mean value of heat release rate and the mean flow speed. Since the heat release rate is assumed to be related to the flame area [22] $(\widehat{Q}(\omega)/Q_0) \propto (\widehat{A}(\omega)/A_0)$, the transfer function can be interpreted as the flame surface area variation with oncoming flow disturbances. Two different Poiseuille flow configurations are considered. One is uniform and the other is non-uniform perturbations. The identified transfer function is shown to be varied with Strouhal number. Ducruix et al. [23] conducted both theoretical and experimental study on a conical laminar premixed flame. A linear transfer function was determined by solving the classical G equation. It was found [22] that the flame responses can be described by using a single non-dimensional frequency $\omega_* = (\omega R)/(S_L \cos\alpha)$, where ω is the angular forcing frequency, R is the burner diameter, S_L is the flame speed and α is the half cone angle. Comparing the results from Fleifil et al. [21] with those obtained by Ducruix et al. [23] reveals that good agreement is obtained for lower frequency.

Recently, Schuller et al. [22] conducted experimental and theoretical investigation on the flame transfer function. They found that the uniformity of the incident velocity field is crucial to determine the flame response. By numerically integrating the classical flame front tracking equation, i.e. G-equation [24], the flame response was determined for both uniform and convective oscillations in the velocity field over a broad frequency range. Later they developed an explicit analytical model describing the flame response to small velocity perturbations by linearizing $G(r,z,t)$ equation. It was found that the flame response was a function of two variables, namely the non-dimensional frequency and the ratio of flame burning speed to the mean flow velocity, which is equivalent to the half cone angle of the flame. In addition, it was found that a conical flame dynamics can be captured by using a second order transfer function. However, first-order approximation of the transfer function in the low frequency range shows that it performs well. These models were however linear and described the response closed to the equilibrium position.

Lieuwen [25] studied the nonlinear dynamics of a laminar premixed flame subjected to harmonic oscillations in velocity field. He found that the amplitude of the flame response was decreased in comparison with that predicted by using the linear transfer function as the amplitude of the flow perturbations was increased. The transfer function was shown to be related to the non-dimensional frequency, the ratio of the flame length to the radius of the burner (which is the flame half cone angle in another form) and the geometry of the flame which is the conical or V-shaped configuration. It was also shown that V-shaped flame behaves linearly only for small amplitudes of perturbations while a conical flame show linear behavior over a large frequency range. This finding is consistent with experimental results. Dowling [26] has shown that when the velocity perturbation amplitude is comparable to its mean value, linearization is no longer valid. Under such conditions, the flame may move upstream of the flame-holder and the boundary conditions must be properly modified to account for such a behavior. In general, most of the



(a) (b)

Fig. 1. (a) Schematic of a conical flame with height ξ, half cone angle α and the radius of the burner R and (b) a photo of a laminar premixed flame.