BRIEF COMMUNICATION

Control of Longitudinal Oscillations in a Constant Area Combustor: Numerical Simulation

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INTRODUCTION

The phenomenon of combustion driven oscillations has long held the interest of scientists and engineers. According to the so-called Rayleigh criterion [1], driving of the pressure oscillations occurs if the periodic heat release rate is generally coincident with the pressure oscillations. The main mechanisms involved are considered to be both thermoacoustic and vortical in nature [2-5]. Useful insight into the fundamental cause of combustion instability can be gained by considering the generalized Rayleigh criterion as advanced by Chu [6]. Due to the inherent complexity of the physical phenomena involved in combustion instability, research in this field has relied heavily on experimental observations [3-5, 7, 8], simplified linear analysis [9], or, more recently, large-eddy simulation [10].

Shyy and Udaykumar [11] have developed a one-dimensional nonlinear model to simulate the flow and heat release in a constant area combustor. The heat release model used there has been extended from experimental observations of Langhorne [12] and is a modified version of the model advanced by Bloxidge *et al.* [9]. The model developed in Ref. [9] follows from a one-dimensional linear stability analysis for acoustic waves in ducts, relating the fluctuations of heat release rate at the gutter to the velocity fluctuations through an empirical factor determined from experiments. The heat fluctuation is then assumed to travel downstream at the average gutter velocity and thus the fluctuations at any downstream location specified. In the present model, instead of specifying the unsteady heat release at every point in time and space, the heat release rate at the gutter is coupled directly to the velocity fluctuation with a time delay incorporated in it. The transport of this heat is modeled through a heat convection equation and the heat release at the downstream locations calculated. This way, the fluid dynamic and combustion mechanisms are treated in a coupled and nonlinear manner.

PROBLEM FORMULATION

The governing equations adopted constitute the one-dimensional Navier-Stokes equations nondimensionalized with respect to the dimensional values of inlet velocity u_∞, inlet density ρ_∞ (= 1.22 kg/m^3), and initial inlet temperature T_∞ (= 288 K). Re_∞ and Pr_∞ are, respectively, the Reynolds and Prandtl numbers calculated using the above reference values.

Our heat release profile is

$$q_{av}(x) = \begin{matrix} 0 & x < x_g, \\ C_1(x - x_g) & x_g \le x \le L, \end{matrix} \quad (1)$$

where x_g is the gutter location and L is the overall length of the duct. Figure 1 shows a schematic of the model combustor. The unsteady heat release is normalized with respect to the mean heat release at every location as follows:

$$q'(x, t) = q^*(x, t) \cdot q_{av}(x) \quad (2)$$

where $q^*(x, t)$ is defined as the perturbation coefficient. The unsteady heat release calculation is initiated by relating the heat perturbation at the gutter to the gutter velocity as follows:

$$q^*(x_g, t) = C_2 \cdot u(x_g, t - \tau_c), \quad (3)$$

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where u is the local convection velocity, and τ_c is the phase factor that represents the aforementioned combustion time delay. The heat transport is modeled through the following heat convection equation:

$$q_t^* + u(x,t) \cdot q_x^* = 0, \tag{4}$$

where the perturbation q^* convects with the local flow velocity, u.

The inlet condition used is the pressure reflection condition:

$$u_1 = 1, \ \rho_1 = 1, \ (p_x)_1 = 0,$$

where 1 refers to the grid point at the inlet. The boundary condition applied at the exit for u and ρ are based on linear extrapolation; the exit pressure is taken the same as the ambient level.

$$u_n = 2u_{n-1} - u_{n-2}, \ \rho_n = 2\rho_{n-1} - \rho_{n-2},$$
$$p_n = p_\infty,$$

where n refers to the grid point at the exit.

Implementation of the Control Strategy

The inlet boundary conditions used for the present simulations are quite conducive to the implementation of active control through inlet mass-flux modulation. As illustrated in Fig. 1, a pressure signal sensed at the gutter is phase shifted, amplified and fed into the inlet velocity condition, viz,

$$u_1(t) = 1 + u_1'(t), \tag{5}$$

$$u_1'(t) = G\left[\frac{P_s(t-\tau_f) - P_r}{P_r}\right], \tag{6}$$

where G = gain of feedback, P_s = sensed pressure signal (at the gutter),

P_r = reference pressure, τ_f = time-lag in feedback

The range of variation of τ_f is 0 to t_p where t_p is the time-period of the dominant frequency of oscillations and G varies from 0 to 1. We also define a phase-lag in feed back as $\phi_f = 2\pi(\tau_f/t_p)$. P_r, the reference pressure is taken to be the time-averaged pressure at the sensor location and is continually updated after each cycle.

A sequence of steps has to be carried out to set up the reacting flow and to initiate the active control. Initially only the linear profile of $q_{av}(x)$ is introduced. Once the system has attained a steady state, the heat profile is perturbed temporarily and simultaneously the coupling between the heat and velocity fluctuations at the gutter is initiated. The system is then allowed to reach a well-defined limit-state as governed by the combustion model and the dominant frequency of the system calculated. The feedback control is now "switched on" and for a given G, and the full range of τ_f is scanned.

RESULTS AND DISCUSSION

For this analysis the system parameters are

$$L = 1.0, \ x_g = 0.5, \ M_\infty = 0.38, \ Re_\infty = 10^4,$$

$$Pr_\infty = 0.7, \ C_1 = 350 \quad \text{and} \quad C_2 = 1.$$

This set of parameters yields a temperature profile resembling that of a typical afterburner. All cases have been run with 401 grid points and

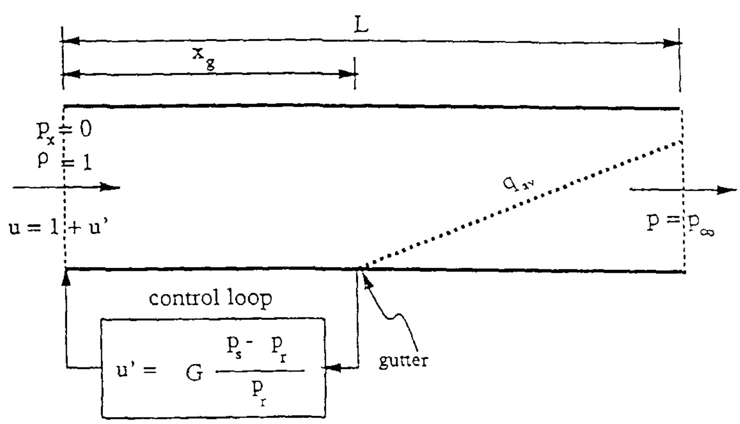

Fig. 1. Schematic of combustor with control loop.

$\Delta t / \Delta x = 0.03$. The values of C_1 and C_2 have been chosen to give a temperature range of 1200–2300 K.

Damköhler Number (Combustion Phase Lag) Effect

If we define a Damköhler number as $Da = \tau_{res} / \tau_c$, where τ_{res} and τ_c are, respectively, the characteristic residence time and characteristic combustion time, then our investigation spans a range of Da from 4.5 to ∞. Figure 2*a* shows the variation of peak-to-peak pressure amplitude of the gutter with Damköhler number, exhibiting a clear maximum for Da = 8.9 ($\tau_c = 1500\Delta t$) that corresponds to the maximum thermoacoustic coupling. There appears to be a finite range of Damköhler number, between 5 and 27, for which noticeable levels of combustion oscillations exist. Outside this range, it seems that the gasdynamic and chemical kinetic mechanisms of the flow can no longer be coupled to produce a combined impact on the flow field. Figure 2*b* demonstrates that the phase-lag in form of the Damköhler number also plays a significant role in determining the dominant frequency of the resonant oscillations in the system. The dependence of the system-frequency on characteristic times has also been demonstrated by Yu et al. [13]. Thus for the reacting case, system acoustics does not seem to be the sole determining factor in the system-frequency selection process.

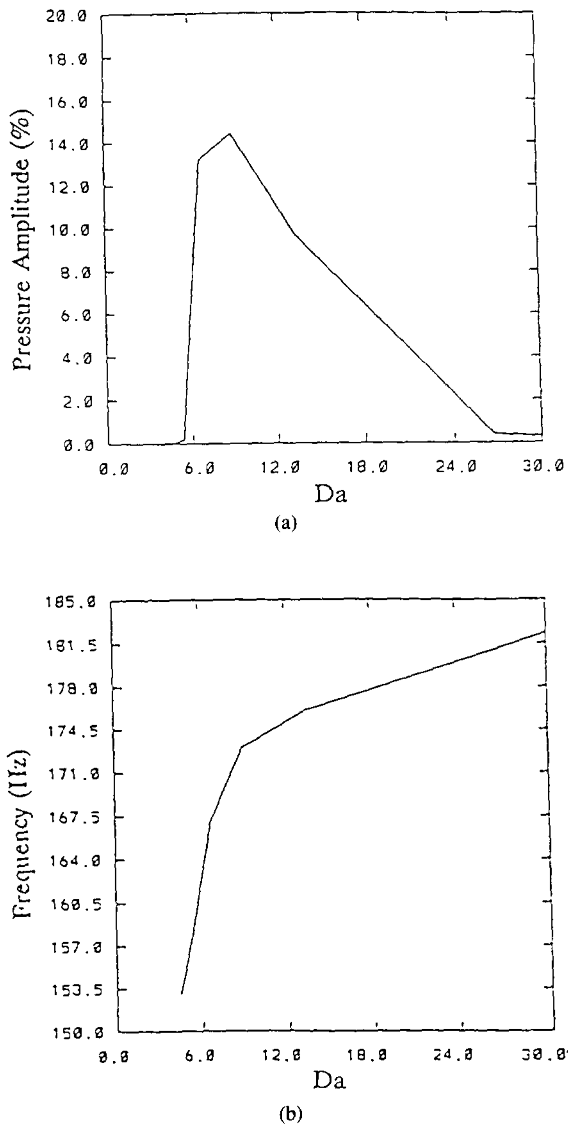

Fig. 2. Effect of Damköhler number on combustion instability. (a) Variation of peak-to-peak pressure amplitude at the gutter versus Damköhler number. (b) Fundamental frequency of oscillations versus Damköhler number.

Active Control

The case with the maximum peak-to-peak pressure amplitude (Da = 8.9) has been chosen for studying the possibility of implementing an active control strategy in order to test the control in the most stringent condition. The primary frequency, 172 Hz in this case, is chosen as the reference to design the phase lag (or time delay) between the pressure signal detected at the gutter and control signal issued at the combustor inlet. For our study we have chosen to detect the signal at the gutter. Three values of control gain, $G = 0.25$, 0.5, and 1.0, have been tested and for each value, the phase-lag is varied over the whole range to explore the characteristics of system response to control signal. The normalized peak-to-peak pressure amplitude at the gutter versus the phase-lag is shown in Fig. 3. For all three values of control gain there is a distinct minimum, that is, a preferred phase lag for which maximum attenuation is attained. Furthermore, Fig. 3 also indicates that within some ranges of phase lag, the combustion oscillations can actually increase in magnitude. Hence, depending on the specific application, the oscillations can be suppressed to protect structural integrity, as in the case of afterburners,

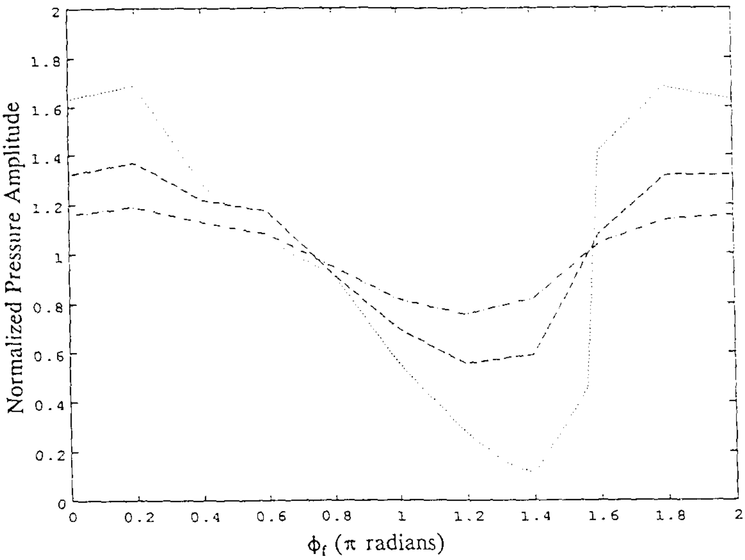

Fig. 3. Variation of peak-to-peak pressure amplitude with phase-lag in feedback (the amplitudes have been normalized with respect to the uncontrolled amplitude).

or enhanced to increase the total heat output, as in the case of a pulse combustor.

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