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Numerical and experimental demonstration of actively passive mitigating self-sustained thermoacoustic oscillations

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HIGHLIGHTS

- Minimizing self-sustained thermoacoustic oscillations is numerically and experimentally studied.
- An actively passive control approach is developed and applied to stabilize combustion systems.
- Nonlinear and nonharmonic flame-acoustics interaction is dynamically characterized.
- Flame transfer function analysis is conducted and flame speed plays a critical role.
- 60 dB sound pressure level reduction is experimentally achieved.

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ABSTRACT

Self-sustained thermoacoustic oscillations resulting from a dynamic coupling between unsteady heat release and flow perturbations are detrimental to engine systems such as boilers, land-based gas turbines and furnaces. In this work, mitigating premixed flame-sustained thermoacoustic oscillations in a combustor is studied by actively passive control of a Helmholtz resonator with an oscillating volume. For this, a numerical model of a thermoacoustic combustor with a Helmholtz resonator attached is developed. As a feedback control technique is implemented on the combustion system to optimize the resonator's damping effect, combustion-driven oscillations are successfully mitigated by approximately 30 dB. In addition, the dynamic response of the flame to oncoming acoustic disturbances is studied. This is achieved by numerically solving a nonlinear G-equation tracking flame front, as the disturbances with multiple frequencies are imposed. Flame transfer function is then derived via linearizing the flame model to obtain analytical results. Comparison is then made between the analytical and numerical results. It is shown from the transfer function analysis that the unsteady heat release linearly depends on the oncoming flow disturbance. However, the numerical results reveal that the flame response is nonlinear. Furthermore, the flame responds strongly to acoustic disturbances at a lower frequency and it behaves like a 'low-pass' filter. The flame speed is also found to play an important role in determining the unsteady heat release. Finally, to validate the effectiveness and performance of the feedback control, a Helmholtz resonator with a controllable oscillating diaphragm is implemented on a Y-shaped Rijke-type thermoacoustic system. Sound pressure level is shown to be reduced by more than 60 dB via tuning the gain and phase of the vibration of the loudspeaker diaphragm. The present investigation opens up an alternative applicable means to stabilize engine systems via minimizing thermoacoustic oscillations.

1. Introduction

To meet more stringent combustion emission requirements by reducing NOx emission and increasing combustion efficiency, LPP (lean premixed prevaporized) combustion technology is widely implemented in land-based gas turbine engines for power generation [1–4]. However, such engine systems are more prone to self-excited combustion oscillations. Such periodic oscillations are known as thermoacoustic or combustion instability [5–7]. Combustion instability has been frequently observed in various types of combustion systems such as industrial boilers, rocket engines or furnaces [8–12]. One of the generation mechanism is the constructive interaction between a flame and its

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surrounding unsteady flow [1]. Premixed or diffusion flame [13] is an energy-efficient noise generator. Any unsteady heat released from the flame generates acoustic pressure perturbations, which propagate within the combustor. When the acoustic perturbations reach to the combustor outlet, part of the perturbations will be reflected back to the flame (due to the boundary impedance change) to further disturb the unsteady heat release process [14]. This feedback process can give rise to the onset of combustion instability, when unsteady heat is added in phase with the pressure oscillations. Total acoustical energy in the combustor [15–18] is increased first and then ‘saturated’ due to the nonlinear effects [11,12]. Such acoustical energy can be converted to generate electricity or used to produce mechanical work. This is the main principle of thermoacoustic prime movers or cooling systems [19,20].

Thermoacoustic instability is undesirable in power generation or propulsion systems [21–24], because it could result in structural vibration, overheating and flashout [1]. To operate engine stably and safely, there is a strong need to develop effective control approaches to minimize thermoacoustic instability [25–29]. In industrial and academic communities, three general control approaches are developed. One means is active feedback control [30–32]. The other means is open-loop control. The open-loop control action does not depend on the combustor response. The last but not the least means is passive control. Active feedback control means involves a closed-loop configuration. An actuator such as a loudspeaker [1,2] in feedback means is controlled by a controller responding to a transducer measurement. The effectiveness and the performance of the feedback control means are strongly related to the controller and the actuator. Feedback control of an unstable turbulent combustor was demonstrated by using FIR (finite impulse response filter) [33]. The attractive features of feedback control means include fast-responding and wide adaptivity. However, feedback and open-loop control means involve introducing additional energy/perturbations to the combustor to be controlled. Thus there is a risk that the combustion system may be more unstable, if the actuation is not properly controlled. Thus feedback and open-loop control approaches are not widely applied in practical engines.

As engine industries are concerned, passive control means is typically preferred and applied. The main idea is to introduce extra acoustic loss/damping to combustors to absorb acoustic perturbations by implementing acoustic dampers. As one of the conventional dampers, Helmholtz resonator (HR) [12,28,34] has been tested on a heavy-duty gas turbine engine [35] to stabilize the combustion system. HR looks like a beer bottle. It composes of a large-volume cavity, which is connected to the combustor via a neck. If the mass of the working fluid in the neck vibrates, then the working medium in HR cavity expands and compresses periodically. At resonance, the vibration of the working fluid is maximized and so the noise damping effect. The main damping mechanisms are thermo-viscous and vortex shedding. The empirical formula to determine the resonant frequency of the resonator is $\omega_r = \sqrt{c^2\mathscr{S}/\mathscr{V}\mathscr{L}_{\text{eff}}}$. Here c is sound speed. $\mathscr{S}$ is the cross-sectional area of the neck. $\mathscr{L}_{\text{eff}} = \mathscr{L} + \Delta\mathscr{L} > \mathscr{L}$ is effective length of the neck. $\mathscr{L}_{\text{eff}}$ is slightly larger than its physical length $\mathscr{L}$. $\mathscr{V}$ is the cavity volume. For a HR with a given geometry and dimensions, there are narrow effective frequency ranges. Moreover, HRs are not able to react to changes in operating conditions, since it lacks of a control system.

An ideal and perfect way of mitigating thermoacoustic instability would combine the advantages of both feedback and passive control means [12,28]. This may be achieved using a feedback controller to actively optimize the acoustic dissipation effect of a HR. Such optimization is achievable via varying HR’s geometry or vibrating its cavity sidewalls. Such control approach ensures that there is only acoustic damping/loss introduced to the combustion system. There is no risk of making the combustor being more unstable. Meanwhile the developed control means can respond to changes in the operating conditions. This overcomes the key drawback of conventional passive acoustic absorbers. As indicated in the HR resonant frequency equation $\omega_r = \sqrt{c^2\mathscr{S}/\mathscr{V}\mathscr{L}_{\text{eff}}}$, ω_r is dependent on the HR geometry and so its noise damping. A HR volume is continuously oscillating as studied previously [12]. The oscillation was optimized by using a FIR filter. Optimizing the neck area to dampen combustion instability in a Rijke tube has been experimentally evaluated [28]. However, mitigating combustion-driven self-sustained oscillations in a combustor by real-time optimizing HR’s cavity volume oscillation has not been experimentally demonstrated. Lack of such investigation motivated partially the current study.

In this work, a modelled unstable combustor with an acoustically compact premixed flame enclosed [4,36] is considered. The presence of the premixed flame gives rise to the mean density, velocity and temperature being jumped from pre- to after-combustion region. A ‘controllable’ Helmholtz resonator is implemented upstream of the combustion chamber. The acoustic damping performance of the HR is maximized by online tuning the phase and gain of the cavity volume oscillation of the resonator. In Section 2, the system governing equations are derived and discussed. $G-$equation and travelling wave expansion method [4,36] are applied to represent the flow perturbations and tracing the flame front. In Section 3, both nonlinear and linearized flame responses to oncoming harmonic flow disturbances are studied, compared and discussed to gain insights on the nonlinear flame-acoustics interaction. In addition, a feedback control strategy is developed and implemented on the modelled thermoacoustic combustor. Its performance on stabilizing the unstable combustion system is evaluated. In Section 4, the developed control means is experimentally evaluated on a Y-shaped Rijke tube with the implementation of a Helmholtz resonator backed by a loudspeaker. In Section 5, the key findings are discussed and summarized.

2. Description of the modelled combustor

2.1. Modelling flame-acoustics interaction

A 1D modeled thermoacoustic combustor with a controllable Helmholtz resonator attached is considered. The schematic of the modelled combustor is shown in Fig. 1. It involves with an open outlet at the downstream and a choked inlet at the upstream [4,12,28]. The modelled combustor is a generic configuration of the primary stage of Rolls-Royce RB211 industrial gas turbine engine. The modelled combustion system involves with three main processes; (1) acoustic perturbations’ generation, propagation and reflection, (2) gutter-holding flame response to oncoming perturbations, and (3) the controllable resonator’s acoustic dissipation. Inside the combustor, there are three assumptions made: (1) both the flame and the resonator are acoustically compact, (2) the controllable resonator is attached upstream of the flame, (3) except the zone containing the gutter with a radius of r_a, the cross-sectional area of the combustor with a radius of r_b remains the same. The governing equations of mass, momentum and energy conserved across the flame are given as

$$\mathscr{S}_c[\rho u]_{a2}^b = 0 \tag{1}$$

$$\mathscr{S}_c[p]_{a2}^b + \mathscr{S}_c\rho_{a2}u_{a2}[u]_{a2}^b = 0 \tag{2}$$

$$\frac{\mathscr{S}_c\gamma}{\gamma-1}[pu]_{a2}^b + \frac{\mathscr{S}_c}{2}\rho_{a2}u_{a2}[u^2]_{a2}^b = \mathscr{Q}(t) \tag{3}$$

where $\mathscr{S}_c$ is the cross-section area of the combustor. $[\mathscr{X}]_a^b \equiv [\mathscr{X}]_b - [\mathscr{X}]_a$, $\gamma = 1.41$ is the specific heat ratio. ρ u,p and $\mathscr{Q}$ are instantaneous density, velocity, pressure and heat release rate respectively. An overbar describes a mean part, while a prime denotes a fluctuating part. Subscript a and b denote the pre- and after-flame regions respectively.

Combustion-drive acoustic perturbations are propagating along the combustor. At the inlet and outlet, the acoustic impedance is changed. Therefore, part of the heat-produced acoustic waves are reflected back