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A review of acoustic dampers applied to combustion chambers in aerospace industry

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ABSTRACT

In engine combustion systems such as rockets, aero-engines and gas turbines, pressure fluctuations are always present, even during normal operation. One of design prerequisites for the engine combustors is stable operation, since large-amplitude self-sustained pressure fluctuations (also known as combustion instability) have the potential to cause serious structural damage and catastrophic engine failure. To dampen pressure fluctuations and to reduce noise, acoustic dampers are widely applied as a passive control means to stabilize combustion/engine systems. However, they cannot respond to the dynamic changes of operating conditions and tend to be effective over certain narrow range of frequencies. To maintain their optimum damping performance over a broad frequency range, extensive researches have been conducted during the past four decades. The present work is to summarize the status, challenges and progress of implementing such acoustic dampers on engine systems. The damping effect and mechanism of various acoustic dampers, such as Helmholtz resonators, perforated liners, baffles, half- and quarter-wave tube are introduced first. A summary of numerical, experimental and theoretical studies are then presented to review the progress made so far. Finally, as an alternative means, 'tunable acoustic dampers' are discussed. Potential, challenges and issues associated with the dampers practical implementation are highlighted.

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1. Introduction

Combustion systems such as rocket motors and aero-engines are associated with acoustic pressure fluctuations even during normal, stable operation of engine systems [1–7]. These pressure fluctuations are typically quite random. The corresponding frequency spectrum is continuous in nature. However, in unstable combustion systems, large concentrations of acoustical energy appear at some frequencies (corresponding to the combustor resonance ones) in the spectrum. The easily recognized peaks (harmonics or non-harmonics) are different from the spectrum of the stable systems with random noise [8–10,3]. For engine combustors, stable operation is one of design prerequisites [2,11], since large-amplitude self-sustained pressure fluctuations (also known as combustion instability) have great potential to cause serious damage and catastrophic engine failure. However, no engine type or propulsion system can be considered inherently 'stable' [12]. There are many factors affecting engine stability, for example the configuration of the engine-feed systems, injector, and thrust chamber as well as operating conditions. Therefore, it is important to address the issue of mitigating self-sustained pressure fluctuations as well as engine performance during the early stages of engine design. Otherwise, required modifications might become too difficult to implement [13,14].

Combustion systems are associated with the burning of the mixture of fuel and oxidizer/air. Unsteady combustion is an efficient acoustic source. It generates acoustic pressure waves. These pressure waves propagate within the combustor, and partially reflect from boundaries to arrive back at the combustion zone, where they can cause more unsteady heat release. This feedback can result in the pressure oscillation amplitudes successively increasing, which is what is meant by a combustion instability [15–19]. Eventually, some nonlinearity in the combustion system will limit the amplitude of the oscillations. Whether or not an instability occurs depends on the nature of the coupling between the unsteady heat release and acoustic waves, as shown in Fig. 1.

Self-sustained combustion oscillations occur frequently in many types of combustion systems, including aero-engine afterburners [20], ramjets [21], stationary power gas turbines [22,23], boilers and furnaces [24]. However, the present work focuses on reviewing how to improve the stability of aeroengines as shown in Fig. 2(a) and rocket motors [25,26], as shown in Fig. 2(b).

In a few instances, aerial vehicles and rockets are lost during flight tests due to combustion instability. However, combustion stability [1,27–29] issues can be resolved during the engine development stage. There are two general approaches to stabilize combustion systems. One is to modify the propellant supply system. The other is to change the combustor geometry. These two approaches have been widely used in different types of propulsion systems [30]. For solid rockets, it is general practice to change the propellant composition or to modify the geometry of the propellant grain. However, it is difficult to alter the reactants in liquid-fueled rocket motors. Thus it has become common practice to adjust the design of the fuel supply system or to add acoustic dampers to the liquid-fueled rocket motors. However, it is worth noting that implementing acoustic dampers may enhance combustion system stability but may also affect combustion performance and combustor heat loads [4,1].

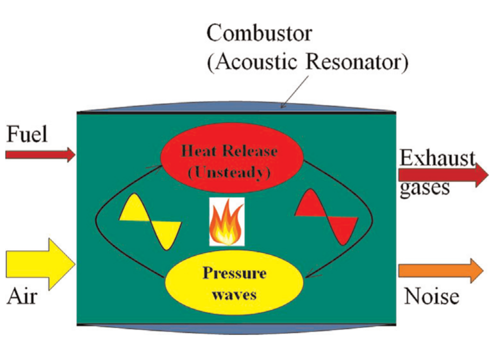

Fig. 1. Schematic of a simplified combustion system.

The most commonly used acoustic dampers include Helmholtz resonators, perforated liners, quarter-and half-wave tubes, and baffles [31,8,32,33]. As all of these are relevant to the present work, we will now introduce briefly their damping mechanisms one by one. Detailed discussion on their implementation and performance is reported in the following sections.

1.1. Brief description of the damping mechanism

- Helmholtz resonators.
  Helmholtz resonators (HRs) have been widely used as acoustic dampers to dampen combustion-excited oscillations [34,23,8,35]. A schematic of a typical set-up is shown in Fig. 3(a). It consists of a volume connected to the combustor by means of a short neck. At resonance, a large volume of fluid in the cavity compresses and expands periodically, while a mass of the fluid in the neck oscillates. This can be explained by studying the relation between the pressure perturbation $p'(t)$ at the neck and the cavity volume flow rate $Q'(t)$ of the resonator with a cavity volume V. For harmonic disturbances i.e. $\exp\{j\omega t\}$, the density change in the cavity $\hat{\rho}_c(\omega) = \hat{Q}(\omega)/j\omega V$ is due to the mass flowing into the cavity [36]. It is also related to the pressure fluctuation in the cavity as

$$\hat{p}_c(\omega) = c_0^2 \hat{\rho}_c(\omega) = \frac{c_0^2 \hat{Q}(\omega)}{V\,j\omega} \quad (1)$$

where c_0 is the speed of sound. According to the momentum conservation law in the neck, the pressure difference between the neck ends equals the rate of momentum change as

$$\Delta\hat{p}(\omega) = \hat{p}_i(\omega) - \hat{p}_c(\omega) = \frac{j\omega l_{\mathrm{eff}} \hat{Q}(\omega)}{S} \quad (2)$$

where S and l_{eff} are the cross-sectional area and the effective length of the neck respectively. After substituting for $\hat{p}_c(\omega)$, it can be shown that

$$\frac{\hat{Q}(\omega)}{\hat{p}_i(\omega)} = \frac{\omega S}{\left(\omega^2 - \frac{c_0^2 S}{V l_{\mathrm{eff}}}\right) j l_{\mathrm{eff}}} \quad (3)$$

The damper resonates at a frequency of

$$\omega_{\mathrm{res}} = \sqrt{\frac{c_0^2 S}{V l_{\mathrm{eff}}}} \quad (4)$$

Near this frequency very small pressure disturbances can lead to large mass variations. The acoustic damping effect provided by a Helmholtz resonator at its resonant frequency depends on the bulk geometry of the resonator. It has been shown [37,2] that the maximum damping occurs by tuning/varying the resonator geometry so that the resonant frequency ω_{res} is close to the oscillation frequency that is to be mitigated in the combustor.
  Factors such as neck shapes are also found to have an influence on the resonator damping effect; for example rounded (see Fig. 3(b)) and square shaped necks [38] produce significantly different acoustic responses [11]. Furthermore, it is found that installing a perforated plate at the resonator neck can dramatically increase the acoustic damping [39].

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