PASSIVE AND ACTIVE CONTROL OF COMBUSTION OSCILLATIONS

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Abstract

Early work and some recent advances in control of combustion oscillations are described. The physics of combustion oscillations, most commonly caused by a coupling between acoustic waves and unsteady heat release, are discussed, and the concept of using passive and active control to interrupt these interactions is introduced. Factors affecting practical implementation are described, and the historical development of control strategy for combustion oscillations is reviewed. Finally, demonstrations of feedback control on full-scale combustion systems are described.

1. Introduction

In many combustion systems, unwanted large-amplitude flow oscillations can occur under certain conditions. The associated pressure oscillations and possibly enhanced heat transfer can lead to a deterioration in the system performance, and may be sufficiently intense to cause structural damage.

Combustion oscillations are of particular current concern due to their frequent occurrence in the new generation of gas turbines, in which reduced emissions are a priority. This affects both industrial land-based gas turbines (Mongia et al. 2003, Schadow & Yang 1996, Seume et al. 1998) and aeroengines (Giuliani et al. 2003, Zhu et al. 2001b). Operating gas turbine combustors under lean premixed conditions reduces nitrous oxide emissions. However, lean premixed combustion is especially prone to combustion instabilities (Correa 1998, Richard & Janus 1998), and this is leading to long and expensive development and commissioning times. Combustion oscillations are not limited to gas turbine combustors. Aeroengine afterburners (Bloxsidge et al. 1988b,c; Schadow et al. 1998), rocket motors (Crocco & Cheng 1956), ramjets (Hedge et al. 1987), boilers, and furnaces (Putnam 1971) are all examples of practical systems that are also susceptible to them, with the most common laboratory-scale combustion oscillations occurring in a simple open-ended vertical tube with a heat source in its lower half, known as a Rijke tube (Rayleigh 1945).

Combustion oscillations most often arise due to a coupling between the unsteady heat release and the acoustic waves. Unsteady combustion is an efficient acoustic source (Candel et al. 2004, Dowling & Ffowcs Williams 1983), and combustors tend to be highly resonant systems. Therefore, when unsteady heat release generates acoustic waves, these reflect from the boundaries of the combustor to produce flow unsteadiness near the flame. This may cause more unsteady heat release, for example through local changes in the fuel-air ratio (Richards & Janus 1998) or through hydrodynamic instabilities (Poinsot et al. 1987, Renard et al. 2000). The acoustically nonlinear form of this, which may be important in applications with very high heat-release rates, involves interactions between shock waves and combustion (Rudinger 1958). These mechanisms are discussed in more detail in review papers by McManus et al. (1993) and Ducruix et al. (2003). Depending on the phase relationship of the unsteady heat-release response, acoustic waves may successively increase in energy leading to large-amplitude self-excited oscillations.

To eliminate combustion oscillations, the coupling between the acoustic waves and the unsteady heat release must be interrupted. Passive control methods (Culick 1988, Putnam 1971) may either seek to reduce the susceptibility of the combustion process to acoustic excitation through ad hoc hardware design changes, such as modifying the fuel injection system or combustor geometry (Richards et al. 2003, Richards & Janus 1998, Steele et al. 2000), or to remove energy from the sound waves using acoustic dampers such as Helmholtz resonators (Bellucci et al. 2004, Gysling et al. 2000), quarter wave tubes (Joshi et al. 1994), perforated plates, or acoustic liners (Eldredge & Dowling 2003). The problem with passive approaches is that they tend to be effective only over a limited range of operating conditions, they may be ineffective at the low frequencies at which some of the most damaging instabilities occur, and the changes of design involved are usually costly and time-consuming.

Active feedback control provides another means of interrupting the coupling between acoustic waves and unsteady heat release. An actuator modifies some system parameter in response to a measured signal. The aim is to design the controller (the relationship between the measured signal and the signal used to drive the actuator) such that the unsteady heat release and acoustic waves interact differently, leading to decaying, rather than growing, oscillations. In the past, approaches to controller design were somewhat empirical, but more systematic approaches such as robust control and adaptive control are now promoted.

In section 2 the physics of combustion oscillations are discussed to identify what is needed for control. A generalized energy equation is derived to explain why combustion instabilities occur. Section 3 then discusses passive control, starting with factors that affect its practical implementation in combustion systems. Active control is introduced in Section 4. The background to feedback control is presented and illustrated through discussion of a simple robust controller to stabilize a simple model combustor. Developments in approaches to controller design are categorized into fixed-parameter controllers and adaptive controllers. In section 5, demonstrations of active feedback control stabilizing full-scale combustion systems are described and the lecture is summarised in section 6.