ACTIVE NOISE CONTROL
APPLIED TO CONFINED FLOWS

Part II: Active Instability Control

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1. Introduction

One consequence of the interaction between confined flows and acoustic waves is that self-excited oscillations may readily occur. This is because flow-field unsteadiness can generate acoustic waves and, at frequencies near the resonances of the enclosure, these waves can be so intense that they act back to perturb flow still further. Instability is then possible. Small perturbations grow in time, and an undesired unsteady flow develops. If left uncorrected large amplitude oscillations may develop. This onset of instability can be damaging and its avoidance can limit performance. Active instability control has been demonstrated to be a feasible way of preventing the build-up of such large-scale oscillations and hence of extending the stable operating range of a variety of different devices.

Even a subsonic jet impinging on a flat plate can produce a discrete frequency tone but oscillations become particularly intense when the jet interacts with a sharp edge or the lip of deep cavity or closed side branch. These vortex dominated flows are amenable to active control but by far the greatest activity has been in active control of instabilities in gas turbines.

Both compression and combustion systems are susceptible to instabilities. Two types of instabilities, 'surge' and 'rotating stall', are commonly observed in compressors. They occur at low mass flow rate, high pressure rise conditions. Surge is a very low-frequency one-dimensional pumping oscillation in which the whole compression system acts like a Helmholtz resonator - interaction between the inertia of an axisymmetric unsteady flow through the compressor and the compressibility of the air within the combustion chamber leads to self-excited oscillations. Rotating stall is of higher frequency and is characterised by a region of reduced air flow rate that rotates around the compressor annulus at a fraction of the rotor speed. Whether the compressor surges or stalls depends on the system configuration and in particular on the ratio of compressibility and inertial effects (Greitzer, 1981). In high-speed axial compressors, the onset of rotating stall in the compression system often triggers surge through a nonlinear interaction (Weigl *et al*, 1998). Both instabilities lead to a loss of compressor performance. Moreover, the resulting large unsteady forces may damage the engine. Recovery from rotating stall is not straightforward and, in practice, may involve shutting down the engine and restarting. Because of these far-reaching consequences, compressor design tends to be very cautious, leaving a good margin between the design mass flow rates and instability onset. This severe limitation on compressor pressure rise can be overcome by applying active control.

Many forms of combustion systems are susceptible to self-excited oscillations, with the resulting pressure waves and/or enhanced heat transfer being so intense that structural damage is done. Such flow instabilities occur because of interaction between unsteady combustion and acoustic waves. Essentially, unsteady combustion is an effective source of sound. However, most combustors are highly resonant systems, in which the acoustic waves are reflected from the boundaries to produce flow unsteadiness near the flame, leading to more unsteady combustion. If the phase relationship is suitable, acoustic waves gain energy from their interaction with the combustion (Rayleigh, 1896). Self-excited oscillations then occur: unsteady combustion generates sound, while the sound waves perturb the combustion.

In gas turbines there are various ways in which flow perturbations cause unsteady combustion, but usually the main coupling is through velocity fluctuations. These can, for example, change the fuel-spray atomisation, which is the main mechanism driving 'rumble' (Zhu *et al*, 2000), a low frequency instability of aeroengine combustors at idle and sub-idle. Alternatively in an afterburner, where the flame is stabilised in the wake of a bluff body, velocity fluctuations near the flame holder physically perturb the flame and thereby alter the instantaneous rate of combustion (Bloxsidge *et al*, 1988a). Lean premixed prevapourised combustion, introduced to reduce NO_x, is proving to be notoriously susceptible to instability. There, since the fuel and air supplies have different acoustic impedances, pressure fluctuations in the combustor cause unsteadiness in fuel-air ratio (Richard & Janus, 1998). When burning lean and premixed, the rate of combustion is very dependent on the instantaneous fuel-air ratio and fluctuates in response.

The feedback is usually through reflection from the combustor boundaries of the acoustic or entropy waves generated by the unsteady combustion, which at certain discrete frequencies reinforces the driving mechanism for unsteady combustion. Linear perturbations can then grow in amplitude. Active control is a way of interrupting the damaging interaction between linear waves and unsteady combustion.

The basic features of applying active control to these compressor and combustor instabilities are illustrated in Fig. 1. The characteristics of the fluid system change with operating point and may display regimes of instability. This is illustrated in Fig. 2, which shows the changes in the power-spectral density of the pressure generated by a premixed ducted flame as the fuel-air ratio varies. When the fuel-air ratio is below a critical value, the combustion system has all the characteristics of a damped harmonic oscillator, the spectral level depending on external excitation which is preferentially amplified near the resonant frequency. An increase in fuel-air ratio reduces the damping, thereby increasing the resonant response. Beyond a critical fuel-air ratio, the system is unstable. Linear perturbations then grow rapidly with time until a non-linear limit cycle is established. New physics set the amplitude of the limit cycle and, in this particular example, it is controlled by saturation effects that occur in the heat-release fluctuation when the fluid velocity reverses. The pressure spectrum now has a different character and a narrow-bandwidth high-amplitude peak occurs. In many practical combustors the onset of instability may result in damaged hardware. The idea of active control is to extend the stable operating range.

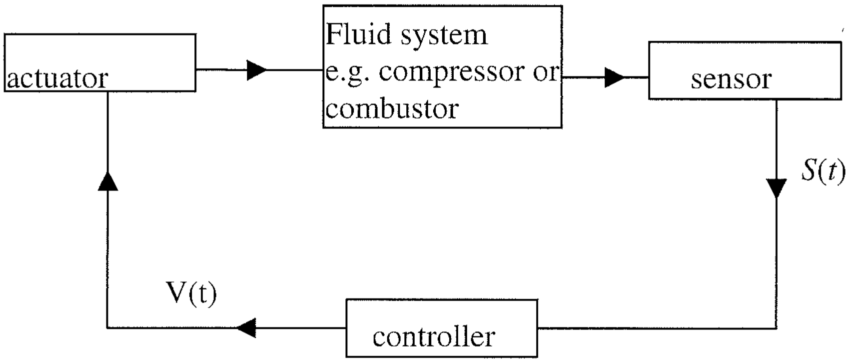

Figure 1 Generic system for active control of a gas turbine instability

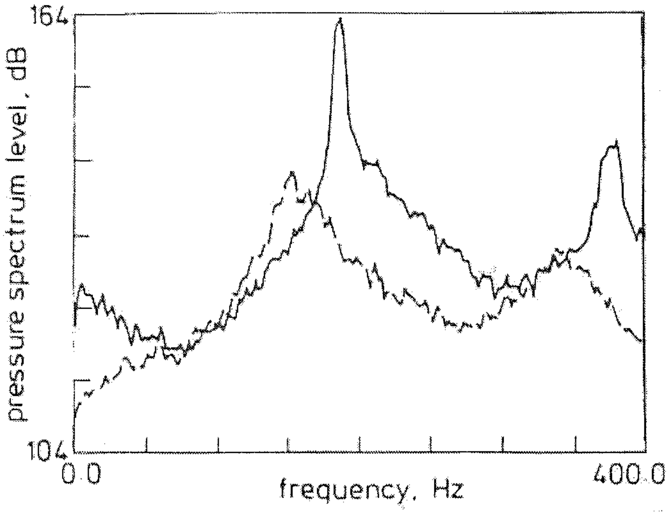

Figure 2 Pressure spectrum of a premixed ducted flame ----- stable, below critical fuel-air ratio
—— unstable, above critical fuel-air ratio
(from Macquisten & Dowling, 1993)

A generic system is illustrated in Fig. 1: the sensor(s) monitors the fluid system, feeding the measured signal(s) $S(t)$ to a controller, which responds by producing an output signal $V(t)$ to drive the actuator(s). The aim is that the combined system fluid, detector, controller and actuator should be stable. Viewed in the form of Fig. 1, active instability control looks like a standard control problem. However, there are some features of the control of instabilities of gas turbines that make this application particularly challenging. The 'fluid system' is distributed, i.e. the variables satisfy partial differential equations, it includes complicated fluid mechanics, e.g. wakes, combustion and turbulence, so that predictive models for the full system are not feasible. Although we may hope to develop sufficiently accurate models to provide help with the choice of location of the sensors and actuators and with the structure of the controller design, we cannot expect to predict all the control parameters. The system is open-loop unstable in part of its range. Moreover, the consequences of instability may be so traumatic that no open-loop data can be obtained in this regime, the frequencies of oscillation are high (up to 600Hz) and time delays of many periods of this oscillation are inherent in the system.

If a strategy for the active control of instabilities in gas turbines is to be practical, it needs to address all these issues. Moreover, it must be effective across all regimes of engine operation. In addition, the designer must be able to give guarantees that the controller will not go unstable and cause harm. This requires the integration of ideas from fluid mechanics, turbomachinery, combustion, control and systems engineering. It is a genuinely multidisciplinary research area. In the next section, we review some of the background, and then current issues are discussed in the following sections.

2. Background

The application of feedback control in both compression and combustion systems has followed similar development paths, starting with control of one-dimensional disturbances on small-scale laboratory systems, using loudspeakers as the actuator. In both cases this was followed by larger-scale control of one-dimensional oscillations. More recently control of circumferential modes in full-scale devices has been demonstrated.