Control of Combustion Instability

Pratt & Whitney FT8 gas turbine

Advances in combustion control are essential for developing engines for propulsion and power generation with high efficiency, increased performance, and low emissions. Lean-burning combustors are needed to meet stringent low-emission requirements and other design criteria, but such combustors are prone to instability.

The potential benefits of lean-burning combustors have been known for decades, as have the challenges. Significant progress was made with passive designs, but achieving the next level of performance improvement and emissions reduction requires integrating active control in the combustor.

From Passive to Active Control of Combustors

Combustion instability results from complex dynamic interactions between acoustics, heat-release, and vortex dynamics. Traditional approaches to controlling instability in combustion turbines have focused on passive mechanisms—no feedback control. One of the earliest examples was the F1 rocket engine, whose initial design, used in the Saturn V rocket, exhibited severe instabilities. Subsequently, a careful, model-based design of baffles helped eliminate the instability.

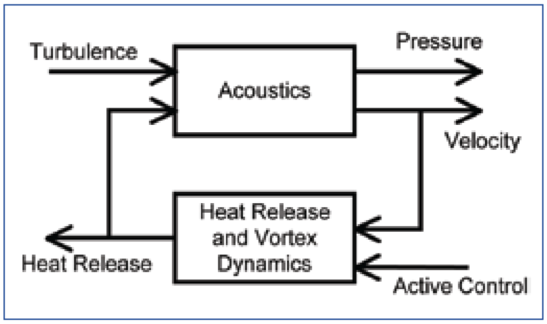
Another example of passive control is the Pratt & Whitney FT8 gas turbine, which features 13 Helmholtz resonators. These passive devices act as vibration absorbers—the geometry of the resonators is chosen so that the absorption is tuned to a particular frequency.

The inherent symmetry of the combustion chamber lends itself to certain natural acoustic modes that are driven into resonance because of the coupling with heat release. Several methods of breaking the symmetry were proven effective in quenching the combustion instabilities.

F1 rocket engine

In active control, incipient instability is dynamically detected and corrected. Active control requires:

- Measurements or estimates of key variables such as pressure and velocity
- Models of the heat release and acoustic phenomena that, in approximated form, can be implemented online
- Actuation capabilities
- Advanced control algorithms that can produce optimized actuation signals based on measurements and models



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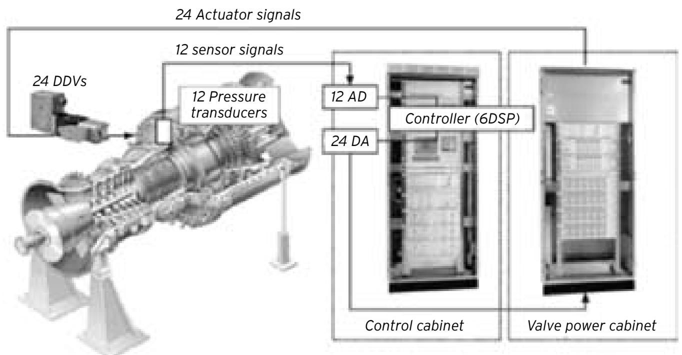
The Reality of Combustion Instability

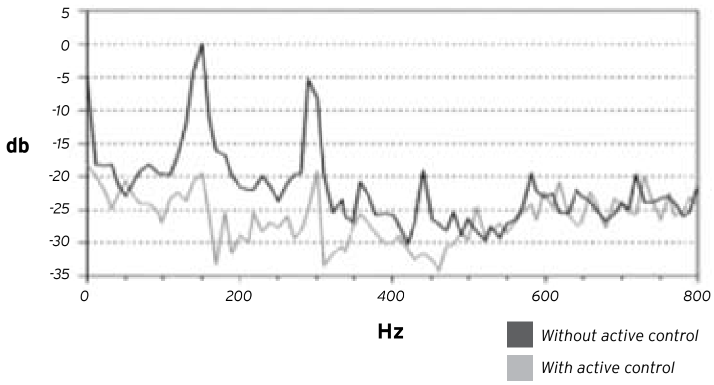
Combustion instability has been a serious problem for gas turbine manufacturers. *The Wall Street Journal* (February 23, 1998) reported the following issues:

- New turbines from a major U.S. and a major European manufacturer, both based on the same design, had to be temporarily shut down after bolts were found to have cracked inside the spinning engines.
- Turbines from another major European manufacturer experienced dangerous levels of vibration. Humming was reported in ring burners with associated flickering gas flames, as well as serious vibration and shaking loose parts. Fixing the faults was a long, sensitive, and costly problem for the manufacturer.
- Yet another major engine manufacturer had bits of the heat shield in their gas turbines break loose, snarling the engine blades.

Similar instabilities were reported in rockets and missiles in the 1960s.



Siemens V94.3A 267-MW gas turbine with control instrumentation



The reduction in acoustic pressure versus acoustic frequency

Active Combustion Control—Progress and Challenges

Fundamental research contributions from numerous academic and industrial organizations have led to a systematic model-based control methodology for instability suppression. Several proof-of-concept demonstrations have been carried out in scaled rigs and fields tests.

- Researchers at NASA GRC and UTRC demonstrated suppression of instabilities in the 300- to 500-Hz range in a single-nozzle combustor rig.
- Research at MIT and the University of Cambridge led to demonstration of instability control in a Rolls Royce RB199 afterburner.
- Instability suppression was demonstrated in the Siemens V94.3A 267-MW gas turbine (see figure above). This design was field-installed and demonstrated successful operation for more than 18,000 hours.
- A range of control design approaches, including advanced linear controllers and adaptive control methods, have been demonstrated successfully.

Major research challenges remain before active combustion control can be commercialized for aerospace propulsion engines:

- Reduced-order models that accurately capture the interactions between acoustics, heat release, vortex dynamics, inlet dynamics, and fuel delivery for a variety of geometries and flame-anchoring mechanisms.
- Controllers that accommodate the intrinsic unstable, infinite-dimensional, uncertain dynamics with limited sensing.
- Actuators such as high-speed valves that can modulate fuel flows in the range of 300 Hz to 1 kHz.