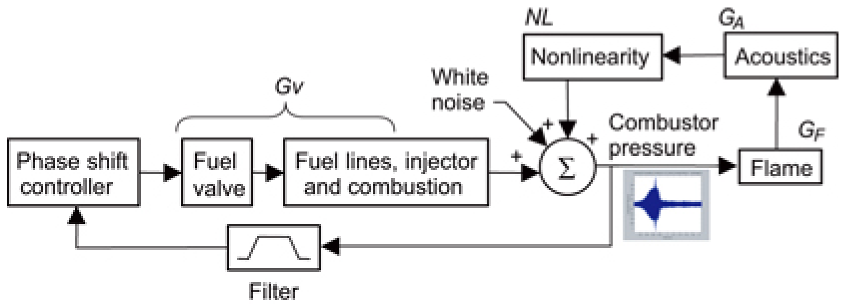
Innovative Adaptive Control Method Demonstrated for Active Suppression of Instabilities in Engine Combustors

This year, an improved adaptive-feedback control method was demonstrated that suppresses thermoacoustic instabilities in a liquid-fueled combustor of a type used in aircraft engines. Extensive research has been done to develop lean-burning (low fuel-to-air ratio) combustors that can reduce emissions throughout the mission cycle to reduce the environmental impact of aerospace propulsion systems. However, these lean-burning combustors are susceptible to thermoacoustic instabilities (high-frequency pressure waves), which can fatigue combustor components and even downstream turbine blades. This can significantly decrease the safe operating life of the combustor and turbine. Thus, suppressing the thermoacoustic combustor instabilities is an enabling technology for meeting the low-emission goals of the NASA Ultra-Efficient Engine Technology (UEET) Project.

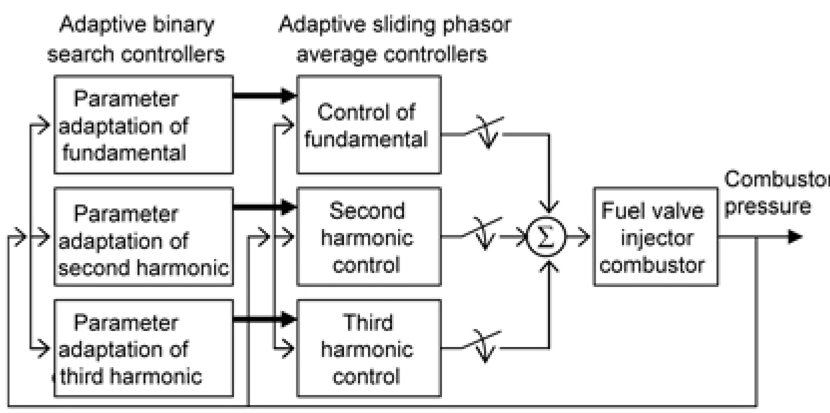
Combustor instability suppression poses a challenging feedback control problem because of unmodeled dynamics, large dead-time phase delays of a few cycles, combustor noise, large amplitude modulations, random phase walks, and a system that continuously transitions through inherently unstable operation at increased suppression levels. To overcome these difficulties, a sophisticated control approach was developed that does not depend on detailed modeling of system dynamics. In this control approach, named "adaptive sliding phasor-averaged control," the controller phase continuously slides back and forth inside the boundaries of an effective stability region that lies within a restricted control region in a stationary frame of reference. The combustor pressure oscillations are sensed through a band-pass filter to isolate the instability from the noise; the filtered pressure oscillations are continuously phase shifted at a rate of 40 Hz in the direction that suppresses the instability; and the phase-shifted pressure signal is used to command the fuel actuator at a rate of 10 kHz to suppress the instability. In addition, discontinuous exponential gain modulation and control parameter adaptation are employed to accommodate the effects of large dead-time phase delay in this process and also to better tune the controller as the control is applied.

This original combustion instability control method was shown to reduce thermoacoustic-driven combustor pressure oscillations and was demonstrated for a high-frequency (530-Hz) instability on a single-nozzle combustor rig at the United Technologies Research Center. This rig emulated an actual engine instability experience and has many of the complexities of a real engine combustor (i.e., an actual fuel nozzle and swirler, dilution cooling, etc.). This was the first known successful demonstration of high-frequency combustor instability suppression in a realistic aircraft engine environment.



Combustion instability control block diagram (adaptive sliding phasor-average controller); G_V, G_F, and $_{GA}$ are transfer functions of the associated combustion process reflected in the figure; NL is a damping nonlinearity that restricts the amplitude of the opened-loop self-excited instability.

Long description of figure. Instability control feedback diagram where the output combustor pressure (overall oscillating combustor pressure) feeds the flame transfer function, which feeds the acoustics transfer function, which feeds a soft limiting nonlinearity block whose output is an input to a summing block, whose output is the overall combustor oscillating pressure. This loop establishes the self-excited combustor instability. The overall combustor pressure is used for feedback and is fed to a band-pass filter to isolate the instability from the combustor noise. This feeds the adaptive phase-shift controller, which feeds the fuel valve and in turn the fuel lines, injector, and combustion block, whose output is the combustor pressure due to the controlled fuel modulation. This combustor pressure due to fuel modulation is another input to the summation block.

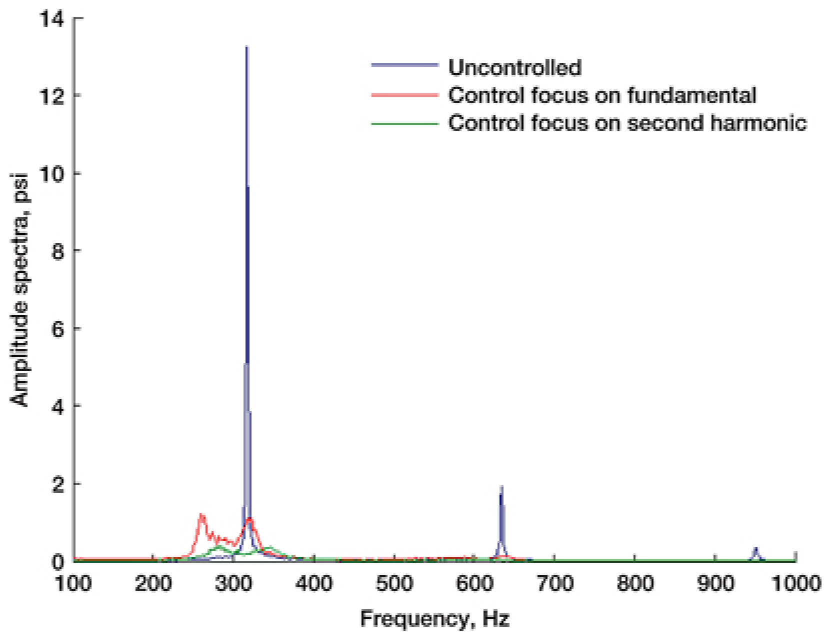


Modified combustion instability control block diagram.

Long description of figure Block diagram showing adaptive binary search controllers (parameter adaptation of fundamental, second harmonic, and third harmonic), adaptive sliding phasor average controllers (control of fundamental, second harmonic, and third harmonic), fuel valve injector combustor, and combustor pressure.

By analyzing these test results as well as results from an earlier low-frequency (~290-Hz) rig configuration, and from an aeronautics engine under development, we discovered a phenomenon called intraharmonic coupling, which causes energy coupling between the instability harmonics. This phenomenon was exploited in the control design by modifying the control algorithm to focus control selectively on the fundamental instability mode and/or any of its harmonics. The original combustor rig at United Technologies Research

Center was transferred and reassembled at Glenn. This rig was configured to simulate a more coherent instability at a lower frequency of approximately 330 Hz. Test results showed that by focusing control action on the second harmonic, both the amplitude spectra and the time-domain pressure oscillations of the instability were substantially reduced (considerably more than when control was focused on the fundamental mode of the instability). The amount of fuel modulation required to achieve this level of suppression was also substantially reduced. In addition, the higher order harmonics were eliminated for all practical purposes. The effects of focusing control action at harmonic frequencies higher than the second harmonic could not be studied in this test because of the limited control bandwidth of the fuel actuator. We plan to investigate this innovative control approach further as part of the low-emission combustor development effort under the UEET Project.



Amplitude spectra density of uncontrolled versus controlled instability for control focusing on the fundamental and the second harmonic.

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Find out more about Active Combustion Control at http://www.grc.nasa.gov/WWW/cdtb/projects/combustor/

Glenn contact: George Kopasakis, 216–433–5327, George.Kopasakis-1@nasa.gov
Author: George Kopasakis
Headquarters program office: Aeronautics Research
Programs/Projects: VSP, UEET