# Controlling Combustion

In this issue of *IEEE Control Systems Magazine*, we invite Prashant G. Mehta of the University of Illinois at Urbana-Champaign to respond to a query about controlling combustion. Readers are invited to submit technical questions, which will be directed to experts in the field. Please write to us about any topic, problem, or question relating to control-system technology.

**Q: In my course on propulsion and combustion, we are learning about flame stability and how it relates to efficiency and pollution. The professor mentioned that control can be used to improve the combustion process. It seems to me that it would be very hard to control something as complicated as combustion, which involves chemistry and thermodynamics. Do you have any information on that subject?**

***Prashant:*** Thank you for asking such a great question! Since the beginning of the 20th century, combustion processes have literally been at the heart of modern transportation. Combustors power the car you drive to work, the jet engines that fly you across the globe to attend control conferences, and the rockets that carried Neil Armstrong to the moon and will one day carry the first human to Mars and perhaps beyond.

Combustors present a wide range of engineering challenges, some of which are related to dynamics and control issues. Since it is not possible to address all the applications and challenges in one go, I will restrict my response to the issues surrounding control of combustion instabilities in jet engines and aerospace applications.

Combustion instabilities arise due to the destabilizing feedback coupling of acoustics with the unsteady heat released due to combustion. This coupling is referred to as a thermoacoustic loop (see Figure 1). First described by Rayleigh in 1845 [10], combustion instabilities have plagued the operation of virtually every jet engine. These instabilities lead to large pressure oscillations that if left unchecked can cause structural damage, including catastrophic failure of the engine (see [6] and [1] for recent reviews). You may be surprised to hear that combustion instabilities are the single-most important factor that limits performance in military jet engines [3].

Since the advent of global warming and concerns associated with environmental pollution, combustion efficiency has become a major concern. As it turns out, efficient combustors, which operate at a lean fuel-air mixture ratio, especially suffer from combustion instabilities. Hence, combustion control technologies can play a critical role in helping reduce environmental pollution. Research, development, and demonstration of these technologies are currently being pursued by several universities and industrial research centers.

The primary challenge in combustion instability modeling and control arises due to the complexity of the combustion dynamics. In jet engines, these dynamics arise due to a complex interaction among high Reynolds number fluid dynamics, heat released due to burning, chemical kinetics, and multiphase fuel transport. Turbulence is a subproblem here. We cannot realistically hope to obtain a control law starting from a first-principles model even if such a model could be written down.

A practical solution for control of combustion instabilities is based on fuel modulation. Figure 2 depicts a 12-MW, three-nozzle industrial combustor device that is used for active

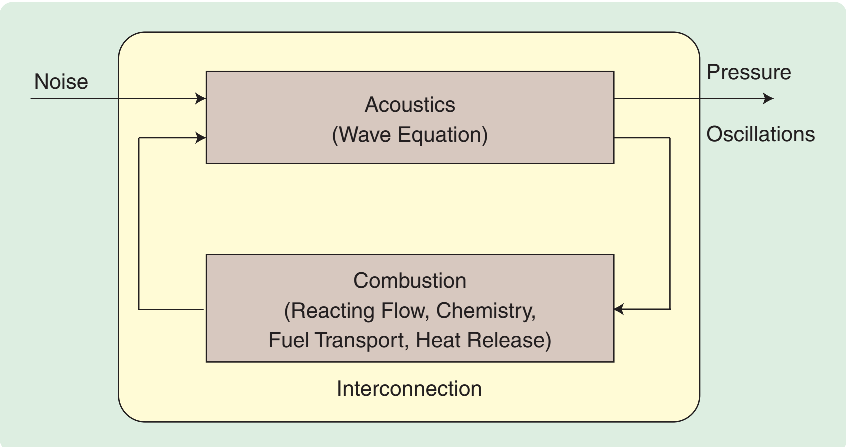


FIGURE 1 Schematic of the thermoacoustic loop. Detrimental thermoacoustic oscillations arise when the eigenvalues of the linearized feedback system cross the imaginary axis into the right-half plane.

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combustion instability control (ACIC) experiments. An annular combustor in a jet engine is comprised of several such devices arranged along the circumference. Additional details on the experiments can be found in [5].

Combustion instability leads to large pressure oscillations inside these devices. The active combustion instability control objective thus is to design a feedback controller that suppresses these oscillations. A pressure sensor is used to sense the oscillation and provide measurements for the feedback controller that modulates fuel. Between 10–17% of the total fuel is typically modulated using linear proportional or nonlinear on-off fuel valves. Fuel modulation has proven to be an effective approach for reducing pressure oscillations in combustors [5], [11], [9], [12], [7].

Figure 3 depicts the power spectral density of the pressure output with and without fuel control for the experiments. You may notice the phenomenon of *peak splitting*, whereby suppression in one frequency band is accompanied by amplification in other bands. The explanation for this phenomenon lies in a fundamental result of linear control theory, namely the Bode integral formula for the sensitivity transfer function. For a loop transfer function with relative degree two or greater, this formula implies a water-bed effect in the closed-loop transfer function, whereby attenuation in one frequency band is accompanied by unavoidable amplification in another.

In ACIC, performance limitations arise primarily due to limited actuator bandwidth and time delays. The time delays are comprised of propagation delays associated with fuel being convected to the flame front as well as the time it takes for the fuel-air mixture to mix and burn. Actuator bandwidth limitations arise due to rate limits on the mechanical valve movement for fuel modulation. Both delays and limited actuator bandwidth constrain the gain and frequency of the feedback control action and thus affect the achievable performance of ACIC systems.

Now that I have described the fuel-based ACIC technology and pointed to some of its limitations, let me get back to your question regarding the challenges of combustion dynamics. With regard to control, complications arise due to nonlinearities as well as the distributed nature of flame and fluid dynamics. In the following, I describe these effects in more detail.

The textbook explanation of thermoacoustic oscillations relies on a classical Hopf bifurcation analysis that assumes a linear model of

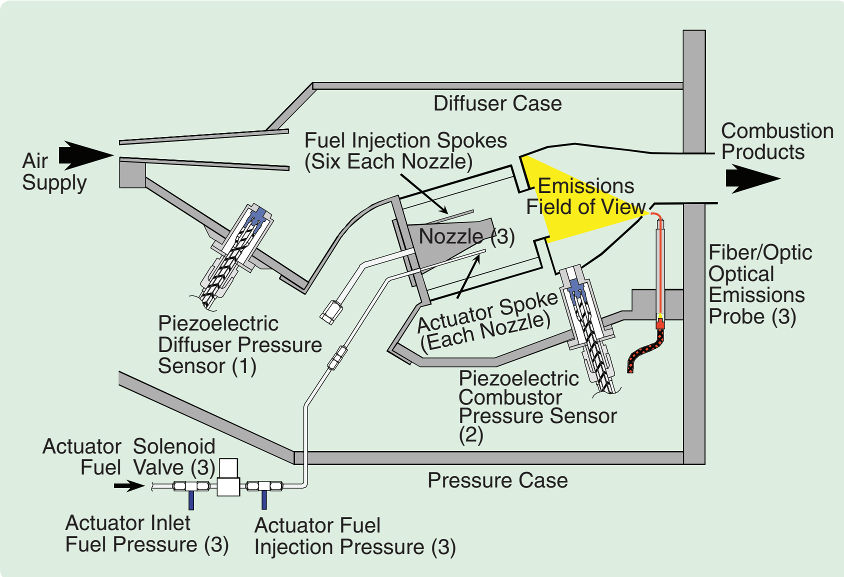


**FIGURE 2** Experimental setup for active combustion instability control using fuel modulation. An annular combustor in a jet engine is comprised of several such devices arranged along the circumference.

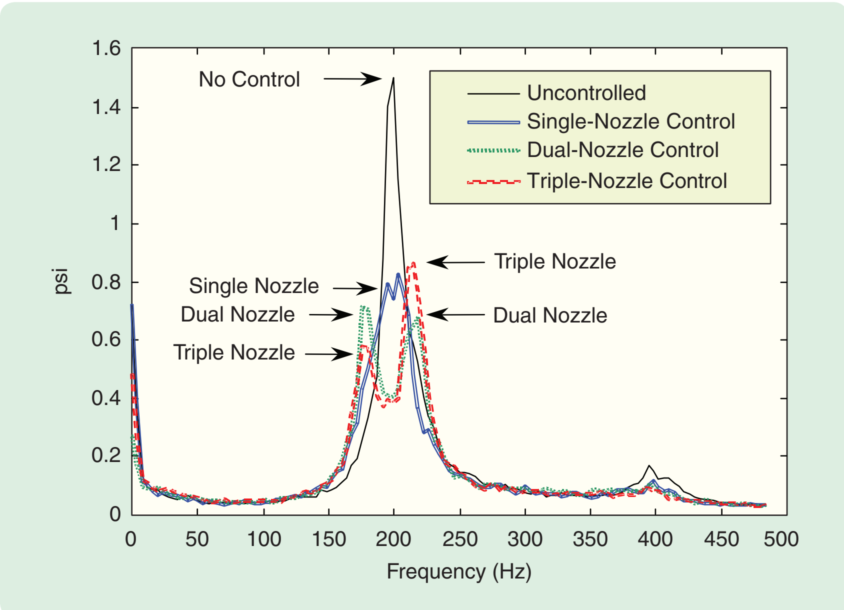


**FIGURE 3** Open- and closed-loop power spectral density of thermoacoustic pressure in experiments performed at the United Technologies Research Center. In these closed-loop experiments, a pressure sensor measures pressure oscillations and provides data to the feedback controller. Between 10% and 17% of the total fuel is modulated for control.

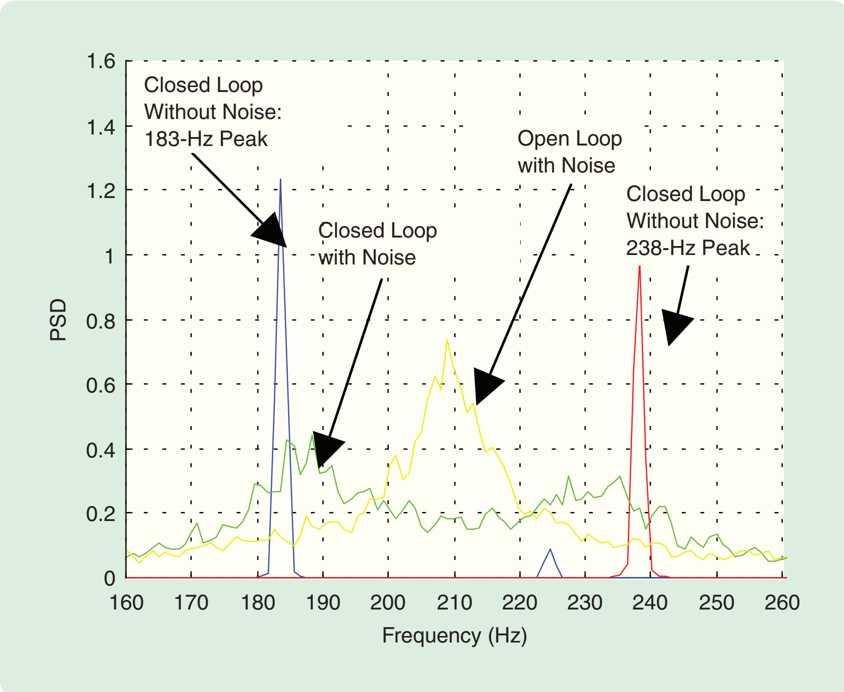


**FIGURE 4** Simulated power spectral density of the thermoacoustic pressure in a model of the thermoacoustic loop with and without noise. For low noise levels, the spectrum is discrete, and the control problem is a stabilization problem. For high noise level, the control objective is to reduce the thermoacoustic pressure over a broad frequency range (see [4] for details).

acoustics and a nonlinear model of combustion. The eigenvalues of the thermoacoustic interconnection are obtained by linearizing the combustion model about a steady operating condition. The first step in the analysis is to observe that the eigenvalues of the combustor-cavity acoustics are lightly damped. Next, feedback coupling due to linearized combustion dynamics causes one of the complex eigenvalue pairs to move into the right-half plane. The ensuing instability results in an exponential growth of thermoacoustic pressure. The linearized models capture only the initial phase of pressure growth because nonlinearities in combustion, such as saturation in burning rate, eventually limit the growth. A finite amplitude limit cycle results, where the amplitude is determined by the assumed model of nonlinearities in combustion.

In jet engines, the bifurcation picture is more complicated due to the presence of the background noise generated by processes both external (such as fan noise) and internal (such as flow noise) to the thermoacoustic interconnection. A Hopf bifurcation analysis predicts a limit cycle whose spectrum is discrete. However, the power spectral density of pressure time-series data in jet engine combustors is typically broadband as in Figure 4, which depicts the spectral density of the combustor pressure, obtained using a saturation-type nonlinear model of combustion, with and without noise. Describing function analysis shows that the presence of high noise levels can stabilize unstable eigenvalues by a dither-like effect [4]. Consequently, noise modeling is important for both analysis and control of oscillations. In particular, for low levels of noise, the control problem is a stabilization problem. For high levels of noise, however, the control objective is to reduce the thermoacoustic pressure over a broad frequency range (see figures 3 and 4). In the latter case, linear control approaches have proved useful in ACIC experiments [4], [1].

Although some papers assume a white noise model, unsteady phenomena related to fluid and flame dynamics contribute to noise. Unsteady fluid dynamics arise due to complicated vortex dynamics of high Reynolds number flow in the engine. The unsteady fluid dynamics both influences and is influenced by combustion processes including mixing of fuel and air and burning at the distributed flame front [3]. In experiments, the input-output model from fuel actuation to the pressure also depends on the operating conditions, such as temperature, altitude, and speed. For this purpose, adaptive feedback controllers are of interest [2].

In short, accurate modeling of combustion processes for ACIC remains a challenging area of research. In certain cases, it is possible to derive conclusions on analysis and control of combustion instabilities that are independent of combustion dynamics. One such model-independent approach for suppressing rotating wave combustion instabilities in annular combustors is to use only the symmetry of the combustion dynamics to carry out both the analysis of the instability and design for its suppression. The instability is explained as a result of skew symmetry in combustion dynamics and mistuning of mean properties such as temperature is used to obtain model-independent control of instability [8].

In closing, given the complexity of combustion dynamics, your question is very reasonable. I would be remiss in my answer if I did not point to the opportunities that come with the difficulties. Although complex behavior is detrimental in many settings, it may come as a bit of a surprise that some complex behavior is nondetrimental, even desirable. An example is the turbulent mixing that is critical for combustion. Without transition from the laminar to the turbulent flow state, the mixing of fuel with air is slow and inefficient to power jet engines. Whether we can systematically exploit the complex combustion dynamics for the purposes of control remains an intriguing open question. The interplay among instability, nonlinearities, noise, and feedback control is subtle and requires further research.

## AUTHOR INFORMATION

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## REFERENCES

[1] A. M. Annaswamy and A. F. Ghoniem, "Active control in combustion instability: Theory and practice," *IEEE Control Syst. Mag.*, vol. 22, pp. 37–54, 2002.

[2] A. Banaszuk, K. B. Ariyur, M. Krstic, and C. A. Jacobson, "An adaptive algorithm for control of combustion instability," *Automatica*, vol. 14, pp. 1965–1972, 2004.

[3] A. Banaszuk, P. G. Mehta, and G. Hagen, "The role of control in design: From fixing problems to the design of dynamics," *Control Eng. Pract.*, vol. 15, no. 10, pp. 1292–1305, Oct. 2007.

[4] A. Banaszuk, P. G. Mehta, C. Jacobson, and A. I. Khibnik, "Limits of achievable performance of controlled combustion processes," *IEEE Trans. Control Syst. Technol.*, vol. 14, no. 5, pp. 881–895, Sept. 2006.

[5] J. M. Cohen, N. M. Rey, C. A. Jacobson, and T. J. Anderson, "Active control of combustion instability in a liquid-fueled low-NOx combustor," *ASME J. Eng. Gas Turbines Power*, vol. 121, no. 2, pp. 281–284, 1999.

[6] A. P. Dowling and A. S. Morgans, "Feedback control of combustion oscillations," *Annu. Rev. Fluid Mech.*, vol. 37, pp. 151–82, 2005.

[7] J. P. Hathout, M. Fleifil, A. M. Annaswamy, and A. F. Ghoniem, "Active control of combustion instability using fuel-injection in the presence of time-delays," *AIAA J. Propulsion Power*, vol. 18, no. 2, pp. 390–399, 2002.

[8] P. G. Mehta, G. Hagen, and A. Banaszuk, "Symmetry and symmetry-breaking in wave equation with feedback," *SIAM J. Appl. Dyn. Syst.*, vol. 6, no. 3, pp. 549–75, July 2007.

[9] C. Paschereit, E. Gutmar, and W. Weisenstein, "Control of combustion driven oscillations by equivalence ratio modulations," in *Proc. Int. Gas Turbine and Aeroengine Congress & Exposition,* Indianapolis, IN, June 1999, ASME Paper 99-GT-118.

[10] J. W. S. Rayleigh, *The Theory of Sound*, vol. 2. New York: Dover, 1945.

[11] S. S. Sattinger, Y. Neumeier, A. Nabi, B. T. Zinn, D. J. Amos, and D. D. Darling, "Sub-scale demonstration of the active feedback control of gas-turbine combustion instabilities," *ASME J. Eng. Gas Turbines Power*, vol. 122, pp. 262–268, 2000.

[12] J. Seume, N. Vortmeyer, W. Krause, J. Hermann, C. Hantschk, and P. Zangl, "Application of active combustion instability control to a heavy duty gas turbine," *ASME J. Eng. Gas Turbines Power*, vol. 120, pp. 721–726, 1998.