Nonlinear self-excited oscillations in a thermoacoustic system

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ABSTRACT

Spontaneous pressure and heat release rate oscillations can get excited in a confined combustion system (for example, gas turbines and furnaces) due to coupling between the acoustic modes of the system and unsteady heat release rate from the source of combustion. These self-excited oscillations result in high noise levels, increased emission of NOx gases and reduced life span of the combustion system. In extreme cases, the emergence of such oscillations can lead to complete system failure. Hence, there is a huge impetus for investigations on thermoacoustic instability in practical combustion systems.

In order to investigate self-excited thermoacoustic oscillations, we conducted an experimental bifurcation analysis for a simple combustion-driven system. The system comprises of a ducted, laminar conical premixed flame with a single flame and the flame location relative to the duct is considered as the control parameter for the bifurcation analysis. We observed that the system exhibits a variety of characteristically different self-excited nonlinear oscillations for different control parameter values. Pressure and flame intensity time series data were acquired and subsequently analysed using nonlinear time series analysis based on phase space reconstruction discussed by Abarbanel *et al.* [1]. The asymptotic states at different control parameter values and the bifurcations were identified and invariant measures such as the correlation dimension and the maximal Lyapunov exponents were calculated for the obtained attractors.

The onset of thermoacoustic instability is marked by a subcritical Hopf bifurcation [2] of the steady state to limit cycle oscillations. This is further followed by a Neimark-Sacker bifurcation leading to the emergence of quasi-periodic oscillations. The quasi-periodic state is followed by a chaotic state via a Ruelle-Takens scenario [3]. The sequence of bifurcations identified for the system has been summarised below.

$$Steady\ state \xrightarrow{sub-critical\ Hopf\ bifurcation} Periodic\ oscillations \xrightarrow{Neimark-Sacker\ bifurcation}$$

$$Quasi-periodic\ oscillations \xrightarrow{Ruelle-Takens\ scenario} Chaotic\ oscillations$$

This dynamical behavior is reflected in the high-speed images of the flame as the flame dynamics is different in the different regimes of oscillations.

The investigation shows that thermoacoustic systems can exhibit complex oscillations in addition to limit cycle oscillations. Practical combustion systems are highly susceptible to frequencies corresponding to natural acoustic modes of the structural components, as presence of such oscillations can lead to structural resonance and can lead to immediate failure. This is more likely to happen during quasi-periodic or chaotic states. Additionally, such aperiodic behavior will cause variable amplitude loading to the structural components, which is known to cause a higher fatigue to the structures, when compared to limit cycle oscillations. Hence such oscillations will reduce the performance and the life span of the system. In this investigation, we arrived at certain interesting results on the nonlinear dynamics of thermoacoustic instabilities through the application of nonlinear time series analysis. In practical systems, it is important to consider such behavior of thermoacoustic oscillations to ensure stable and safe operation.

REFERENCES

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