Modeling turbulent thermoacoustic transitions using a mean-field synchronization approach

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Abstract. We develop a mean-field synchronization model where the heat release rate fluctuation within the confinement is modeled as an ensemble of phase oscillators evolving under the influence of acoustic pressure oscillations. The model captures the continuous and abrupt transition to thermoacoustic instability observed in disparate combustor configurations. Most importantly, the model captures spatiotemporal synchronization and pattern formation, which underlies the observed transition. The model encapsulates states of spatiotemporal desynchronization, chimeras, and global phase synchronization very well. The generality of the model highlights the possibility of extending the present model to predict limit cycle transitions in other fluid dynamical systems beyond thermoacoustics.

Introduction

Thermoacoustic instability in gas turbine combustors has disastrous consequences and presents a significant challenge in developing next-generation aircraft and power generation engines [1]. These instabilities develop through spatiotemporal synchronization of pressure and heat release rate fluctuations, resulting in self-sustained oscillations [2]. The instability is notoriously difficult to predict and control, and can have disastrous consequences such as severe damage to the engine components and even mission failures [3]. Therefore, the motivation of the present model comes from the observation that the transition to the state of thermoacoustic instability is associated with the emergence of global phase synchronization of the acoustic pressure and heat release rate fluctuations [2, 4]. In this study, we consider the flame response as an ensemble of phase oscillators restricted to evolve at a collective rhythm under the influence of acoustics. We derive the limit cycle solution using the method of averaging and estimate the amplitude and phase of the limit cycle oscillations for the thermoacoustic mean-field model. We demonstrate the applicability of the model in capturing both continuous and abrupt transitions to limit cycle oscillations. We show that the model is able to describe disparate transitions based on the underlying synchronization characteristic. We depict that the continuous and abrupt transitions to the limit cycle oscillations are associated with second-order and first-order synchronization transitions, respectively.

Results and Discussions

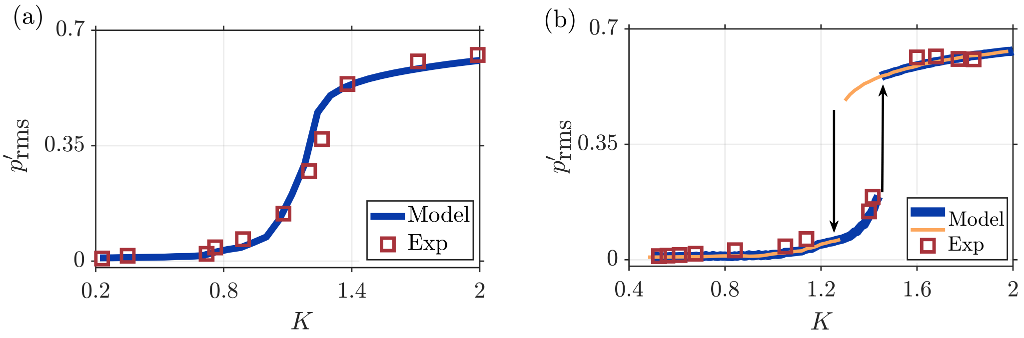

Figure 1: The bifurcation plot depicts the variation of normalized p'_{rms} as a function of coupling strength (K) in different combustors.

Figure 1 shows the comparison of the bifurcation diagram obtained from the model (–) and experiments (□). In figure 1a, we show a continuous, sigmoid-type transition to the state of thermoacoustic instability through intermittency observed in the bluff-body dump combustor when the control parameter (K) is varied. In contrast, figure 1b exhibits an abrupt transition to the state of high-amplitude thermoacoustic instability through intermittency and low-amplitude thermoacoustic instability observed in the swirl-stabilized dump combustor. Importantly, the model has the ability to capture the states of spatial desynchronization, chimera, and synchronization underlying these transitions (not shown here). Therefore, we believe the model emerges as a powerful tool capturing the synchronization characteristics underlying different transitions by taking frequency distribution from an experimentally measured heat release rate spectrum as the only input.

References

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