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Nonlinear determinism in degenerated combustion instability in a gas-turbine model combustor

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HIGHLIGHTS

- We studied the dynamic behavior of degenerated combustion instability.
- Nonlinear forecasting has potential use for extracting nonlinear determinism.
- The multiscale CECP is valid for exploring the presence of chaotic dynamics.
- Complex networks are useful for dealing with combustion dynamics.

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ABSTRACT

We present a detailed study on the dynamic behavior of pressure fluctuations in degenerated combustion instability [Gotoda et al. Phys. Rev. E 92 (2015) 052906] in a lean premixed gas-turbine model combustor in terms of symbolic dynamics, statistical complexity, complex networks, and nonlinear forecasting. The permutation spectrum test enables us to extract nonlinear determinism in degenerated combustion instability. The possible presence of chaotic dynamics in degenerated combustion instability is reasonably shown by considering the multiscale complexity–entropy causality plane incorporating a scale-dependent approach.

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1. Introduction

Nonlinear time series analysis inspired by dynamical systems theory has revealed the deterministic nature hidden in complex phenomena, leading to a review of standard and conventional methods of linear analysis such as the power spectrum [1]. Recent advances have led to constructive attempts to encompass the understanding of the nonlinearity in dynamics observed in many disciplines from physics to engineering [2]. The potential utility of dynamical systems theory for magneto-hydrodynamic instability [3], flame front instability induced by swirl/buoyancy coupling [4,5], radiative-heat-loss-induced flame front instability [6–8], and spatiotemporal chaos in a falling film flow [9] has been highlighted by one of the authors. Self-excited thermoacoustic combustion oscillations involving large-amplitude oscillations of a pressure field arise in a confined combustion system, leading to grave structural breakage in engines such as gas-turbine and related propulsion systems. The detailed physical mechanisms of the self-sustainment stemming from the intense mutual coupling of fluctuations in the unsteady pressure field and heat release ratio have been excellently summarized by Lieuwen [10]. Thermoacoustic combustion oscillations possess diverse highly nonlinear dynamics, and their characterization

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is an important subject in a broad range of areas in present-day combustion science and engineering. Progress on the characterization is being made through nonlinear time series analysis based on dynamical systems theory. The emergence of quasi-periodicity, intermittency, and chaos has been intensively explored for various types of confined combustors both with and without turbulent flow conditions [11–16], showing the high applicability of nonlinear time series analysis for extracting the hidden nature in complex combustion dynamics. We have also carried out detailed studies [17,18] on the presence of stochastic dynamics dominated by anti-persistence process, low-dimensional chaos, and periodic oscillations, focusing on the transition process from blowout to thermoacoustic combustion oscillations in a lean premixed gas-turbine model combustor. These studies have quantified the various types of nonlinear nature: the parallelism of nearby trajectories in phase space based on orbital instability, the singularity spectrum in terms of self-affine structure, and the short-term predictability and long-term unpredictability. Our recent study [19] has shown the possible existence of quasi-periodic oscillations and chaos in the degeneration of thermoacoustic combustion oscillations using the maximal Lyapunov exponent, which is commonly used in conventional nonlinear time series analysis. We also used color-coded recurrence plots to visualize the order and disorder patterns of the distances between the phase space vectors, and the local predictor model to extract the short-term predictability and long-term unpredictability.

The main purpose of this study is to conduct an in-depth analysis to show the possible presence of nonlinear determinism in degenerated combustion instability in terms of symbolic dynamics, statistical complexity, and nonlinear forecasting based on a neural network. Shannon entropy considering the probability distribution of possible existing rank order patterns in a time series, referred to as the permutation entropy proposed by Bandt and Pompe [20], is a useful nonlinear measure that incorporates the concept of symbolic dynamics. It has been widely applied to a wide spectrum of physical settings from the nonlinear dynamics of a falling thin film flow [9,21] to flame front instability induced by radiative heat loss [6]. We first consider the permutation entropy to quantify the randomness of combustion dynamics. The permutation spectrum test proposed by Kulp and Zunino [22] has potential use for distinguishing chaotic and stochastic dynamics. Its practical utility for the study of thermoacoustic combustion systems has been clearly shown by Tony et al. [23]. We also use the permutation spectrum test in this study. In addition to the permutation spectrum test, another useful method of nonlinear time series analysis in terms of statistical complexity for distinguishing nonlinear deterministic dynamics from stochastic dynamics, referred to as the complexity–entropy causality plane, has been proposed by Rosso et al. [24]. It can quantify not only the randomness of dynamics but also the degree of disequilibrium, and has been adopted for turbulent plasmas in the area of fluid physics [25]. On the basis of a previous study by Li and Zuntao [26], in this study, we consider the multiscale complexity–entropy causality plane [27] incorporating the variations in the delay time of the phase space to test for the determinism in degenerated combustion dynamics. A nonlinear deterministic process has the important feature of short-term predictability. A generalized basis function network, which is a neural network based on regularization theory, has been shown to ensure reliable performance in quantifying the short-term predictability of nonlinear deterministic process. It can be treated as an inverse approach in the sense that a predictive model constructed from the observed temporal behavior expresses the underlying nonlinear dynamics. The importance of the generalized radial basis function network has been reported in previous studies [18,28] on combustion instability. We adopt the generalized radial basis function network to test whether or not nonlinear deterministic process is dominant in degenerated combustion dynamics. The rest of this paper is organized as follows. In Section 2, we provide a brief description of the experimental apparatus and method. In Section 3, we describe the mathematical treatment in nonlinear time series analysis. We present the results and a discussion in Section 4, and concluding remarks are given in Section 5.

2. Experiments

We employ a lean premixed swirl-stabilized combustor with a length of 630 mm and a 100×100 mm^2 cross section, which is identical to that used in a previous study [29]. A swirler with a vane angle of 45 deg relative to the premixture stream inlet is used as a flame holder. Air preheated to 700 K is supplied to the combustor while maintaining a mass flow rate of 78 g/s. Methane is used as the main fuel in this study. The overall flow field in the combustion chamber mainly consists of two stable recirculating flows: (1) a vortex breakdown bubble at a location away from the centerbody induced by a strong swirl and (2) a recirculation flow in the damp region of the combustion wall owing to the backward-facing step flow. Dynamic behavior of two predominant flames: an inverted-conical flame sustained by (1) and a rim flame sustained by (2), has a significant impact on the formation of thermoacoustic combustion oscillations in our experiments. The heat release rate significantly fluctuates in the formation regime of the rim flame during thermoacoustic combustion oscillations that satisfy the Rayleigh criteria [29]. These fluctuations are induced by mutual interference between the flame front and convective large-scale vortical structures in the shear layer. We use two pressure transducers (Kulite Semiconductor Products, Model XTEL-190-15G): one is set 10 mm downstream from the inlet of the combustion chamber so as to capture the significant changes in the pressure field owing to the spatiotemporal fluctuations of the rim flame, and the other is set 150 mm upstream from the inlet of the combustion chamber to study the dynamic behavior of pressure fluctuations of the premixture. Note that only the former was used in the previous study [19]. We analyze the simultaneously measured pressure fluctuations at a sampling frequency of 25.6 kHz. Similarly to in the previous study [19], we consider a range of equivalence ratios ϕ from 0.52 to 0.59 to focus on degenerated combustion dynamics. One of our primary interests in this study is to investigate whether or not the degeneration process affects the coupling of both pressure fluctuations. Time series of pressure fluctuations at $\phi = 0.56$ are shown in Fig. 1 as a representative case ((a) inside the combustion chamber and (b) in the premixture region).

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