Non-periodic motion of a Bunsen flame tip with burner rotation

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Introduction

Chaotic flame motions are of fundamental interest to combustion instability issues, and also to turbulent flame research. Several type of chaoic motions in premixed flame (e.g., Bunsen flame subjected to acoustic forcing [1], [2], pulse combustion [3], [4], flat flame [5]), have been experimentally investigated. With respect to an rotating Bunsen flame, we recently showed that as both the jet flow velocity and burner rotation rate increase under the condition of $Le > 1$, the buoyancy-induced flame tip motion varies from periodic to non-periodic chaotic motion through quasi-periodic motion, adopting the analytical method based on a deterministic chaos theory (attractor and correlation dimension) [6]. In real experimental system, however, noises are always included in the time series data and make it difficult to confirm the data is deterministic or not. In order to test the data, the statistical null hypothesis procedure, i.e., surrogate data method proposed by J. Theiler [6], is recently widely applied.

The objective of the present study is, then, to investigate the nonlinear deterministic characteristics in real time series data of the non-periodic oscillating flame tip on a rotating Bunsen flame, adopting the surrogate data method.

Experimental Apparatus and Method

The rotating burner system is the same as that used in our previous works [7]. A short honeycomb is installed in the burner tube to give rigid-body rotation of the premix mixture. Rich CH_4-Air mixture at the equivalence ratio ϕ =1.43 is used in the present study, since it forms a typical non-periodic oscillating flame at the mean axial flow velocity U = 1.1m/s. The burner tube is rotated up to 2800 rpm. To normalize the flow-rotation, a swirl number S is introduced as functions of burner rotation rate and mean flow velocity [7].

To obtain time series of the non-periodic oscillating flame motions, a laser tomographic technique is used as shown in Fig. 1 [7]. Silicon oil droplets about 1 ~ 2 μm in diameter are used as scattering particles. The upstream side of the flame zone is then determined as the vaporized front of the silicon oil droplets. A slit (3mm × 25μm) is set at the focal plane in front of a photomultiplier along the centerline to detect the motion in the flame tip. Mie scattering intensity through the slit is proportional to the height of the flame tip. The output current from the photomultiplier (Hamamatsu, C1556) shows the time series variation in the one-dimensional motion of the flame tip. The time series signal from the photomultiplier is recorded by a digital recorder (Teac Co., RD-125). The sampling frequency in the present study is 1kHz, and the data number n is 15,000 for each analysis

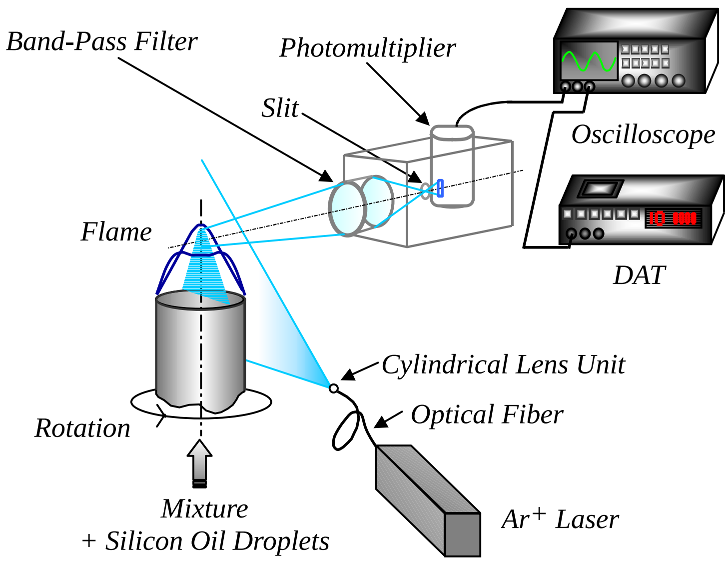

Fig. 1 Measurement system of flame tip motion

In the present study, the attractor is reconstructed from the time series data based on Taken's embedding theorem. This embedding theorem used in the present study is similar to the one Sterling used for pulse combustion [3], which is reported in our previous paper [7].

Two types of surrogate data method, based on the algorithm proposed by Theiler et al. [6], are used in a way similar to its use in Refs. [8] as following:

(1) RS surrogate method (Random Shuffled surrogate method)

Uniform random numbers are produced and then shuffled to follow the rank order of the original time series. The statistics histogram of the original data is preserved in this method.

(2) FT surrogate method (Fourier Transformed surrogate method)

The algorithm is based on the null hypothesis that the data come from a linear Gaussian process. The original time series and surrogate data sets have an identical power spectrum.

The surrogate data method assumes existence of stochastic process against time series as a null hypothesis. If the time variation in original data is different from the surrogate data, the null hypothesis can be rejected, resulting in the dynamics of the original time series is evaluated as deterministic chaos.

Experimental Results and Discussion

Time variations in the original data, RS(Random Shuffled surrogate method) surrogate data, and FT(Fourier Transformed surrogate method) surrogate data are shown in Figs. 2 as well as the reconstructed 3-dimensional attractor ($\Delta y_f(t)$, $\Delta y_f(t+\tau)$, $\Delta y_f(t+2\tau)$). Here, Δy_f is defined as the deviation of the flame tip location from the centerline. When the RS surrogate method is applied to the original data, the characteristic of the original data is completely destructed. This indicates that the original data is not produced by the white noise. The time series and the attractor of FT surrogate data seem to have similar characteristics with original data. It suggests that it is difficult in this stage to distinguish the original data from the FT surrogate data. In other words, some stochastic properties are supposed to be included in the data. These results indicate that detailed deterministic properties of real complex time series data can be addressed when the data are analyzed by the surrogate method.

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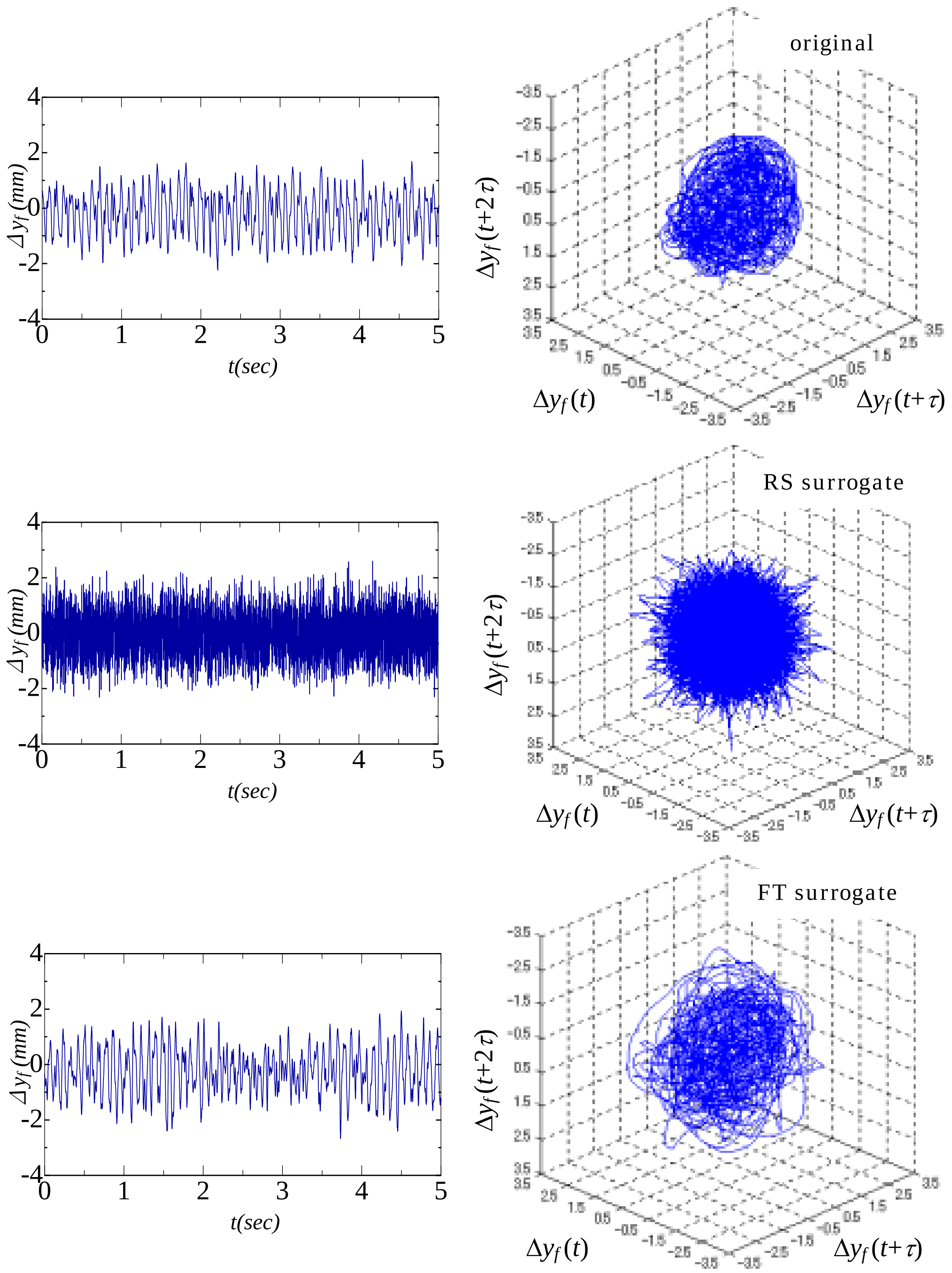

(a) time series data

(b) attractor

Figure 2 Comparison between original data, RS surrogate data and FT surrogate data