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Quantification of scaling exponent with Crossover type phenomena for different types of forcing in DC glow discharge plasma

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HIGHLIGHTS

- Effect of external forcing is investigated on the scaling exponent obtained via detrended fluctuation analysis (DFA).
- Two prominent scaling regions are observed when external forcing is added on chaotic fluctuation (P = 0.04 mbar).
- We have carried out DFA analysis to quantify scaling exponents for different amplitudes of sinusoidal, square forcings (at P = 0.12 mbar) and we identify crossover phenomena for P = 0.04 mbar.
- The transition in the dynamics is observed through recurrence plot, recurrence quantification analysis.
- In case of sinusoidal, square forcing applied on fluctuation acquired at P = 0.12 mbar only one dominant scaling region is observed.

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ABSTRACT

We have carried out a detailed study of scaling region using detrended fractal analysis test by applying different forcing likewise noise, sinusoidal, square on the floating potential fluctuations acquired under different pressures in a DC glow discharge plasma. The transition in the dynamics is observed through recurrence plot techniques which is an efficient method to observe the critical regime transitions in dynamics. The complexity of the nonlinear fluctuation has been revealed with the help of recurrence quantification analysis which is a suitable tool for investigating recurrence, an ubiquitous feature providing a deep insight into the dynamics of real dynamical system. An informal test for stationarity which checks for the compatibility of nonlinear approximations to the dynamics made in different segments in a time series has been proposed. In case of sinusoidal, noise, square forcing applied on fluctuation acquired at P = 0.12 mbar only one dominant scaling region is observed whereas the forcing applied on fluctuation (P = 0.04 mbar) two prominent scaling regions have been explored reliably using different forcing amplitudes indicating the signature of crossover phenomena. Furthermore a persistence long range behavior has been observed in one of these scaling regions. A comprehensive study of the quantification of scaling exponents has been carried out with the increase in amplitude and frequency of sinusoidal, square type of forcings. The scalings exponent is envisaged to be the roughness of the time series. The method provides a single quantitative idea of the scaling exponent to quantify the correlation properties of a signal.

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1. Introduction

In recent years there has been growing evidence that many physical and biological system have no characteristic length scale and exhibit a power law correlation. Traditional approaches such as power spectrum, correlation analysis are suited to quantify correlations in a stationary signal [1,2]. However many signals that are output of complex physical [3] and biological system are said to contain nonstationarity. Almost all methods of time series analysis, traditional linear or nonlinear, must assume some kind of stationarity [4]. A number of statistical tests for stationarity [5,6] in a time series have been proposed in the literature. Most of the tests we are aware of are based on ideas similar to the following: Estimate a certain parameter using different parts of the sequence. If the observed variations are found to be significant, that is, outside the expected statistical fluctuations, the time series is regarded as nonstationary. In case of traces of nonstationarity being detected, we are allowed to carry out modified root mean square analysis termed as detrended fluctuation analysis (DFA) [7]. The advantages of DFA is that it permits the detection of long range correlation embedded in a seemingly non-stationary time series and allows the detection of scaling exponent in noisy signal with embedded trend that can mask the true correlations. From a practical point of view if the fluctuations driven by uncorrelated stimuli can be decomposed from the intrinsic fluctuations generated by dynamical system, then these two classes of fluctuations may be shown to have different correlation properties. In the last one decade DFA has emerged as an important technique to study scaling and long range temporal correlation in a nonstationary time series [8] which has been extensively studied in literature. It has been successfully applied to the diverse areas of research such as DNA [9,10], neuron spiking [11], heart rate dynamics [12,13], economical time series, long time weather report [14]. DFA is based on the idea that if the time series contains nonstationarities then the variance of the fluctuations can be studied by successively detrending using linear quadratic, cubic higher order polynomial in a piecewise manner. Most real time series exhibit persistence i.e subsequent element of the time series are correlated [15]. The study of the self similarity and scaling in physics, socio economic sciences in the last several years has brought in new insights and new ideas for modeling them. For instance one of the important empirical results of the market dynamics is that the probability distribution of price returns r in a typical market displays a power law [16] i.e $P(r) \sim r^{\alpha}$ where α =3. Similar power laws appear for the cumulative frequency distribution of earthquake magnitudes [17]. While the spectral analysis (Fourier method), wavelet transform modulus maxima (WTMM) analyze the time series directly the DFA is based on the random walk theory, similar to the Hurst rescale range analysis. Presence of strong trends associated with nonstationarity can lead to the false detection of scaling exponent. So for the reliable detection of power law exponent (α) it is essential to distinguish trends [18] from the long range fluctuation [19,20] intrinsic in the data. Most economic and financial time [21–23]series are persistent with $\alpha > 0.5$. Changes in the dynamics during the measurement period usually constitute an undesired complication of the analysis. In many applications of linear (frequency based) time series analysis [24], stationarity has to be valid only up to the second moments (weak stationarity). Then the obvious approach is to test for changes in second or higher order quantities, like the mean, the variance, skewness, kurtosis [25–28]. The purpose of this paper is to discuss the matters pertaining to the study of the scaling exponent by applying different forcing amplitude along with the reliable detection of the change in the value of scaling exponent in different scaling region characterized as crossover phenomena [29].

Recurrence plot (RP) and Recurrence quantification analysis [30,31] is a relatively new and advanced technique which helps to identify different dynamical properties of a system under consideration. They have been extensively used in diverse fields such as earth science, plasma, earth science, economy to gain understanding about the nonlinear dynamics of complex system. It has also been utilized as an emerging tool to analyze simulation data of ion temperature gradient turbulence [32] and dissipative trapped electron mode turbulence [33] and to characterize transport dynamics. The knowledge of transition between chaotic, laminar or regular behavior is essential to understand underlying mechanism behind a complex system [34]. While linear approaches are not appropriate, there are several nonlinear methods that can suitably account for the transition. The traditional recurrence quantification analysis (RQA) [35] that does not require long time observation is one such appropriate nonlinear method. We can also graphically detect different patterns and structural changes in time series data using recurrence plot (RP's) which exhibit characteristic large and small scale patterns caused by the typical dynamical behavior [36].

The paper is organized as follows. In Section 2, we present a brief schematic of the experimental setup, followed by the results of the analysis of floating potential fluctuation, Recurrence plot, Recurrence quantification analysis in Section 3. Section 4 represent a comprehensive analysis of nonstationarity with detrended fluctuation analysis (DFA). The results of the analysis for DFA method to estimate the scaling exponent for different forcing amplitude along with the exploration of crossover phenomena have been carried out in Section 5. Conclusions are presented in Section 6.

2. Experimental setup

The experiments were carried out in a cylindrical hollow cathode DC glow discharge argon plasma with a typical density and temperature of $\sim 10^7/cm^3$ and 2–6 eV respectively. The chamber was evacuated by rotary pump to attain a base pressure of 0.001 mbar. Experiments were performed under different forcing amplitudes like sinusoidal, square, noise for two operating neutral pressure i.e 0.12 mbar, 0.04 mbar respectively with discharge voltage (DV) being fixed at 435 V. An unbiased Langmuir probe was used to obtain the floating potential fluctuations acquired with a sampling time of $1 * 10^{-6}$ s. A signal generator was also coupled with the DV through a capacitor for observing fluctuations in presence of forcing as shown in the schematic diagram of Fig. 1.

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