Complexity and onset of chaos control in a DC glow discharge magnetized plasma using all pass filter

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ARTICLE INFO

Article history:
Received 25 February 2017
Revised 27 May 2017
Accepted 20 July 2017
Available online 27 July 2017

ABSTRACT

Complexity dynamics of the plasma oscillations is explored under the variation of the discharge voltages in two constant magnetic fields and control of complexity, particularly chaos, has been achieved by using an all pass filter circuit. Appearance of the long diagonal lines in the recurrence plot of the controlled signal, strongly conjecture the regularity of the system after switch on the control. The negative to positive transition of the skewness and the significant change of the intensity of color in the wavelet spectrum also indicates the chaos to order transitions in the plasma system once the control is switch on.

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1. Introduction

Complexity and chaos are omnipresent in all real physical systems that develop a rich domain of research in nonlinear dynamics and gain a lot of attention in past two decades. Although chaos has wide applications in different fields of science and engineering, but still it is undesirable mainly due to its unpredictable nature and harmful consequences in the dynamical systems. Therefore, the investigation of complexity and the ability to control of complexity or chaos in a system is of much practical importance.

Plasma is a complex system which exhibits various modes of instability in presence of the external perturbation and the different control parameter. The instability causes complexity which appears as nonlinear phenomena in the dynamics of the plasma system, such as intermittency, homoclinic bifurcations, period doubling, strange attractors, and other routes to chaos [1-4].

Recent studies have revealed that chaos has a wide range of applications in various fields such as information transmission with high power efficiency [5], generating truly random numbers [6,7] and novel spread spectrum [8], ultra wide-bandwidth [9,10], and optical [11] communication schemes. For many of these applications, it is desirable to operate the devices in the fast regime where the typical time scale of the chaotic fluctuations is on the order of 1 ns [12,13].

Regardless of the intended application, chaos has some disadvantages too. Chaos leads vibrations, irregular operation and fatigue failure in mechanical system. It may develop temperature oscillations which may exceed safe operational conditions of thermal system [14].

Chaos in magnetized confined plasma may develop turbulence and lead to the anomalous energy and particle cross-field transport. Understanding and controlling complexity and chaos in low temperature plasma device is an important research problem due to its applications in low temperature plasma based procedure such as etching, spectro chemical analysis, deposition in thin film etc. All these circumstances lead the chaos control as a subject of intense research. Although several numbers of experimental and theoretical works are performed on the subject of chaos control in a complex system yet very few results have been reported in the plasma system. These works are mostly based on the algorithm proposed by Ott, Grebogi, York (OGY) [15] and Pyragas. A time-delayed feedback technique, suggested by Pyragas [16,17] seems to be more appropriate for the experiment than the OGY method.

All pass filters have a wide range of applications especially in the field of electronics. They are used for linear phase shifting, while keeping the signal amplitudes constant over the desirable frequency range. They can also be used to implement high quality-factor frequency-selective filters and to realize bi quadratic filters to synthesize quadrature and multiphase oscillators [18,19]. In addition, all pass filters are key components in the realization of time delays. All pass filters have also been finding applications in circuits that conventionally relied on digital delay stages. The conventional implementation of such circuits relies on analog-to-digital converters (ADCs) for digitizing the signals, which are subsequently passed through a digital FIR filter-based delay circuit.

The present work reports the investigation of complexity and the onset of chaos control in a DC glow discharge magnetized plasma oscillations in presence of an inverted fireball. A Langmuir probe is kept inside a spherical mesh grid which is...
connected to the constricted anode. The floating potential fluctuation shows different complexity patterns when discharge voltage is varied in presence of two constant homogenous low magnetic fields. An all pass filter is used to control the dynamics of the plasma oscillations. The power spectra, recurrence plot, wavelet analysis, skewness and kurtosis confirm that the complexity in the undriven magnetized sheath plasma oscillations have been suppressed when the elements of the all pass circuit are carefully chosen. Although the dynamical control of chaos has been demonstrated in other plasma systems, to the best of our knowledge, this is the first time that such control has been achieved in sheath plasma oscillations using an all pass filter circuit.

The paper is organized as follows: a brief review of the experimental setup and circuit diagram, are presented in the Section 2. Section 3 demonstrates the results and corresponding nonlinear analysis such as recurrence plot, skewness, kurtosis and wavelet analysis. Section 4 draws the conclusion.

2. Experimental setup

The experimental investigation is performed in collision less Argon plasma produced in a stainless steel cylindrical chamber of 50 cm in length and 40 cm in diameter. The schematic diagram of the experimental setup is displayed in Fig. 1. Such plasmas are nearly collisionless, quiescent and show different dynamical transitions viz. chaos to order, order to chaos, intermittency and homoclinic bifurcation and mixed mode oscillations with the variation of control parameter. Two mesh grids, cylindrical and spherical of optical transparency 80% is introduced vertically in the middle of the chamber. The cylindrical mesh grid is kept negative and the spherical grid is made positive and the whole chamber is grounded. The chamber is evacuated by a rotary pump to attain the base pressure of $9.2 \times 10^{-3}$ mbar. Argon gas is injected by a needle valve into the chamber to acquire the working pressure of $2.3 \times 10^{-3}$ mbar. A magnetic field is generated by Helmholtz coil wound over the chamber wall. The uniform axial magnetic field of up to 224 G is applied to confine the ions and electrons. Finally a discharge is struck by a 240 V DC discharge voltage. Three Langmuir probe of diameter 0.5 mm and length 2 mm are inserted inside the spherical mesh grid, outside the spherical mesh grid and outside the cylindrical grid. In the present work, we have considered the inside probe signal and all the analysis are carried out on this signal. The signal picked up by the inside Langmuir probe is acquired directly in a 4 channel digital oscilloscope with bandwidth up to 400 MHz and storage up to $2.5 \times 10^6$ samples. For control purpose, we have send the inside Langmuir probe signal to the all pass filter circuit. The output signal from the all pass filter is then visualized and stored in the oscilloscope. Typical plasma parameters viz., plasma density and electron temperature for various imposed conditions are found to be of the order of $10^8 - 10^9$/cc and 3 – 4 eV.

3. Results and discussions

The dynamics of the floating potential fluctuations are observed in different discharge voltages in presence of external magnetic field. The discharge voltage (DV) and the magnetic field are considered as the control parameter of the experiment. DV is varied from 270 V to 370 V in presence of two different magnetic fields such as 22 G and 42 G. The magnetic field is varied by varying the current passing through the Helmholtz coil. Fig. 2 shows the calibration curve of the magnetic field versus discharge current passing through the magnetic coil. In the present study, two mesh grids are introduced in the system, especially a luminous region is formed inside the spherical mesh grid, named inverted fireball [20–22] to observe the dynamical changes of the floating potential fluctuations. Inverted fireballs are considered as a glowing sheath region that forms within a highly transparent positively biased hollow grid electrode. When electrons from ambient plasma are accelerated into the spherical mesh grid they start to ionize neutrals inside the spherical grid and form the inverted FB, i.e. the fireball is trapped inside the spherical grid. We have observed that the oscillations of the floating potential fluctuations show spiky complex behavior from the very beginning of the discharge. It has been observed that the complexity is generated due to the presence of the mesh grids. It develops sheath around it that considered as the cause of the low frequency instability.

3.1. Control of chaos

In order to control the chaotic plasma oscillations, an active all pass filter (APF) is used in the experiment. The circuit and the corresponding block diagram are shown in the Figs. 3(a) and (b).
Block diagram presents that the signal (floating potential fluctuations) from the plasma system directly send to the input \( V_i \) of the all pass filter circuit and the output is considered as the controlled signal. The detailed analysis of the circuit has been recently reported [13,23]. The signal obtained by the inside Langmuir probe is passed through the all pass filter. We have continuously captured the signal of the floating potential fluctuations before and after passing through the all pass filter in different discharge voltages. We have used a first order all pass filter. The circuit is an analog circuit, consisting of two constant resistances, one capacitor and a variable resistance. The constant resistance \( R_1 \) and \( R_2 = 10 \Omega \), capacitor \( C = 1 \text{nF} \) and the variable resistance \( (R) \) is kept at 410 kΩ. The circuit has a single constant time-delay and it describes the nonlinearity. The delay of the circuit mainly depends on the variable resistance and the capacitance. In the circuit, the delay \( (T) \) is considered as 410 μs, calculated by \( T = RC \). The fundamental mode of the plasma oscillation is shown in the power spectra of the floating potential fluctuations [Fig. 3(c)]. We have chosen the circuit component to obtain the delay which will be nearer to the dominant frequency of the floating potential fluctuations. We obtain the frequency from the delay element as 345 Hz which is near to the experimental dominant frequency (302.8 Hz). It is noticed that when the floating potential signal is fed to the circuit, the dynamics of the oscillation is showing a sudden transition from complex to regular state. This transition to regular dynamics is clearly uncovered by the subsequent nonlinear and statistical analysis.

**3.2. Recurrence plot of plasma oscillation**

Recurrence plot (RP) analysis of nonlinear time series is a relatively new and advanced technique introduced by Eckmann et al [24]. RP develops on the basis of phase space reconstruction of a dynamical system. It gives visual information about the complexity associated with the system along with the quantitative measures reflected in the RP plot. In compliance with Taken’s embedding theorem [25] utilizing a time series data \( X(t) \) an embedding can be constructed applying the vector \( Y_i = X_{t_i}; X_{t_i+1} \) \( i = (d-1) \) where \( d \) is the embedding dimension and \( t \) is the time delay. False nearest neighbor and mutual information method [26,27] are usually used to estimate the correct embedding parameters preserving the topological property of phase space. The original time series is now
converted into a d-dimensional reconstructed phase space. Whenever a trajectory visits approximately the same region of phase space it considered as recurrence. It is a fundamental phenomenon of a dynamical system. The RP is a graphical representation of the square matrix $R_{ij} = H(\varepsilon - |Y_i - Y_j|)$ where $\varepsilon$ is a predetermined threshold, $H$ is the Heaviside unit step function. Both the axes of the graph represent the temporal extent to which the signal spans. There are several statistical measures to characterize the different structures appearing in a RP, they develop a diagnostic tool known as RQA [28-31]. The RQA measure determinism (DET) quantifies the ratio of the number of recurrence points in the diagonal lines to all the recurrence points. Determinism (DET) becomes close to unity for deterministic dynamics and approaches zero when the behavior is random as for random behaviour there will be no diagonal lines in the RP, only non-homogenously distributed black points will appear. Other parameters related to diagonal lines such as average diagonal line length or Shannon entropy (ENT) of the probability distribution of the diagonal line lengths also reflect the complexity of the deterministic structures in the system. The inverse of the longest diagonal $L_{max}$ in the RP is proportional to the largest Lyapunov exponent as it directly relates to the exponential divergence of phase space trajectory.

Figs. 4 and 5 show the RP of the signal of the floating potential fluctuations at 270 V, 310 V, 340 V and 370 V in 22 G and 42 G magnetic field. Figs. 4(a-d) and (a1-d1) show the RP of the floating potential fluctuations obtained before and after the control. Figs. 4(a-d) reflect very small diagonal lines associated with non-uniformly distributed recurrence points. At 270 V some small diagonals are visible which diminishes to RP points, with the further increase of discharge voltage at 300 V (Fig. 4(b)). Finally at 370 V the increasing complexity evolves the system dynamics to chaotic state. However in Fig. 4(a1-d1) recurrence point forms many diagonal lines that indicate the dynamics is emerging towards ordered state at the respective discharge voltages. It is seen that in lower discharge voltages the length of the diagonal lines are larger compare to higher discharge voltage which reflects that in higher discharge voltage the signals appears as quasi periodic (370 V).

However when magnetic field is increased further to 42 G the RP plot show prominent diagonal lines (Fig. 5(a1-d1)) which uncovers the periodicity emerging in the dynamics of the floating potential fluctuations. It is clearly observable in Figs. 4(a1-d1) and 5(a1-d1) that after the control the RP reflects long non interrupted diagonal lines which conjectured that the dynamics of the floating potential fluctuations are being controlled and move towards the periodic state. Moreover the RP reveals that the controllability of the plasma oscillation is sensitive to the applied magnetic field. It is observed that when magnetic field is increased from 22 G to 42 G the RP reflects more long diagonal lines. At 22 G the potential fluctuations shows transition from chaos to quasi periodic while at 42 G it traverse to periodic state. It uncovers that in higher magnetic field control is better and signals are becoming more periodic.

3.3. Skewness and kurtosis

The degree of asymmetry of a distribution around the mean data is characterized by the statistical measures, skewness. Skewness and kurtosis are well known statistical tools to investigate the complexity of the raw data in the glow discharge plasma system [32]. A distribution will be symmetric if it looks same to both left and right from the centre point. When the data are concentrated more to the left of the mean than to the right skewness shows negative and vice versa. The value of skewness of the normal distribution (Gaussian distribution) is always zero. Skewness of a distribution of a data is estimated by

$$S = E\left[\left(\frac{X - \mu}{\delta}\right)^3\right]$$

Where $x$ is the data, $\mu$ is the mean of $x$, $\delta$ is the standard deviation of $x$, and $E$ is the expected value of the quantity.

The peakedness or flatness of a distribution of fluctuations around the data mean is estimated by kurtosis. A higher and lower value of kurtosis reflects a sharper peak and flatter peak than the normal distribution, with values concentrated around the mean of
the distribution. For the normal distribution, kurtosis becomes 3. Kurtosis of a distribution is given by

\[ k = E \left( \left( \frac{X - \mu}{\delta} \right)^4 \right) \]

Where \( x \) is the data, \( \mu \) is the mean of \( x \), \( \delta \) is the standard deviation of \( x \), and \( E \) is the expected value of the quantity.

Fig. 5 shows the skewness and kurtosis of the floating potential fluctuations before and after the control at the 22 G magnetic field. The skewness shows an increasing trend with the increase of the discharge voltage. When control is not applied skewness reaches the maximum at 330 V (3.45) and then started to decrease. The similar increasing trend is observed for the case of kurtosis also. It has been seen that up to 330 V the kurtosis is increasing and appears maximum (43.33) at 330 V.

With the further increase of discharge voltage, it shows the decrease. The skewness of control signal shows negative value for all the discharge voltages. Hence it is evident that when control is applied the signal becomes ordered.

Overall skewness shows positive to negative transition which reveals the dynamical transition of the plasma dynamics toward order state. It has been observed that very small variation exist in both the skewness and kurtosis in the controlled signal. However, this explores that control is consistent throughout all the variation of the discharge voltages.

Fig. 6(a) display the skewness of the floating potential fluctuations before and after the control at the 22 G magnetic field. The skewness shows an increasing trend with the increase of the discharge voltage similar to the 22 G magnetic field. Skewness reaches maximum (4.59) at 310 V and then starts to decrease. We observed that the skewness of the controlled signal shows almost linear behavior with respect to the discharge voltage.

Fig. 6(b) shows kurtosis of the floating potential fluctuations of the controlled and uncontrolled signal. Kurtosis is increasing with respect to discharge voltage. Kurtosis becomes maximum (49.12) at 310 V and then start to decrease with the further increase of discharge voltage. It is seen that both the skewness and kurtosis show the similar trend.
It is noticed that in both the change of the magnetic field, after the control, the signal of the floating potential fluctuations shows almost similar behavior which uncovers that the complexity of the signal decreases after the application of the all pass filter signal. It elucidates that the complexity is suppressed and dynamics evolves towards regular state when control is activated.

3.4. Wavelet analysis

Wavelet analysis is an advanced and well-known technique which gives an additional benefit of local investigation of frequency spectra compared to the Fourier spectra [33,34]. Wavelet decomposes the signal in different scales and extracts the hidden information of the time series. Scaling and shifting are two operations of the wavelet. Shifting indicates the displacement of the wavelet with respect to time and scaling presents the contraction and expansions of the wavelet. It converts the original time series into frequencies and reveals the time scale at which the frequency occurs. The wavelet transforms are mainly of two types i.e continuous wavelet transform (CWT) and discrete wavelet transform (DWT).

For the present work, we have used time-scale decomposition using the Daubechies (db4) orthogonal wavelet function of the MATLAB software to detect the chaos-order transition of the dynamics of the floating potential fluctuations. Here for a particular voltage at DV = 340 V in 22 G the wavelet analysis has been displayed to corroborate the other analysis. It gives an additional evidence of the emergence of regularity, after the use of the all pass filter circuit, in the dynamical system. It uncovers the intermittent periodicity via the localized observation in different scale.

Figs. 8 and 9 show two-dimensional wavelet spectra of the signal of the floating potential fluctuations obtained, before and after the control at 340 V in presence of 22 G magnetic field. The Color intensity of the plot indicates the magnitude of the wavelet co-

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**Fig. 7.** (a) Skewness and (b) kurtosis of the floating potential fluctuation signals before and after the onset of control at B = 42 G.

**Fig. 8.** Two dimensional wavelet spectrum for the time series of the floating potential fluctuations obtained before the control at DV = 340 V in 22 G.
Fig. 9. Two dimensional wavelet spectrum for the time series of the floating potential fluctuations obtained after the control at $DV = 340$ V in 22 G.

Fig. 10. Wavelet spectrum of the before control signal zoomed in the scale region of 40–97.

Fig. 11. Wavelet spectrum of the after control signal zoomed in the scale region of 40–97.

efficients. When the intensity of the color is high, it reflects high wavelet coefficient and vice versa. The bright region of the spectrum is mainly considered for the analysis. Figs. 10 and 11 present the wavelet spectrum (Zoomed) of the before and after control signal. These display the bright scale regime of the Figs. 8 and 9 for the detailed scale from 40 to 97.

Although the oscillations of the floating potential fluctuations reflects different variations in dynamics but one can see the clear difference in the wavelet spectrum before and after the control.

Fig. 12 illustrates the wavelet coefficients at scale 55 of the Fig 10. It shows chaotic behaviour for the signal obtained before the control. On the other hand for the controlled signal it reflects periodic nature for the same scale. The wavelet coefficient extracted at scale 55 for both the signal confirms that after control, periodicity appears in the dynamics of the floating potential fluctuations as shown in Fig. 13.

4. Conclusion

When the all pass filter control is applied to the typical chaotic state, chaotic orbit changes to periodic one. The chaotic state caused by sheath induced instability is well controlled using the all pass filter circuit. Furthermore, even in different discharge voltage, the chaotic state traverses to periodic state. The controllabil-
ity of the system has been shown to be sensitive to the change of discharge voltages in constant magnetic field. After the action of the control, the dynamics of the plasma oscillations appears in the regular state. The long diagonal lines emerging in the RP plot and the positive to negative transition in skewness strongly suggest the dynamical transition of complex to order state. Moreover, the uniform intensity of the color of the wavelet spectrum is also supportive of the appearance of the regularity. The localized presentation of different frequencies by the wavelet spectrum makes it easier to find the transition even in microscopic scale and after control, the periodic pattern has also been observed.

Acknowledgments

The authors are thankful to BRNS-DAE, Govt. of India for the financial support under the project grant (Reference No. 2013/34/29/BRNS).

Reference


