

A frequency-domain analysis of the order-to-disorder transitions of a perturbed double layer dynamics

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In this paper we present new results on the investigation of the transitions between ordered and disordered states of a perturbed double layer containing plasma. Performing a frequency-domain analysis frequency-frequency diagrams representing the connection between the DL plasma response and the frequency of the perturbing voltage are obtained. The results of a computational model are in reasonable agreement with experiment.

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1. Introduction

The appearance of the space-charge structures known as double layers (DLs) is one of the most common phenomenon in both collisional and collisionless plasmas [1]. Having a proper dynamics, the DLs are connected with instabilities that are observed in the states of the plasmas supporting them. The interest about the DL phenomenology is still high due to their connection with the chaotic phenomena in plasma devices. In this context, one of the possibilities to control such phenomena is to generate a perturbed regime on the DLs, fact which can be realized either by a harmonic voltage [2, 3] or by a noise-like one [2, 4] superposed on the continuum biasing which drives the DL structure. The dynamics of the perturbed DLs, consisting in ordered or disordered states, depends on the parameters of the perturbation, amplitude or frequency for the harmonic case and noise level for the random case. In this work, we only consider harmonic perturbation. It is observed that the perturbation which is applied to a DL in a chaotic state can induce transitions to other chaotic states or to windows of periodic behavior [5]. Using methods of frequency-domain analysis on the transitions between such states, new results are obtained as frequency-frequency diagrams representing the connection between the frequency of the DL plasma response and the frequency of the perturbing voltage which is continuously varied.

The experimental results are compared with numerical ones of a theoretical model based on coupled oscillators.

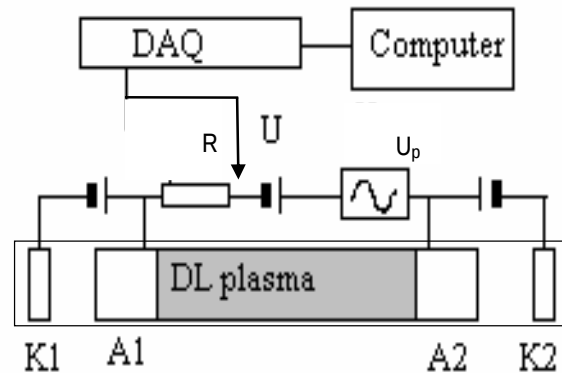


Fig.1. Experimental device.

2. Experimental procedure and results

The experimental device is sketched in Fig.1. Two electrical glow discharges are running in the same glass tube (100cm length, 8cm inner diameter) between the cylindrical anodes A₁ and A₂ and plane cathodes K₁ and K₂, respectively. The tube is filled with flowing argon at low constant pressure. The two anodes, set at 40cm, are biased one against the other by a dc power supply with voltage U .

The DL is formed at the contact region of the two short glow plasmas generated between K₁ - A₁ and K₂ - A₂, respectively. Other details of the experimental set-up are given elsewhere [5]. In order to control possible chaotic states of this space charge structure

(DL), we connect in series with the dc biasing source a sinusoidal generator which gives the additionally bias U_p of the two coupled discharges. In this way, while U assures the appearance of a DL, U_p , due to its characteristics (amplitude and frequency), can perturb and consequently control the dynamics of the DL. The situation obtained when the amplitude of the harmonic perturbation is changed was presented in a previous study [5]. Now the control parameter is the frequency of the U_p perturbing bias.

Concerning to the procedure we consider that the current I_{12} flowing through the DL-forming region can be taken as a global observing parameter for the investigation of the DL dynamics. It was detected via the potential drop on the series resistor R by a data acquisition system. With increasing of the biasing potential U , slightly above the ionization potential of the working gas, periodical oscillations are observed. Then, for higher values of U , more and more complicated dynamics, evolving to chaos are induced.

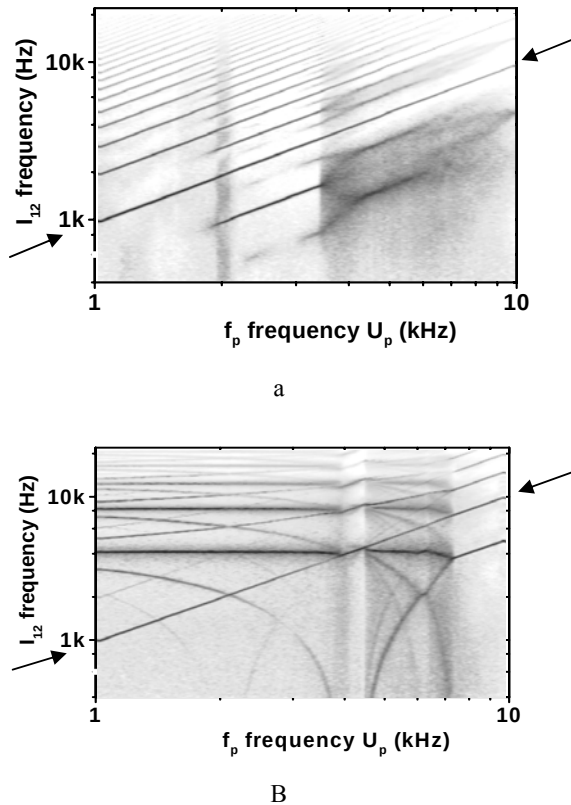


Fig. 2 Experimental log-log-axes spectrograms of the inter-anode current frequency versus the frequency of the sinusoidal perturbation: (a) $U = 20V$, regular unperturbed dynamics; (b) $U = 30V$, complex unperturbed dynamics; $U_p = 2V_{vv}$. The arrows show the perturbing frequencies.

The spectrograms [6] in Fig. 2 show the appearance of domains of ordered and disordered states and the transitions between them with changing of the perturbation frequency, for constant amplitude U_p . The grey scale shows the amplitude for a given frequency (white is the lowest level (-90dB) and black is the highest level (0dB)). The different traces represent the appearance and evolution of different “spectral lines” of the current oscillations versus the perturbation frequency. A uniform grayish domain represents a region of chaotic behavior. As expected, for chaotic domains the low frequencies are predominant. There were displayed only the range of 1-10 kHz, because the interesting phenomena appear close to internal frequencies of the system which are situated around 5-6 kHz.

From Fig. 2 it is easy to observe that the transitions from order to disorder or vice-versa can be induced gradually, as shown by the zones of spectrum coalescence, or discontinuously. In the case of Fig. 2(a) it is shown how the perturbing signal around 2 - 3.5 kHz induces a sequence of period doubling and chaotic states after that.

For a higher biasing potential ($U=30V$) the DL plasma system has a proper periodic dynamics. The characteristic spectral components appears as horizontal black lines in Fig. 2(b). The perturbation of the system with a signal with frequency just below 5 kHz shifts to a higher value the characteristic frequencies of the system on a background of lower ones. At perturbation frequencies above 8 kHz the proper oscillations of the system go into sub-harmonics of the driving signal.

3. Mathematical model and numerical simulation

Coupled nonlinear oscillators have been extensively used in the modeling of a large class of complex system [7-10]. Various nonlinear dynamics observed in the behavior of the twin electrical discharge plasma are satisfactorily reproduced by the following model system of equations:

$$\begin{cases} x_1'' = a_1 x_1 (1 - m x_1^2) - b_1 x_1' + d_1 x_2 + c_1 \sin \omega t \\ x_2'' = a_2 x_2 (1 - n x_2^2) - b_2 x_2' + d_2 x_1 + c_2 \sin \omega t \end{cases}$$

A modified version of a system of two coupled oscillators [8,9] corresponds to the two discharges coupled by a dc biasing on which a sinusoidal perturbation (amplitude $c_1=c_2$) is superimposed. The variables x_1 , x_2 represent currents of the two discharges and the inter-anode current is modeled by their difference.

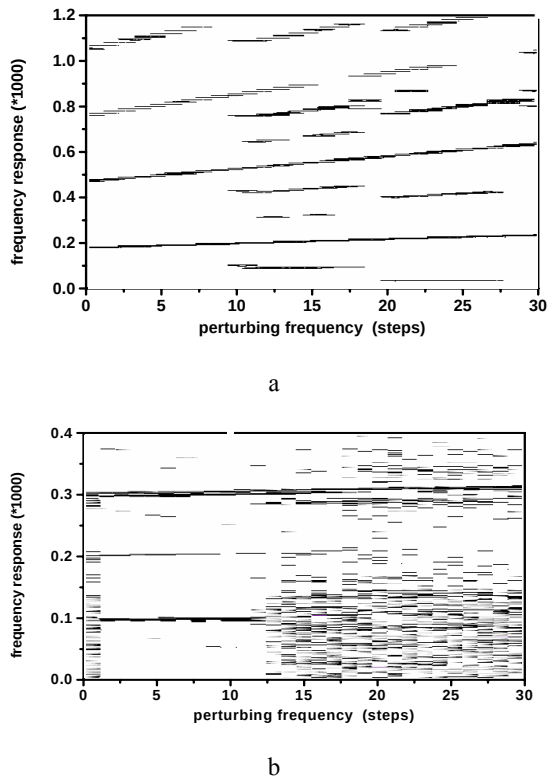


Fig. 3. Sequences of FFT-spectrograms from numerical computation; the horizontal axis represents the forcing frequency and the vertical one gives the corresponding response frequency of the system. Numerical values of the parameters are: $a_1=1$; $a_2=0.5$; $b_1=0.2$; $b_2=0.1$; $m=3.2$; $n=1$; $c_1=c_2=2.1$; for (a) $d_1=d_2=0.1$, one step $\sim 10\text{Hz}$; (b) $d_1=d_2=0.4$, one step $\sim 6\text{Hz}$.

The dc biasing U is modeled by the parameters $d_1=d_2$. In this study the role of the control parameter is played by the frequency of the perturbation $\omega/2\pi$. We consider the effect of these perturbations on the dynamics of the system with non-linearity coefficients $a_1=1$; $a_2=0.5$; $m=3.2$; $n=1$.

Fig. 3 shows preliminary computed FFT spectrograms using a Mathematica® software. For a restricted range of the perturbing signal frequency, two period doubling sequence transitions are shown in Fig. 3 (a). For a higher value of the coupling constant, transition to chaotic behavior by period doubling scenario is observed in Fig. 3(b).

4. Conclusions

Three-dimensional spectrograms give deep insight into the complexity of the non-linear dynamics of DL generated in electrical discharge plasmas. This type of analysis easily emphasizes behaviors such as period doubling sequences and evolution to chaos by Hopf bifurcations.

Using fine and continuous variation of the frequency of the perturbation as control parameter it is possible to investigate the DL dynamics based on frequency-domain analysis. The harmonic perturbation of a chaotic DL can induce transitions from ordered to disordered states and vice-versa. The observed spectrum coalescence creates the possibility of control of chaotic states of this device in another way than by changing the dc bias supply. The numerical results of the model are in reasonable agreement with the experiment.

Acknowledgement

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