

Order-to-disorder transitions in the dynamics of a biharmonically-perturbed plasma double layer

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In this paper we present new experimental results on the biharmonic forcing of double layers (DLs) formed in the plasma generated in the contact region of two coupled glow discharges. We analyze the effect of a biharmonic perturbation on the DL dynamics. States which result following different transitions as order-to-disorder or order-to-order due to this type of perturbation are investigated and their characteristics are studied. Appearance of low frequencies in the subharmonics domain of the spectral response, so-called ghost or vibrational resonances, is observed.

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1. Introduction

The interest in the study of the DLs dynamics is still vivid due to its connection with the chaotic plasma phenomena [1-3]. The main possibility to control the dynamics of DL containing plasmas is by control of the DL states using various perturbations. The most popular type of perturbation consists of combinations of harmonic signals and noise [4-6].

In this paper we present new experimental results on the biharmonic forcing of a DL formed in the plasma generated in the inter-anode space between coupled electrical discharges. This kind of perturbation is a special type of nonfeedback chaos control which is also used in other fields of science such as physics of fluids or acoustics [7,8]. The states which result following different transitions as order-to-disorder, disorder-to-order or order-to-order, due to this kind of perturbation are investigated. Characteristics of the states between which the DL evolves in connection with the parameters of the perturbation were studied.

We have investigated two experimental situations involving either two comparable frequencies or two frequencies in a high ratio.

The appearance of low frequencies in the subharmonics domain can be classified either as so-called ghost resonances or as vibrational resonances. These phenomena are well known as characteristic of perturbed nonlinear systems [9-12]. In this work we analyze such phenomena in the discharge plasma dynamics.

The ordered and disordered states of the biharmonically perturbed DL are studied by nonlinear analysis of time-series of the current flowing through the DL generating region. We mainly process the experimental data by the techniques of frequency – domain analysis, consisting of frequency – frequency or

frequency – amplitude diagrams, phase-plane plots and statistical analysis. These clearly reveal the connection between the DL plasma response and the two parameters (frequency and amplitude) of the perturbing voltages.

2. Experimental set-up

The experiments were carried out in a plasma DL created as a result of coupling of two adjacent independent glow discharges that are biased one against the other.

The set-up of the experimental device is shown in Fig.1a. The two independent electric discharges in flowing Argon at low pressure (40-70 mTorr) are running with equal discharge currents (around 7mA) between the electrodes K_1 - A_1 and K_2 - A_2 , respectively. The two discharges take place in the same glass tube and the inter-anode distance is 40 cm. Other experimental details can be found in previous papers [4, 13-15].

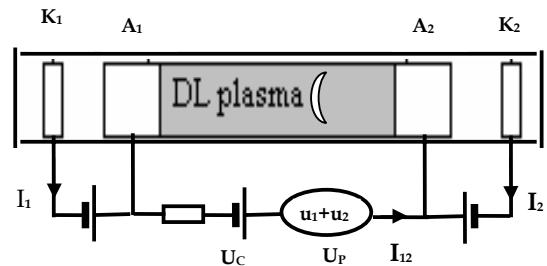


Fig.1. Experimental set-up: K_1 , K_2 – plane cathodes; A_1 , A_2 – cylindrical anodes; $U_p = u_1 + u_2$ perturbing harmonic generators; U_c – dc inter-anode biasing.

In certain experimental conditions the DL is formed at the contact region of the two negative glow plasmas,

between the two anodes A_1 and A_2 that are biased one against the other by a dc power supply whose voltage U_c is considered as the experimental control parameter.

A perturbed regime is realized when a small (periodical or not) potential difference U_p is superimposed on the dc biasing of one anode with respect to the other. In the present case, this supplementary bias is a superposition of two harmonic voltages, u_1 and u_2 , together denoted U_p in Fig. 1, connected in series with the U_c dc biasing. In fact, U_c assures the generation of the DL while U_p , due to its characteristics, can control the dynamics of space charge configuration [5].

3. Experimental results and discussion

We study the DL dynamics as reflected in the fluctuation of the inter-anode current i_{12} under various types of perturbation. The argument for using the current fluctuations is based on the observation that the temporal behavior of the light emitted from the DL structure follows the same temporal characteristics [13-15].

Adequate methods for experimental data manipulation and analysis, such as phase-plane plots, frequency spectra, 3D spectrograms and statistical evaluation are used [16].

Previous experiments showed the generation of periodic or chaotic oscillations of the current i_{12} flowing through the A_1A_2 region, with no perturbation ($U_p = 0$) and the change in the dynamics as function of the U_c biasing was monitored [13-15].

We consider the biharmonic perturbation in two cases, depending on the frequency ratio of the two perturbations, f_1/f_2 : first, when the ratio is in the neighborhood of unity and second, when the ratio is above 17.

In the first investigation, one perturbation (u_1) is characterized by a fixed frequency (f_1) and constant amplitude and the other oscillation (u_2) has constant amplitude and variable frequency (f_2). Fig. 2 presents a recorded 3D spectrogram of the response of the DL plasma system under this type of perturbation, the initial state being a periodic (coherent) one. We stress upon the fact that the scale on both axes is logarithmic. Consequently, the fundamentals and the harmonics/subharmonics of u_1 and u_2 are represented by straight lines and their intercombination tones by logarithmic curves. The grey scale is in relationship to the amplitude of the various spectral components - white is the lowest level (-90 dB) and complete black is the highest level. The different transitions as order-to-order, order-to-disorder, disorder-to-order, etc., are reflected by the change in the patterns on the spectrogram. A uniform dark domain corresponds to a region of chaotic behavior. The black curves reveal different relationships of the response frequencies as function of f_1 and f_2 , as shown in Fig. 2.

The dynamics of the system is extremely complex, except for the situations where the frequency of the u_2 is in close neighborhood of the frequency of u_1 or of its harmonics, where the spectrum mainly consists of the

fundamental and its harmonics. This situation is shown in the range enclosed by the dotted lines on Fig. 2. Taking into account that the unperturbed state was a coherently oscillating one, different types of transitions as order-to-order (OO) or order-to-disorder (OD) are observed.

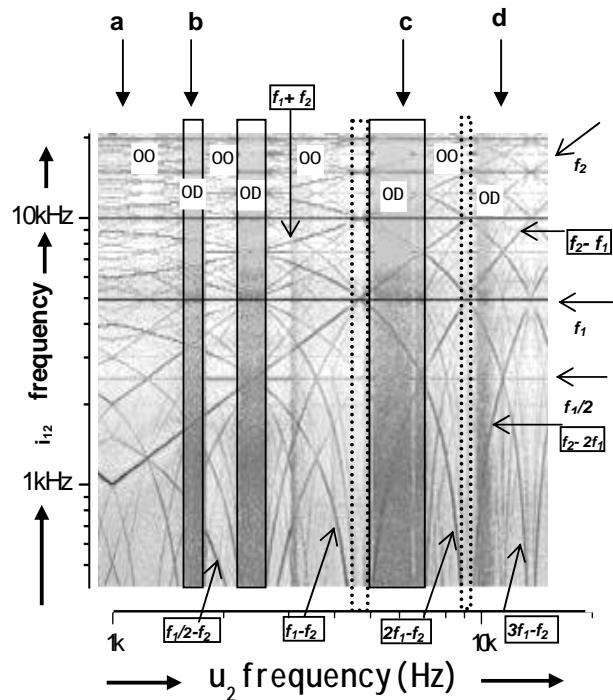


Fig. 2 Inter-anode i_{12} -current frequencies - f_2 perturbing frequency 3D spectrogram in log-log scale. The arrows marked a, b, c, d indicate the position for the FFT spectra shown in Fig. 3. Different intercombination tones of the DL-system response are shown as relationships between f_1 and f_2 .

Apparently, the chaotic states are related to the coincidences between the harmonics of u_2 and the fundamental of u_1 and its harmonics.

These situations are confirmed in Fig. 3 by some FFT spectra taken for the states which are indicated with arrows in Fig. 2. Here the (b), (c), (d) cases correspond to chaotic states resulting from order-to-disorder transitions due to the biharmonic forcing.

From Fig. 2 and Fig. 3 we observe the following: i) the system response to the harmonic perturbation u_2 decreases monotonously with the increasing of its frequency; ii) different kinds of transitions, order-to-order or order-to-disorder ones, are possible; iii) appearance of subharmonics in the low frequency ($< f_1, f_2$) domain; iv) the chaotic component has important amplitude in the low frequency range of the spectrum and v) the main harmonic components persist over the level of chaos.

Concerning the possibility to identify so-called ghost frequencies generated by ghost resonance [12], in the low frequency domain of the subharmonics (lower than f_1 and f_2), relationships as $f_1/2 - f_2$, $f_2 - f_1$ or $f_2 - 2f_1$ between

the response frequency and the f_1 and f_2 perturbing frequencies could be some examples (see Fig.3).

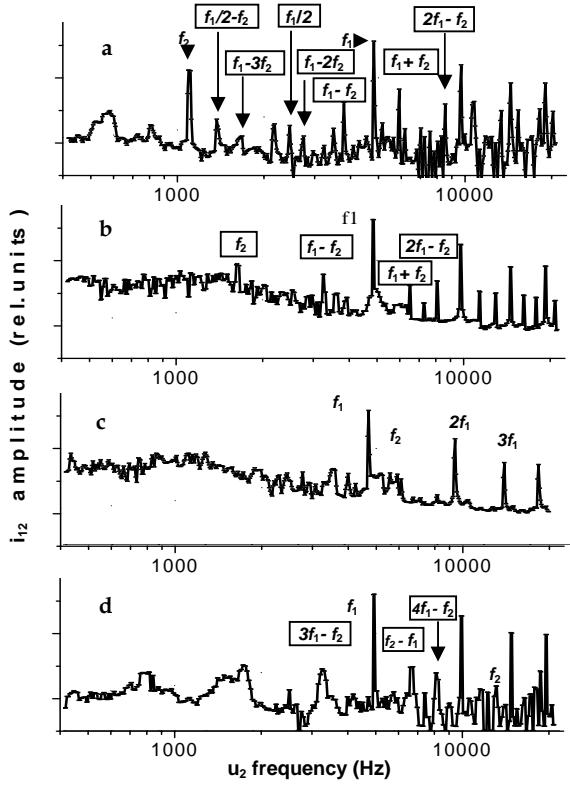


Fig. 3. FFT i_{12} amplitude spectra corresponding to the frequency of u_2 indicated by the arrows on Fig.2.

In the second investigation, the low frequency perturbation (u_1) has fixed frequency f_1 close to the free (unperturbed) DL frequency (about 4kHz) and the second oscillation (u_2) has a much higher frequency; here $f_2 = 70$ kHz.

For illustrating the case of an order-to-disorder transition, Fig. 4 shows the situation when the f_1 is 6 kHz and f_2 is 70 kHz with fixed amplitude. As seen from the time series, FFT spectra, histogram, plane phase and the graph of the correlation dimension (showing a value of 4.3 ± 0.2) the perturbed-DL state presents characteristics of chaotic behaviour. Also for this case of biharmonic perturbation ($f_2 \gg f_1$), the behaviour of the perturbed DL-plasma system can be understood as ghost resonance in some instances and as vibrational resonance in others.

In the spectral response, these phenomena appear either as generation or as amplification of subharmonics respectively observed during the amplitude variation of the higher frequency perturbation. Such phenomena were previously reported for other nonlinear systems as in acoustics or laser physics [12].

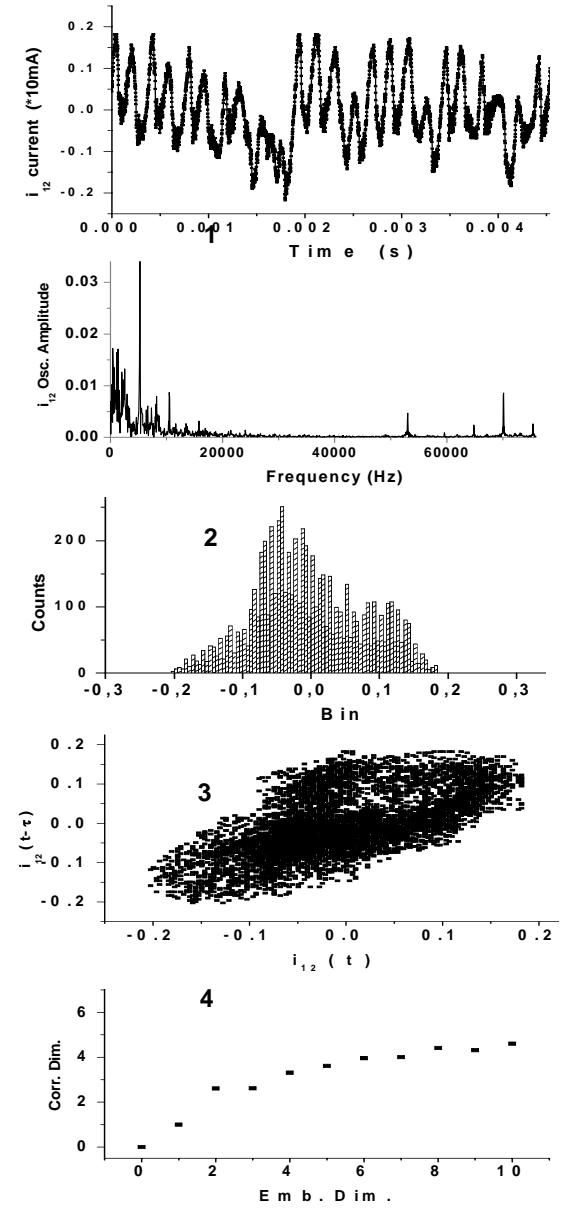


Fig. 4. i_{12} temporal series (1), the corresponding FFT spectra (2), histogram of appearance of the i_{12} values (3), $i_{12}(t-t) - i_{12}(t)$ phase plane plot (4) and the graph of the correlation dimension versus the embedding dimension (5) of a state showing a chaotic response due to the biharmonic forcing of the DL plasma system. ($f_1 = 6\text{kHz}$, $f_2 = 70\text{kHz}$).

Figs. 5 and 6 present results concerning a situation of resonance of low frequency component f_g (ghost frequency) appearing in the subharmonics domain ($f < f_1, f_2$) of the spectral response of the DL system. The increasing and decreasing of the dark grey degree of the trace for the f_g frequency shows a resonance-like phenomenon with the increasing of the u_2 amplitude (see

Fig. 4a). This frequency is named ghost because it is not present in the spectral structure of the perturbing voltage.

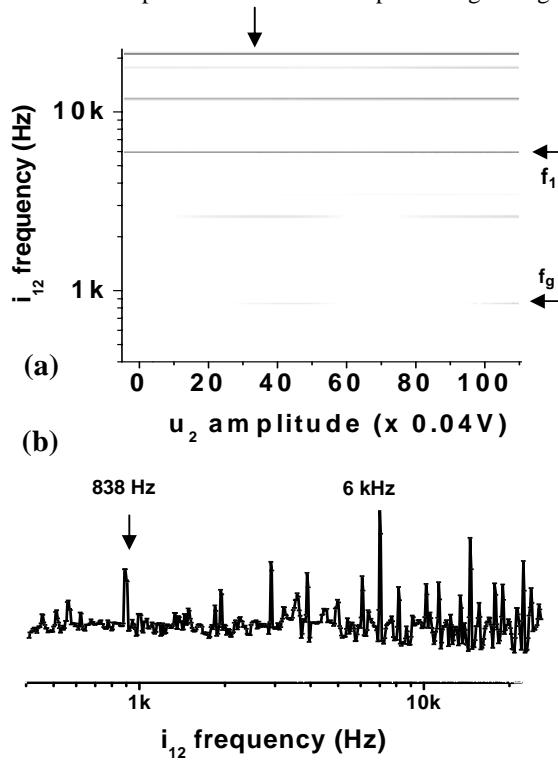


Fig.5 (a) 3D Spectrogram in a semi-logarithmic scale of the i_{12} current versus the amplitude of the u_2 perturbation. (b) FFT amplitude spectrum of the i_{12} oscillations taken for $u_2 = 1.4 V$ - see the vertical arrow in Fig.5a. ($u_1 = 5V$, $f_2 = 70kHz$).

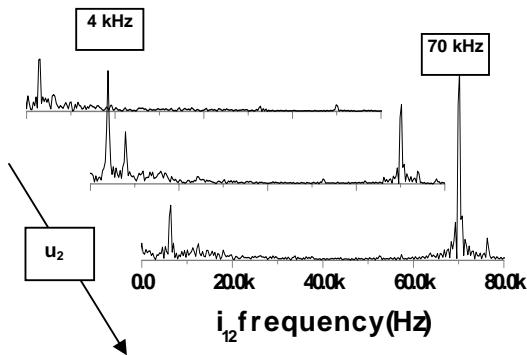


Fig.6. FFT amplitude spectra of the i_{12} inter-anode current for three increasing successive values of the u_2 amplitude perturbing voltage. ($f_1 = 4kHz$, $f_2 = 70kHz$; the arrow shows the increasing of the u_2 perturbing voltage).

In Fig. 6 we present FFT amplitude spectra of the inter-anode current for the same type of DL biharmonic perturbation ($f_1 < f_2$) but different unperturbed initial state. Now, the dc biasing is in the neighborhood of the threshold value for the appearance of the coherent oscillations in the unperturbed system. The increasing of

the amplitude of the low frequency component (f_1) with increasing of the high frequency (f_2) amplitude is a fingerprint of the vibrational resonance phenomenon. From our knowledge this is the first time the vibrational resonance is reported in a discharge plasma structure.

4. Conclusions

We have investigated the dynamics of a biharmonic perturbed DL plasma system. Transitions order-to-disorder and order-to-order have been observed. The existence of the ghost resonance frequencies and the vibrational resonance phenomenon has been experimentally demonstrated.

The detailed explanation of these phenomena and other questions concerning the relation between the parameters of the biharmonic perturbation (amplitudes and frequencies) and the parameters of the temporal response of the DL system requires future work. A computational model based on coupled nonlinear oscillators is in progress.

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