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Response of laboratory plasma influenced by a feedback loop to external force

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This study experimentally examines the sensitivity of laboratory plasma influenced by a feedback loop to applied external force, with the objective of gaining insight into chaos control in plasma. The ionization waves in laboratory plasma are adopted as the medium of a typical nonlinear system. In the case of a system without the influence of feedback (defined as *system A*), the orbit of the chaotic system changes to a periodic one as the intensity of the applied external force increases. In the case of a system with the influence of feedback (defined as *system B*), the chaotic orbit changes to a periodic one by the application of external force with lower intensity (approximately two-thirds) compared to *system A*. This reveals that the feedback loop enhances the response of the system to external forces.

Subject Index A54, J24

1. Introduction

In recent years, nonlinear phenomena such as chaos [1–7], chaos control [8–15], synchronization [16–20], stochastic resonance [21–24], and coherence resonance [25–27] have attracted considerable attention and have been investigated in dissipative and excitable systems. Plasma is an appropriate medium for testing the universal properties of the nonlinear behaviors of such dissipative and excitable systems; hence, studies on nonlinearity have been performed on laboratory plasma [1–3,6,13,14].

Stochastic and coherence resonance is a typical nonlinear phenomenon in which the oscillation responses of an excitable system become most coherent, i.e., the fundamental frequency for external perturbation and background noise. Resonance occurs due to the effect of appropriate noise and perturbed signals, which have moderate intensity as an external force. When coherence and stochastic resonance occur, the chaotic orbit of the system changes into a periodic one, as indicated by the increase in the signal-to-noise ratio (SNR). It is natural for external periodic modulation to convert a chaotic system into a periodic one. As a result of the alignment of the system with the external force, the chaotic orbit becomes periodic. In addition, a feedback loop is used to change a chaotic orbit into a periodic one in chaos control, such as in the time-delayed auto-synchronization method [10,13,14].

This study investigates the response of a chaotic system to external force, using laboratory plasma influenced by a feedback loop. The reminder of this paper is organized as follows. Section 2 describes the experimental setup for the laboratory plasma. Section 3 presents the experimental results and discusses the response of a feedback-influenced system to external force. Finally, Sect. 4 summarizes the study.

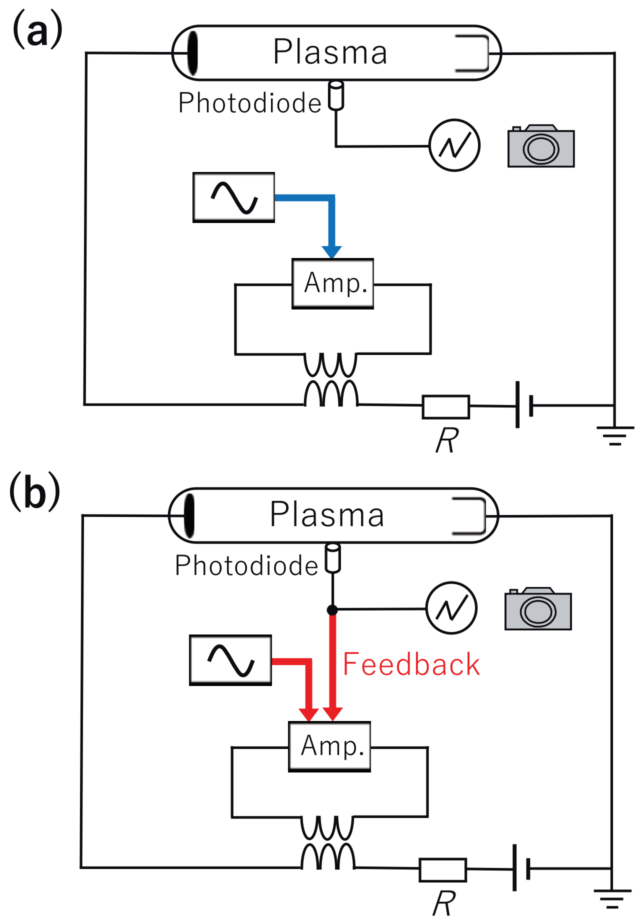

Fig. 1. Schematic of the experimental configuration: (a) system without the influence of feedback (defined as *system A*) and (b) system with the influence of feedback (defined as *system B*).

2. Experimental setup

The experimental setup for the generation of laboratory plasma is shown in Fig. 1. A series of experiments was performed in which a glass tube with a diameter of 2.0 cm and a length of 75.0 cm was utilized. After the tube was evacuated to high vacuum, Ne gas was confined in the glass tube at a pressure of approximately 478 Pa. Ne plasma was generated under a glow discharge condition between two electrodes 60.0 cm apart when a DC electric field generated using a regulated DC power source (HV1.5–0.3, Takasago) was applied.

Photodiodes (S6775, Hamamatsu), a line-scan camera (TL-4096ACL, Takenaka), and a digital oscilloscope (GDS-1072A-U, GW Instek) were used to sample the light fluctuations as time series signals for analysis. A function generator (33220A, Agilent) was used to generate an electric field as the external force. A transformer (EF-4N, Shimadzu) and an amplifier (4015, NF Electronic Instruments) were used to amplify the external force and feedback signal.

In this study, we focus on the ionization waves [28–33] in a positive column caused by glow discharge in plasma. Ionization waves in the laboratory plasma were employed as the medium of a typical nonlinear system. The typical electron and ion temperatures in Ne plasma were 10 and 0.025 eV, respectively. Various nonlinear phenomena, such as chaos, have been observed in ionization waves in which the discharge current was used as a control parameter. Such systems can be governed by changing the intensity of the discharge current. When dynamic behaviors are observed as the time series of the fluctuation of the emitted light intensity, it can be determined that the system exhibits various types of dynamic behaviors such as chaos and a periodic state. In the series of experiments performed, the DC discharge voltage and current were set to 605 V and 22.9 mA, respectively. The value of the external force intensity was renormalized by the discharge voltage value of 605 V.

In the experiments, two cases were examined: (a) a system without the influence of feedback (we define this state as *system A*), and (b) a system with the influence of feedback (we define this state as *system B*). In *system A* and *system B*, an electric field was applied as the external periodic force, and its intensity was increased gradually. The application of the external force and feedback are denoted by arrows in Fig. 1. A photodiode was fixed 31.0 cm from the anode for measuring the time series of the light intensity fluctuations in Ne plasma.

3. Results and discussion

Figures 2(a) and (b) display the time series and power spectrum for *system A* and *system B*, respectively. The upper and lower traces in each figure depict the states before and during the application of external force, respectively. The root mean square (RMS) of the external force and feedback signal is calculated as the effective value. In (a) *system A*, the discharge DC voltage between the two electrodes is 605 V and the current is 22.9 mA. The fundamental frequency is 2.33 kHz and the effective value of the sine-wave external force is 143.1 V (normalized value: approximately 0.237). In (b) *system B*, the discharge DC voltage is 605 V and the current is 22.9 mA. The effective value of the feedback signal is 16.8 V (normalized value: approximately 0.028). The fundamental frequency is 2.33 kHz and the effective value of the sine-wave external force is 65.1 V (normalized value: approximately 0.107). In both systems, the chaotic orbit changes into a periodic one. The time series changes from disordered to regular. The features of the power spectra vary from broad peaks for the chaotic orbit to sharp peaks for the ordered one.

Figure 3 shows the spatiotemporal structure of *system B* observed using a line-scan camera. In a spatiotemporal structure of ionization waves, the reconnection of two waves is caused by a slip between the two wavenumbers. Such phenomena can be explained as follows. The state is caused due to Eckhaus instability [34]. When the wavenumber bifurcates in order, the spatiotemporal structure exhibits a regular pattern; in contrast, it exhibits a chaotic pattern in the case of disorderliness. The space and time series signals are sampled every 0.2 mm and 35.0 μs, respectively, as fluctuations in the intensity of the light emitted by Ne plasma. Using a line-scan camera, the emission is obtained directly without an interference filter, and the light intensity is converted into an 8-bit value. Figures 3(a) and (b) depict the states before and during the process of application of external force, respectively. The applied experimental parameters are the same as those mentioned in Fig. 2(b). Although the spatiotemporal structure exhibits certain discontinuous reconnections, which cause spatiotemporal chaos in Fig. 3(a), it changes to ordered behavior with respect to time and space in Fig. 3(b). In the spatiotemporal structures, the space and the time both change from chaos to order by the application of external force, as shown in Fig. 3.

Figure 4 displays the SNR calculated based on the changes in the system power spectra with respect to the intensity of the applied external force. The error bars represent the standard deviation calculated for more than seven measurements of each parameter. The applied external force is a sine wave with a frequency of 2.329 kHz, and the effective value of the voltage is normalized by the discharge voltage of 605 V between the electrodes. The SNR is calculated to estimate the periodicity of the time series quantitatively. It is derived based on the intensity of the fundamental frequency peak

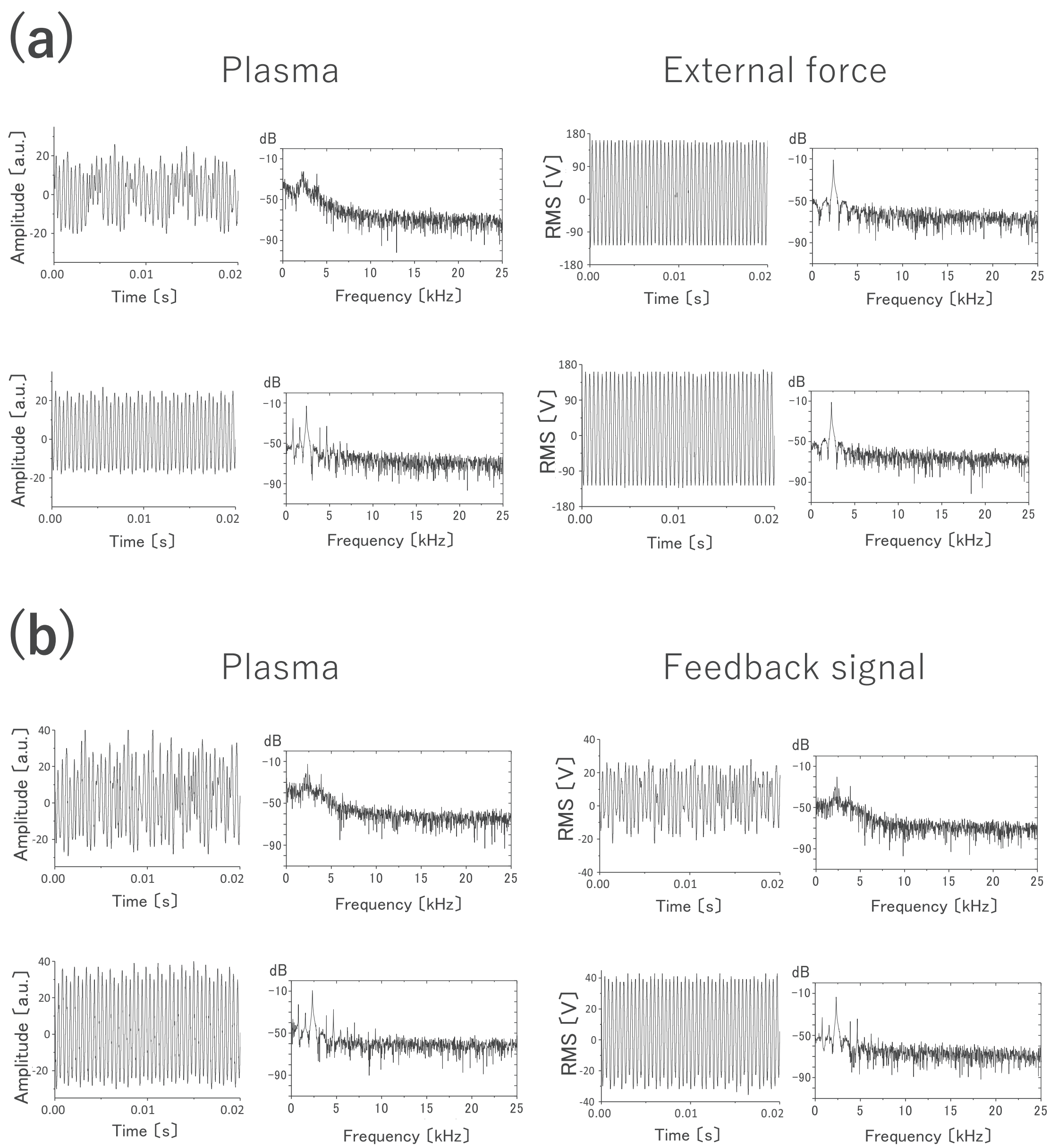

Fig. 2. Time series and power spectrum of (a) *system A* and (b) *system B*. The upper and lower traces are for the states before and during the application of external force, respectively. The root mean square (RMS) of the external force and feedback signal is calculated as the effective value. In *system A*, the discharge DC voltage is 605 V, current is 22.9 mA, fundamental frequency is 2.33 kHz, and the effective value of the sine-wave external force is 143.1 V (normalized value: approximately 0.237). In *system B*, the discharge DC voltage is 605 V, current is 22.9 mA, effective value of the feedback signal is 16.8 V (normalized value: approximately 0.028), fundamental frequency is 2.33 kHz, and the effective value of the sine-wave external force is 65.1 V (normalized value: approximately 0.107).

in comparison with the base level of the spectrum. Therefore, a higher value of the SNR indicates that the system becomes more coherent with higher periodicity.

Figure 4 shows the SNR of the systems without (denoted by blue squares, *system A*) and with (denoted by red circles, *system B*) a feedback loop. The effective value of the feedback signal is

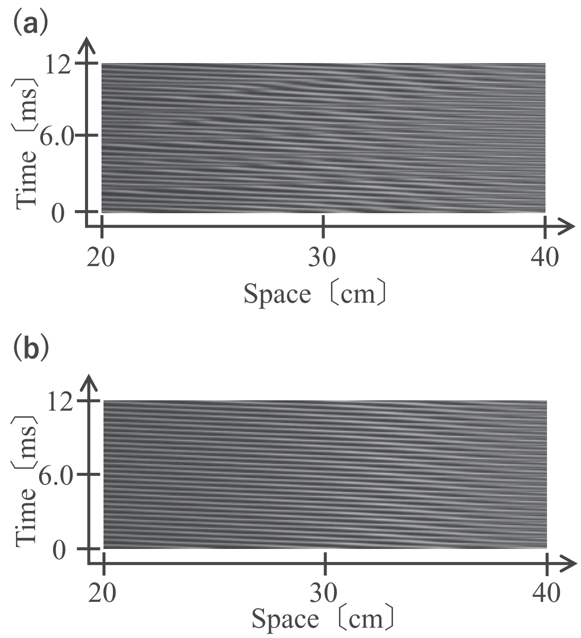

Fig. 3. Spatiotemporal structures of *system B* observed using a line-scan camera: State (a) before and (b) during the process of external force application. The space and time series signals are sampled every 0.2 mm and 35.0 μs, respectively, as fluctuations in the intensity of light emission. The experimental parameters are the same as those applied in Fig. 2(b).

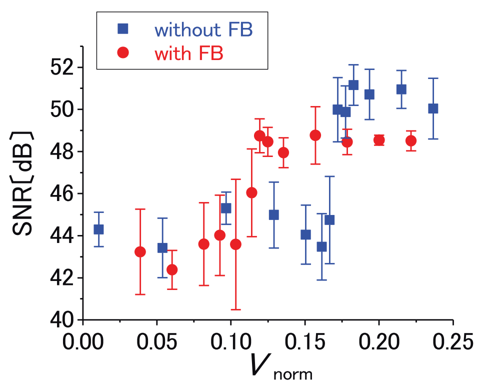

Fig. 4. Signal-to-noise ratio (SNR) against the intensity of the applied external force. The error bars represent the standard deviation. A sine-wave external force of 2.329 kHz is applied, and its effective voltage value is normalized by the discharge voltage of 605 V. *System A* without a feedback loop is denoted by blue squares, whereas *system B* with feedback is denoted by red circles. The effective value of the feedback signal in *system B* is approximately 16.8 V (normalized value: approximately 0.028), and its value is added to the intensity of the applied external force in *system B*.

approximately 16.8 V (normalized value: approximately 0.028), and its value is added to the intensity of the applied external force in *system B*. The SNR increases gradually and saturates at a certain value with increasing intensity of the applied external force in the systems without and with a feedback loop. Therefore, both systems are stabilized to a periodic state by the application of external force. The difference between the two systems is that *system B* becomes periodic on the application of an external force with lower intensity compared to *system A*.

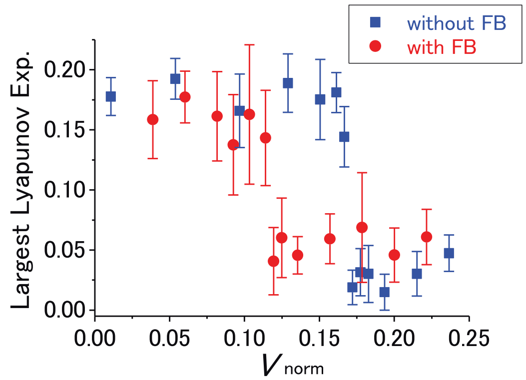

Fig. 5. The largest Lyapunov exponents against the intensity of the applied external force. The error bars represent the standard deviation. *System A* without a feedback loop is denoted by blue squares, whereas *system B* with feedback is denoted by red circles. The intensity of the applied external force in *system B* includes the effective value of the feedback signal (normalized value: approximately 0.028).

Figure 5 depicts the largest Lyapunov exponents against the intensity of the applied external force. The error bars represent the standard deviation calculated for more than seven measurements of each parameter. The largest Lyapunov exponents are calculated quantitatively in order to examine the change in dynamic behavior on the application of external force. The exponents were calculated using the time series sampled by photodiodes in a series of experiments based on the algorithm described in Ref. [35]. The maximum Lyapunov exponent indicates a positive value for the chaotic oscillations, which is larger for a more chaotic state. The value approaches zero for a state with periodic oscillations.

In Fig. 5, *System A* without a feedback loop is denoted by blue squares, whereas *system B* with a feedback loop is denoted by red circles. The intensity of the applied external force in *system B* includes the effective value of the feedback signal (normalized value: approximately 0.028). The value of the largest Lyapunov exponent decreases and approaches zero as the intensity of the external force increases in both systems. Therefore, as shown in Fig. 5, both systems are stabilized to a periodic state, and *system B* becomes periodic on applying an external force with lower intensity compared to *system A*. In the case of *system A*, the system changes to a periodic state when the intensity of the applied external force exceeds approximately 103 V (normalized value: approximately 0.17). On the other hand, for *system B*, this value is approximately 68.2 V (normalized value: approximately 0.113).

It should be noted that *system B* is stabilized to a periodic state by the application of an external force with lower intensity (approximately two-thirds) than that applied to *system A*. Therefore, it is concluded that the system influenced by a feedback loop is sensitive to the application of external force.

4. Conclusion

In this study, the response of a system to applied external force was investigated experimentally in laboratory plasma influenced by a feedback loop. For two systems with and without the influence of feedback, a sine-wave external force was applied, and the change in the system dynamics was investigated. The chaotic orbits of both systems became periodic with an increase in the intensity of the applied external force. For the two systems, the SNR and largest Lyapunov exponent were calculated in order to estimate the system dynamics qualitatively. The results revealed that, in the case of the chaotic system with the influence of feedback, the chaotic orbit changed to a periodic one on the application of external force with lower intensity (approximately two-thirds) than the system without the influence of feedback. Thus, through experiments using laboratory plasma, it was established that a feedback loop enhances the sensitivity of the system to external force.

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