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OCCURRENCE OF MIXED-MODE OSCILLATIONS IN A DUSTY PLASMA

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Nonlinear instabilities can appear in laboratory plasmas containing dust particles. These unstable phenomena are easily observed during experiments and their analysis reveals that they correspond to mixed-mode oscillations (MMOs). In this paper, experimental results and their preliminary analyses are presented.

Keywords: Dusty plasmas; Complex plasmas; Instabilities; Mixed-Mode Oscillations.

1. Introduction

The plasma state of matter is ubiquitous in nature and also quite common in our everyday life. Plasmas are gases that are partly or fully ionized, meaning that some (or all) the atoms have lost a part of (or all) their electrons. Classical plasmas are thus a mixture of still neutral atoms, free electrons and positive ions. This electrically conductive gas can be influenced by electromagnetic fields and is an energetic medium with thermal, reactive and radiative properties. It is the most encountered state in the universe as all stars are just plasma balls and is also present in comets or nebulae. On Earth, natural plasmas also exist, like aurora borealis and lightnings. In our houses, plasmas can also be found in fluorescent tubes, compact fluorescent lamps and plasma TVs. Most of the electronic devices like mobile phone or computers use processors that are fabricated partly thanks to plasmas. Plasmas are also used or considered for many other applications, like ion

thrusters, plasma torches, medical applications, pollution control, fuel cells, solar cells, ... Plasmas are finally expected to be a solution for the mass production of energy thanks to thermonuclear fusion.

In many cases, another component can be found in addition to atoms, molecules, ions and electrons. Indeed, solid bodies with sizes ranging from a few nm to a few cm can be present in the plasma. These dust particles get electrically charged by attaching plasma free electrons. This new massive electrical species can strongly disturb the original plasma properties. It gave birth to a new field of research named dusty (or complex in analogy with complex fluids) plasmas.^{1,2}

Dusty plasmas are thus multi-component systems with similarities with colloidal suspensions or granular media. They are encountered in many environments such as astrophysics^{3,4} (comet tails, planetary rings or atmospheres), industrial processes^{5,6} (in microelectronics and nanotechnologies) and thermonuclear fusion.⁷ These dust particles can come from regions surrounding the plasma or can be formed by the plasma itself. Indeed, in the plasma phase, some molecules can be at the origin of complex chemical and physical reactions leading to the formation of dust particles.⁸ In laboratory plasmas, dust particles are usually formed by using reactive gases like for example silane or acetylene, or by ion sputtering of the surfaces exposed to the plasma. In this last case, either big parts (already formed dust particles) or molecules (acting as reactive gases) are removed from the surfaces. Dust particle formation has to be taken into account in many laboratory or industrial plasmas as these particles can be desired (for example for designing useful nanoparticles) or unwanted when cleanliness is required (in many microelectronics processes).

2. Instabilities in dusty plasmas

The presence of this additional charged species can strongly disturb the plasma equilibrium due to the important loss of free electrons captured by the dust particles. This effect is particularly important for high dust densities. In this case, self-excited instabilities can appear in the plasma.⁹ Due to the high mass of the dust particles (relatively to ions and electrons), these unstable phenomena have typical frequencies ranging from a few Hz (for dust particle size in the μm range) to a few kHz (in the nm range). These instabilities can consist of quite regular oscillations or in more chaotic ones. In the present study, instabilities have been experimentally observed in the following conditions:

- During dust particle growth: the instability shape and frequency evolve as the dust particle size and density are changing. It has been observed in silane^{10,11} and sputtering discharges¹²⁻¹⁴ during the growth of the first dust particle generation. As long as molecular precursors are provided in the plasma discharge, the dust particle growth appears to be cyclic. A different type of instabilities is observed during these successive generations.¹⁵⁻¹⁷
- Once the dust cloud is formed (when only one generation is grown), the central dust-free part of the plasma can oscillate. Indeed, it has been observed that dust particles are removed from the central part of the plasma. Thus, the dusty plasma consists of a mixture of dust particles and plasma except in a small central region where only plasma exists. This region, named the void, is characterized by an enhanced plasma emission.² It is sustained by the equilibrium between an outward ion drag force expelling dust particles (positive ions push away negatively charged dust particles) and an inward electric force induced by the plasma potential difference existing between the inner part and the outer part of the void (attracting dust particles toward the center¹⁸). This equilibrium can be broken leading to complex void size oscillations: the heartbeat instability¹⁹ (due to its apparent similarity with a beating heart).
- A recently discovered instability, consisting of small plasma spheroids rotating around the plasma.^{20,21} Their origin is still misunderstood but seems to be related to dust particle growth.

In the following, we will focus on the heartbeat instability that appears to be strongly nonlinear. In particular, its behavior has been shown to be associated to mixed-mode oscillations²²(MMOs). Indeed, the self-excited heartbeat instability can stop by its own through the occurrence of more and more failed contractions²³ similar to MMOs.

3. Mixed-Mode Oscillations

MMOs consist of an alternation of small and large (spikes) amplitude oscillations. The system relaxes through the spikes while it undergoes sub-threshold oscillations in between the spikes. This dynamical behavior is encountered in many different fields, like in chemistry,^{24,25} especially in the well-known Belousov-Zhabostinskii oscillating reaction,^{26,27} or in natural sciences,²⁸⁻³⁰ for example in the Hodgkin-Huxley model of neuronal activity.^{30,31} In this last context, MMOs are strongly related to spiking and

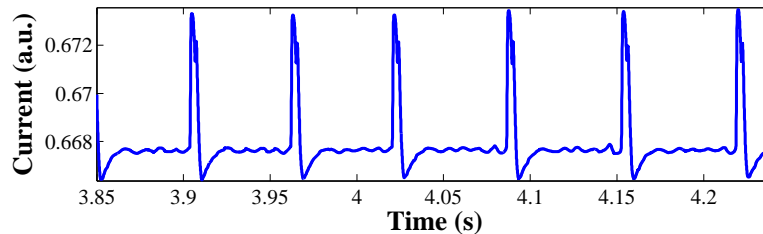


Fig. 1. Part of the evolution of the discharge current during the ending phase of the heartbeat instability. Using the MMO notation, a transition between the 1^4 state and the 1^5 state is observed around 4.05 s.

bursting activities in neurons.^{32,33} They have also been discovered in electrical circuits^{34,35} and in plasma physics in some dc glow discharges.^{36,37} More recently, their existence has been revealed in dusty plasmas.^{22,23} MMOs are characterized by using a notation based on the number of spikes and subthreshold oscillations:^{24,27} the MMO state is identified by a pair of integers L^S where L and S are respectively the number of spikes and subthreshold oscillations. For example, a pattern consisting of 1 spike and 4 subthreshold oscillations will be noted 1^4 (like the first three patterns in figure 1, while the last three patterns are in the 1^5 state).

To analyze and explain these characteristic oscillations appearing in so diverse scientific fields, the use of dynamical system theories is of high interest. These studies deal with well-defined behaviors like for example canards,^{28,30,38} subcritical Hopf-homoclinic bifurcations^{31,39} or Shilnikov homoclinic orbits.^{40,41}

4. Evidence of MMOs in dusty plasmas

The heartbeat instability appears to be strongly nonlinear as evidenced by the complex shape of the measured signals. One of the easiest and interesting signal to follow is the amplitude of the discharge current collected on the electrodes (see for example Ref. 19 for details on the experimental setup). A typical signal is presented in figure 1 recorded during the ending phase of the heartbeat instability. The signal shape clearly corresponds to typical MMOs and is remarkably similar to waveforms measured or modeled in chemical systems^{24,25,27,41} or in neuronal dynamics.^{28,30,33,42,43} During the fully-developed instability, only the main spikes exist. As the instability is about to stop, intermediate oscillations with a very small amplitude appear between the spikes. As the instability "loses energy", more and more small oscillations occur and the spike frequency decreases. In our case these

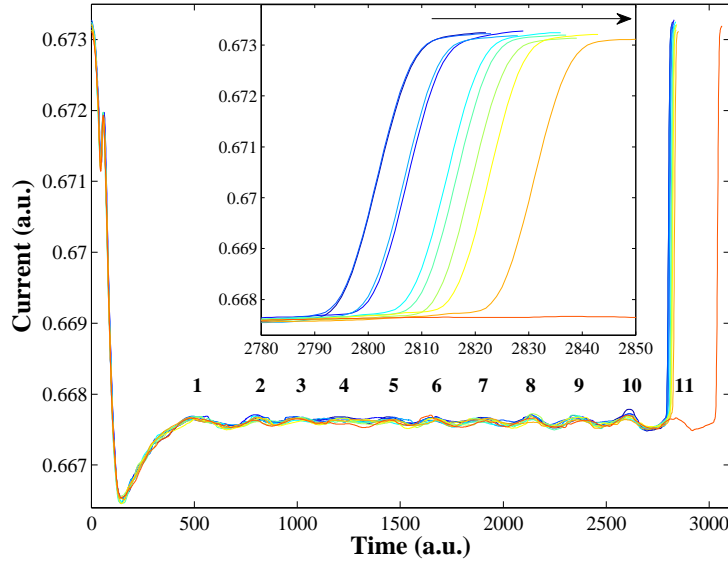


Fig. 2. Superimposition of eight successive 1^{10} patterns and the first consecutive 1^{11} pattern. Each subthreshold oscillation is numbered. In the insert, zoom on the spike increase showing a slight shift from one pattern to the next one.

subthreshold oscillations correspond to failed contractions of the void.²³ In figure 1 a transition between the 1^4 state and the 1^5 state is observed through the appearance of an additional subthreshold oscillation. It is interesting to observe that during the first patterns of the 1^5 state, the new subthreshold oscillation has a higher amplitude than the other ones. In a sense, it keeps partly the characteristics of the spike it was during the previous pattern. It can also be observed that the spike of the first 1^5 pattern has a higher amplitude than the last ones of the 1^4 state.

5. State transition

In order to better characterize the transition between a L^S state and a L^{S+1} state, we superimposed successive 1^{10} states up to the transition to the first 1^{11} state. In figure 2, eight successive 1^{10} patterns have been superimposed by using as a common reference the current minimum value preceding the first subthreshold oscillation (around 150 on the x-axis). Each subthreshold oscillation is indicated by its number. From the first, up to the 10^{th} subthreshold oscillation, each pattern appears to be similar to the pre-

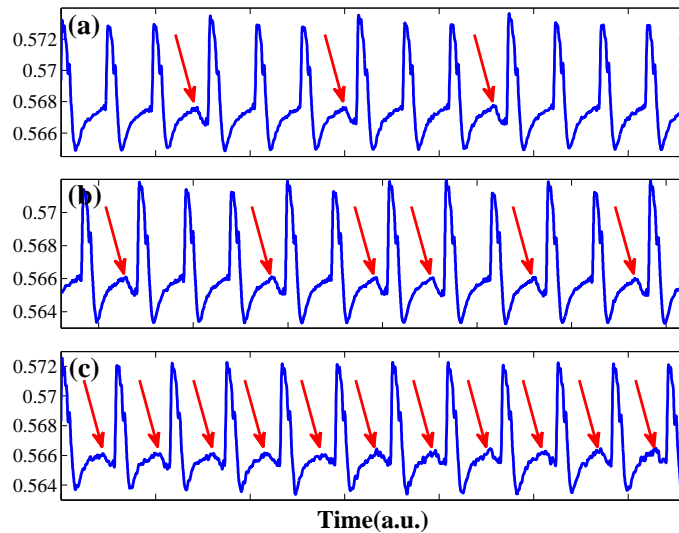


Fig. 3. Progressive occurrence of the 1^1 state during the 1^0 state. The 1^1 state appears (a) sporadically, (b) more regularly, (c) establishes itself as the dominant state.

ceding one (excluding experimental noise). No clear difference in position or amplitude is observed during this part of the patterns. Nevertheless, a slight difference is localized on the abrupt increase of the spike. A zoom of this part is shown in figure 2 insert. It clearly appears that the occurrence time of the spike is slightly delayed from one pattern to the next one. This progressive shift during the 1^{10} patterns partly creates the space for a new subthreshold oscillation to occur, as observed in figure 2 with the transition to the 1^{11} state.

6. State alternation

In figures 1 and 2, progressive transitions from L^S to L^{S+1} states have been evidenced: several patterns of the L^S state are followed by several ones of the L^{S+1} , then L^{S+2} , etc ... In some conditions, the transition between a L^S and a L^{S+1} state is not definitive and regular or irregular alternations of L^S and L^{S+1} states are observed.

In figure 3(a), the dominant pattern is the 1^0 with sporadic 1^1 states (indicated by arrows) appearing approximately every two 1^0 patterns. It indicates that the transition from the 1^0 state to the 1^1 state is not stable

and the systems goes back to the previous state. Like in the transitions observed in figures 1 and 2, the amplitude of the transition spike is higher than the one of the two surrounding spikes. In figure 3(b), the 1^1 state appears more and more often and can exist during two consecutive patterns. This behavior means that the 1^1 state is becoming little by little the dominant state. Finally, in figure 3(c), the 1^1 state establishes itself as the only state with the disappearance of the 1^0 pattern. The progressive appearance of a given state during another one and its final establishment, is quite similar to the behavior of a devil's staircase.²² In this structure, the number of steps is nearly infinite and in between two parent states, intermediate states exist that are related to the parent states by the Farey arithmetic.^{24,27,44} This specific structure has been observed in chemistry in the framework of MMOs^{24,25,27,44} but also in a wide range of other fields like in physiology⁴⁵ or in wave-particle interaction.⁴⁶ Thus, the structure obtained in figure 3 can be an incomplete devil's staircase with an unidentified control parameter evolving with time. It can be suggested that more intermediate states could be obtained with a system which vary slower, and that the staircase could be partly completed.

7. Conclusion

In this paper, we showed that mixed-mode oscillations can also be observed in the field of dusty plasmas and preliminary analyses of the obtained patterns have been performed. A particular attention has been paid on the transition between L^S and L^{S+1} patterns. It has been shown that the transition occurs consecutively to an increasing delay in the spike appearance while subthreshold oscillations seem to be similar. Situations where the transition is not definitive have been presented. In these cases, the system cannot stay in the new L^{S+1} state and comes back to the previous L^S state. The system oscillates between the two states with a progressive change of the dominant state. Indeed, while the L^S state is the dominant one at the beginning, the L^{S+1} state little by little establishes itself as the dominant one. This step by step transition is quite similar to a devil's staircase.

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