Self-Excited Irregular Oscillation of Positively Charged Fine-Particles in Magnetized Double Plasmas

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We have investigated behaviors of positively-charged fine particles in a cross-sheath between magnetized double plasmas with different potentials separated vertically by the horizontal magnetic field. In the sheath the charges on the particles become positive, because ion current flowing from a lower high-potential plasma surpasses electron current coming across the magnetic filed from an upper low-potential plasma. We have observed self-excited irregular oscillations of the positively-charged fine particles in vertical direction. In this paper, we report the characteristic property of the oscillations and discuss the mechanism of the irregular oscillation by taking account of the mutual interaction between the particles and charging processes on the particles.

Keywords: dusty plasma, positively-charged fine particle, ion beam, cross-field sheath, magnetized double plasmas

1. Introduction

Fine particles with a diameter of the orders of μ m, generated in the reactive plasmas or introduced into the plasma from outside, are usually charged negatively due to the large electron mobility. Under such circumstances, various characteristic phenomena concerned with a strongly coupled state of dusty plasmas [1], such as the formations of Coulomb crystals, dynamic motions of Coulomb fluids, and various wave phenomena, have been reported. By employing a completely dc-charge plasma, it became possible to control the behavior of fine particles more systematically. The effects of vertical magnetic field on the fine-particle behaviors were also investigated and rotational motion of fine-particle cloud has been observed [2][3]. Recently, in order to eliminate the effect of the gravity, microgravity experiments have been proposed, and characteristic features of fine particle behaviors have been discovered [4]-[6]. Under the microgravity condition using a parabolic flight experiment we have observed formations of a fine-particle cloud with no void inside in a parallel plate and a spherical grid-cage radio frequency discharges [7]. Various aspects of dusty plasmas were summarized in [8].

In this paper we report positively charged particles, formed by positive ion beam irradiation [9]. To date, almost all previous-experiments were concerned with negatively charged fine particles. Here, we clarify fundamental features of the positively-charged fine particles by using a magnetized double plasma system.

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2. Experimental Apparatus and Method

Figure 1 shows a schematic of the experimental apparatus. Double plasmas (upper and lower plasmas) are produced independently along the horizontal magnetic field by dc discharges with different anode potentials and separated in the vertical direction by a cross-field sheath [9]-[11]. The cathode-anode distance in both plasmas is 40 mm. The anode potential of the upper plasma is grounded, while dc bias voltage V_A can be applied to the anode of the lower plasma.

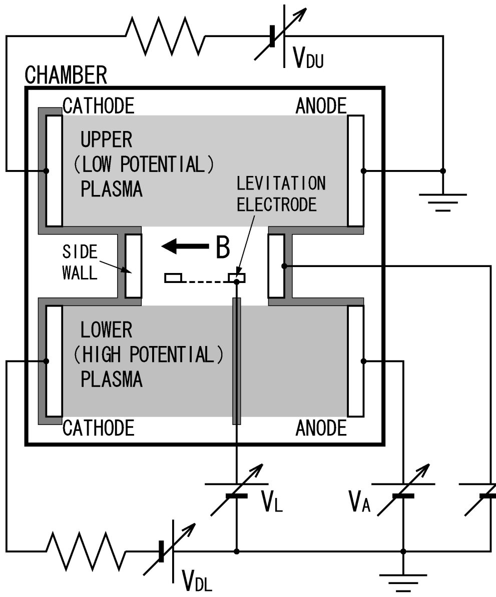

Fig. 1 Experimental apparatus.

When $V_A > 0$, we can produce electric field directed upward in the cross-field sheath region. In order to avoid a mixing of both plasmas, the strength of the horizontal magnetic field is kept in the range B = 0.9 - 1.4 kG. Therefore, we can fix the upper plasma potential almost grounded even when positive V_A = 10 - 60 V is applied to the anode of the lower plasma.

Fine particles made of acrylic bolls with diameter of 1.5 μ m are injected by a small dust dropper, consisting of a 12 mm-diameter stainless-steel pipe with 100 mesh grid attached at the outlet of the particles. The particles are injected in the upper plasma region by vibrating the dust dropper. After the injection, although the particles are charged negatively by the electrons in the upper plasma, the polarity turns to positive during dropping into the cross-field sheath region, because the transit time of particles across the cross-field sheath, i.e. $T = \Delta / v_d$ is much longer than the charging time $\tau (= q / j_i)$ by positive ions in the cross-field sheath. Here, v_d is particle velocity, Δ is sheath width, q is particle charge, and j_i is ion current.

We put a levitation electrode, made of a stainless ring plate of 10 mm in diameter with a central hole of 4.5 mm in diameter. Fine stainless mesh (100 mesh) is welded on one side of the ring. Since the plate is set on the horizontal plane between the upper and lower plasmas, the ion and electrons are able to pass through the hole in vertical direction. The potential distribution in the cross-sheath may be changed by the levitation electrode, but we can adjust the potential profile by biasing the plate to satisfy the particle levitation condition.

The levitation of the particles can be detected by illuminating laser sheet beam on the particles. The right-angle scattering of the laser beams can be measured by charge-coupling device (CCD) cameras and high-speed CCD camera of 125 frames per second.

3. Experimental Results

Figure 2 shows several fine particles levitated above the levitation electrode. These particles oscillate spontaneously in the vertical direction around their equilibrium positions in the cross-field sheath region. The phase and amplitude of each particle were not uniform. The oscillation frequency $\omega_{dust}/2\pi$ was changed by the plasma conditions and electric field strength in the cross-filed sheath region. In order to analyze the particle motion more precisely, we measure the particle position as a function of time from video frames. Figures 3(a) shows a temporal variation of one of the particles in the vertical direction. The motion of the other particles is similar. The waveform was not a simple sinusoidal but a relatively irregular. The amplitude was not constant, but the amplitude itself seemed to oscillate, something like a beat waveform. The oscillation period was not also uniform, and the frequency seemed to fluctuate. We performed Fourier analysis of this fluctuation and the frequency spectrum was obtained as shown in Fig. 3(b). We found a fundamental frequency around 25 Hz, together with the strong peak around 45 Hz. The spectrum was not sharp one, but the width was rather broadened. The broadness of the spectrum in the very low frequency regime was conspicuous.

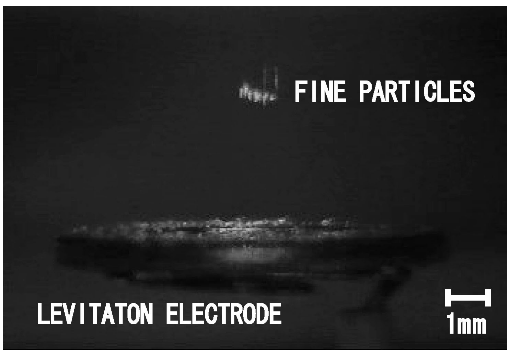

Fig. 2 Fine particles moving with self-excited oscillation in vertical direction above the levitation electrode in the cross-field sheath region.

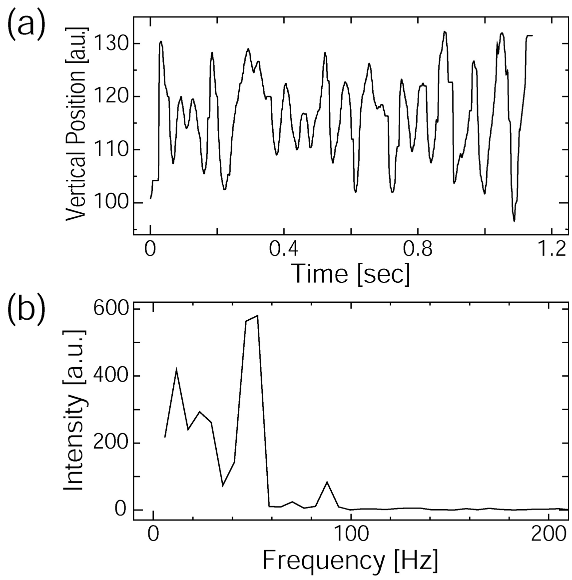

Fig. 3 (a) Temporal evolution of particle position in the vertical direction and (b) frequency spectrum of the oscillation.

4. Discussions

We first discuss the mechanism of the self-excited oscillation. The characteristic frequency of the dust can be derived from the dynamics of a single fine particle. Here, we consider spatial profiles of plasma parameters in the cross-field sheath in the steady state as shown in Fig. 4 [10], where the potential ϕ, upward ion current j_i and downward electron current j_e at the equilibrium position of fine particle z = 0 are denoted by ϕ_0, j_{i0}, and j_{e0}, respectively. Ion current (flux) is conserved along the ion flow in vertical z direction.

Equation of motion of a single fine particle of mass

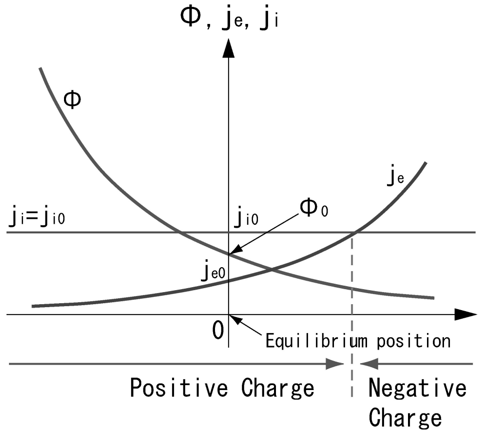

Fig. 4 Profiles of potential, ion and electron currents near equilibrium position of fine particle.

m_d and charge q in the cross-field sheath is given by

$$m_d \frac{d^2 z}{dt^2} = qE(z) - m_d g - m_d \nu_c \mathrm{v}_d , \tag{1}$$

where $E(z)$ is electric field at vertical position z, g is the gravity, ν_c is collision frequency between the particles and neutral gas, and v_d is particle velocity. The charging equation of the particles is given by

$$\frac{dq}{dt} = j_i(z) - j_e(z) = j_{e0}(\delta e^{-\frac{\phi_d}{V_i}} - e^{bz}) \quad . \tag{2}$$

Here, $\delta = j_{i0}/j_{e0}$, $j_i(z)$ and $j_e(z)$ are ion and electron currents at z, eV_i is incident ion energy, ϕ_{d_0} is particle potential ϕ_d at the equilibrium position, b^{-1} is a scale length of electron suppression by the magnetic field.

Here, we note that the electric field has to diminish in the upward direction for an existence of the equilibrium levitation position in the steady state. Therefore, we assume the potential variation to be

$$\Phi_{(z)} = \frac{\Phi_0}{1+az} , \tag{3}$$

where a^{-1} is a scale length of the cross-field sheath, determined in the followings. The equilibrium position is $z = 0$. Then, we get the electric field,

$$E_{(z)} = -\frac{d\Phi}{dz} = \frac{E_0}{(1+az)^2} , \tag{4}$$

where $\Phi|_{z=0} = \Phi_0$, $E|_{z=0} = a\Phi_0 = E_0$.

From Eq. (2) we obtain the dust potential $\phi_{d_0} = V_i \ln \delta$ at $z = 0$. So, the charge of fine particle at $z = 0$ can be given by

$$q_0 = C_d \phi_{d_0} = C_d V_i \ln \delta = \frac{m_d g}{E_0} = \frac{m_d g}{a\phi_0} , \tag{5}$$

where C_d is particle capacitance. Therefore, we obtain

$$a = \frac{m_d g}{\phi_0 C_d V_i \ln \delta} . \tag{6}$$

Characteristic frequency ω_0 can be derived from Eq. (1) by the Taylor expansion of E(z) around $z = 0$,

$$\omega_0^2 \approx \frac{2aq_0 E_0}{m_d} - \frac{\nu_c^2}{4} . \tag{7}$$

Since $q_0 E_0 = m_d g$, in the limit $\nu_c / \omega_0 \to 0$, the characteristic frequency ω_0 is given by, in term of a ,

$$\omega_0 = \sqrt{2ag} . \tag{8}$$

Although the characteristic frequency was derived, we have to consider two particles at least to explain the irregular motion in the experiment. We next discuss the motion of two particles in the vertical z direction, which are levitating simultaneously with a spacing $L = |x_1 - x_2|$ in the horizontal x direction. As shown schematically in Fig. 5, these particles are moving in the vertical direction under a mutual interaction depending on the spacing L. If L is short, the interaction will be strong. Here, we note that these particles are trapped in a potential well in the horizontal direction by an external electric potential given by the levitation electrode. Therefore, their motion in the horizontal direction can be limited. In fact, we observed only vertical motion in Fig. 2.

Taking account of the mutual interaction force, Eq.

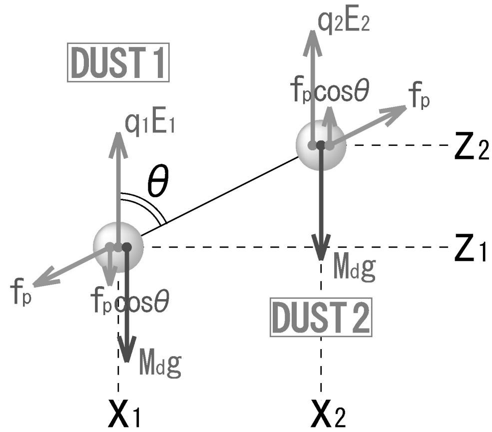

Fig. 5 Mutual interaction force acting on two particles.

(1) can be expressed as follows for the two particles.

$$m_d \frac{d^2 z_1}{dt^2} = q_1 E(z_1) - m_d g - m_d \nu_c \mathrm{v}_{d1} + f_p ,$$

$$m_d \frac{d^2 z_2}{dt^2} = q_2 E(z_2) - m_d g - m_d \nu_c \mathrm{v}_{d2} - f_p , \tag{10}$$

and

$$f_p = \frac{q_1 q_2}{4\pi\varepsilon_0 \ell^2} \exp\left(-\frac{\ell}{\lambda_D}\right) \cos\theta . \tag{11}$$

Here, $\ell^2 = (x_1 - x_2)^2 + (z_1 - z_2)^2$, θ is an angle shown in Fig. 5. The shielding effect by the electrons can be neglected, because the electron density is quite low around z = 0, so the Debye length satisfies $\lambda_D >> \ell$.

Figure 6 shows the temporal variations of the particle positions z_1 and z_2 when the spacing $L/z_0 = 0.1$. Here, z_0 (= $1/a$) is a scale length of the cross-field sheath in the vertical direction. The trace of z_1 is drawn by broken curve, while the trace of z_2 is drawn by solid curve. We can see that when these particles approach each other, the directions of their motions suddenly change and turn their motions to the opposite directions. This phenomenon is something like a Coulomb collision between two charged particles. So long as these particles are sufficiently separated, these particles oscillate almost independently.

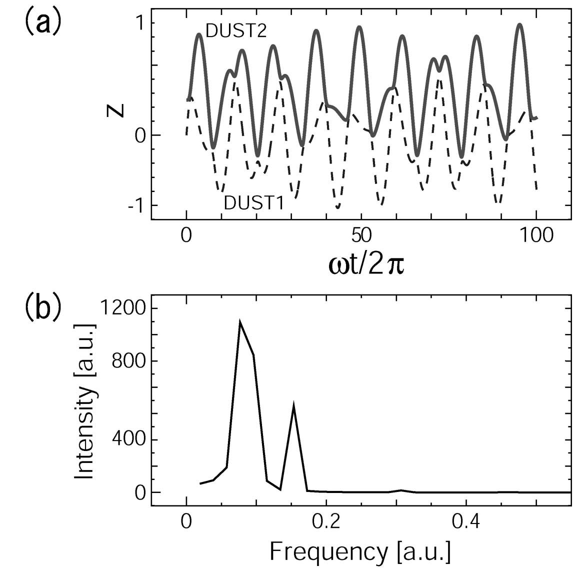

Fig. 6 (a) Temporal evolution of the positions z_1 and z_2 of two particles for the spacing L/z_0 = 0.1. (b) Frequency spectrum of the trace z_2. ν_c / ω_0 =0.007.

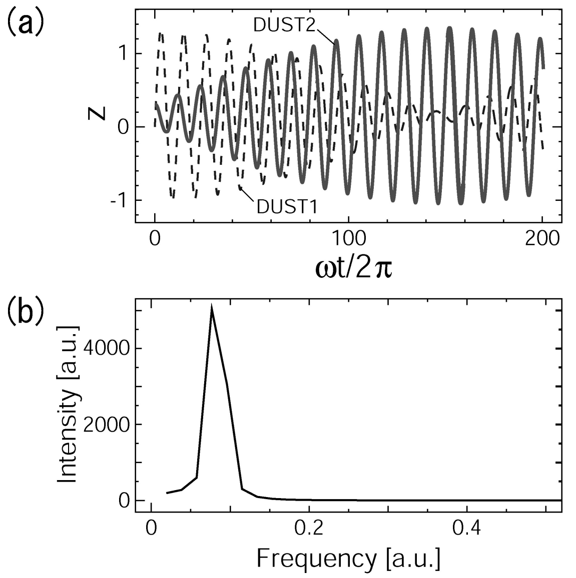

Fig. 7 (a) Temporal evolution of the positions z_1 and z_2 of two particles for the spacing L/z_0 = 0.2. (b) Frequency spectrum of the trace z_2. ν_c / ω_0 =0.0075.

The envelope of the amplitudes z_1 and z_2 also fluctuates like a beat oscillation, similar to the experimental result shown in Fig. 3(a). The Fourier analysis was also performed and the frequency spectrum was obtained as shown in Fig. 6(b). We can find a fundamental frequency, together with a small peak around the second harmonics. The broadness of the spectrum is remarkable. These properties are well consistent with the experimental results shown in Fig. 3(b), where may exist more particles.

In Fig. 7(a) the oscillations for the case of large spacing L/z_0 = 0.2 are shown, where we find only a beat-like oscillation and no irregular oscillation is observed. The frequency spectrum has a single peak with a broad width. We found that a strong mutual interaction caused by short particle spacing and less shielding effect was of crucial for the appearance of irregular oscillation. The strength of the mutual interaction can be evaluated by a factor $\sim\exp(-L/\lambda_D)/L^2$ from eq. (11). In our case, since $L/\lambda_D \approx 0.1$, the mutual interaction in the case of L/z_0 = 0.1 is about 4 times larger than that in the case of L/z_0 = 0.2.

5. Conclusions

We observed an irregular oscillation of positively-charged particles, together with several peaks around the harmonics in the frequency spectrum. The Coulomb collisions between adjacent particles are of crucial because of less shielding effect. The experimental results are compared with a theoretical model with mutual interaction between two particles. The phenomena observed in the experiments are well consistent with the theoretical model.

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