FORCED VERTICAL OSCILLATION OF A SINGLE DUST PARTICLE IN A STRATIFIED GLOW DISCHARGE

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Introduction

The investigation of dust particle oscillations, induced by themselves or by external drive forces, is important for understanding the dynamic processes in dusty plasma systems. For example, the oscillatory motion of dust particles was exploited to obtain insight into the mechanism for the efficient energy transfer between degrees of freedom of the dusty plasma system. In /1/ it was shown that the particle charge fluctuation is the reason for the appearance of forced resonance, which heats vertical oscillations.

Investigation of the dust oscillations is one of the methods used to determine the dust particle charge. In /2/ authors had proposed the method, in which the resonant frequency and damping coefficient of dust particle oscillations in the sheath of rf discharge was used to determine particle charge. The vertical oscillations of the single-layer dust crystal were excited by rf voltage modulation.

In the paper /3/ the experimental method of dust particle charge determination based on the particle oscillations was suggested too. In the experiment the relaxation oscillations of a single dust particle caused by low-frequency discharge current modulation were observed. The calculation of the dust particle charge with the help of the eigenfrequency and damping coefficient was made. In /3/ the theoretical method of the dust particle charge calculation in consideration of the non-locality effect, which occurs in the stratified glow discharge of low pressures and small currents was proposed.

In the present paper, the vertical oscillations of a single dust particle induced by discharge current modulation are investigated in a stratified glow discharge. Amplitude-frequency characteristics (AFC) in dependence on pressure are measured. The AFC measurements for different shapes of modulating signals were made. The quantitative description of the resonance behaviour of the dust particle based on the theory of the forced harmonic oscillator was made. The calculation of the dust particle charge with the help of eigenfrequency is made. The Q-factor of dusty plasma system is measured.

Experiments and results

The experimental investigation was conducted in stratified glow discharge, which produced in neon in the range of pressures 0.06-0.66 torr and currents 2-3 mA with calibrated monodisperse spherical melamine formaldehyde particles with diameters d=4.10±0.14 μm. The detailed description of the experimental setup was presented in /4/.

The discharge current modulator provides square wave output signals with different on/off ratios α. The current switching from i_1 = 2 mA to i_2 = 2.6 mA leads to the rigid shift of all striations by an order Δz = 2 mm. When the current switches back from i_1 to i_2 the striations return to the initial positions. The periodical displacement of the striation excites the vertical oscillation of the dust particle.

The modulation of the discharge current was used to excite the forced vertical oscillations of the dust particle. The frequency of the driving force coincides with that of current modulation. Under the square wave modulation of discharge current, which allowed us to measure the amplitude-frequency characteristic of dust particle oscillations, the driving force takes the form

$$f(t) = \begin{cases} f_{max}\ , for\ \ 0 < t < \alpha T \\ f_{min}, for\ \ \alpha T < t < T \\ f(t + (j+1)T) = f(t + jT)\ \ j = 0,1,2 \ldots \end{cases} \quad . (1)$$

Here, f_{min}, f_{max} are the values of the driving force corresponding to the current values i_1, i_2, T is the period, α is the on/off ratio.

AFC of dust particle oscillations were obtained in the range of pressures p=0.06-0.66 torr. The main resonance peaks at the frequency, close to the eigenfrequency of the dusty plasma system, were observed at lowest pressures. Maxima at multiple of the resonant frequencies were obtained /4/.

Discussion.

In the present paper the quantitative description of the experimentally obtained resonance curves is based on the theory of the forced harmonic oscillator. Thus the equation of oscillatory motion of the single dust particle is given by obvious relation $\ddot{z} + 2\beta\dot{z} + \omega_0^2 z = f(t)$, where β is the damping coefficient, ω_0 is the eigenfrequency, f(t) is the driving force given by equation (1). In the case of the square wave driving force the response function is obtained as the superposition of the response functions of each component in the Fourier series expansion of the driving force

$$A_{sqr}(\omega) = \sum_k \frac{\sqrt{sin^2(k\pi\alpha)}}{k\pi} * \frac{(f_{max} - f_{min})}{\sqrt{\left(\omega_0^2 - (k\omega)^2\right)^2 + 4\beta^2 (k\omega)^2}}. \quad (2)$$

In figure 1 the multi-resonance curve is shown at pressure of p= 0.16 torr. The AFC of dust particle oscillations obtained under the square wave discharge current modulation with on/off ratios $\alpha = 3/8$ and $\alpha = 1/2$ at pressure p=0.16 torr were described by equation (2). In fig. 1 a it is observed that the main resonance peak at ν_{res} =22.3 Hz and the subharmonic peak at $\nu_{res}/2$ =11.4 Hz are well described by the theoretical curve. The value of eigenfrequency $\nu_0 = 21.8$ Hz and the damping constant and $\beta = 14\,\mathrm{s}^{-1}$ were determined by fitting the experimental data. In fig. 1 b the AFC obtained under the square wave discharge current modulation with on/off ratio of $\alpha = 1/2$ is shown at pressure of p=0.16 torr. The resonance curve described by equation (2) with the values of $\nu_0 = 21.6$ Hz and $\beta = 17\,\mathrm{s}^{-1}$ shows the main resonance peak at ν_{res} and the subharmonic peak at $\frac{\nu_{res}}{3}$ as expected. One can see that the value of eigenfrequency obtained by fitting the experimental data is of order of 22 Hz and it is invariant in pressure and in shape of modulating signal. The error in measurement of ν_0 is about 12%.

The single dust particle in the striation can be represented as a simple damped harmonic oscillator, which qualitative behavior can be determined by Q-factor value. Q-factor were determined by the following expression $Q_1 = \frac{A_{\max}}{A_0}$, where $A_{\max}$ is the amplitude of the main resonance peak, A_0 is the static zero-frequency offset (see Fig 1, dotted line). At pressure p=0.16 torr the Q-factor value is $Q_1 = 5$.

The eigenfrrequency of this the dusty plasma oscillatory system can be determined by following relation $\omega_0 = \sqrt{\frac{qE'(z_0)}{M_d}}$ ($E'(z_0)$ is the derivative of the electric field profile at point z_0) as suggested in [3,4]. The calculation of the charge of the single dust particle was made using the value of the eigenfrequency obtained through the approximation of the experimental data (fig. 1). The value of dust particle charge number $Z_d = q/e$ is $Z_d = (1.5 \pm 0.4) * 10^4$. The dust particle charge determined using our experimentaly obtained data differs less than 2 times from values obtained for dust particle of the same diameters d=4.10±0.14 μm at pressure p=0.5 torr in /5/. The comparison shows that the experimentally obtained charge number is in good agreement with the value determined through the relaxation oscillations of a single dust particle under the same experimental conditions in /3/.

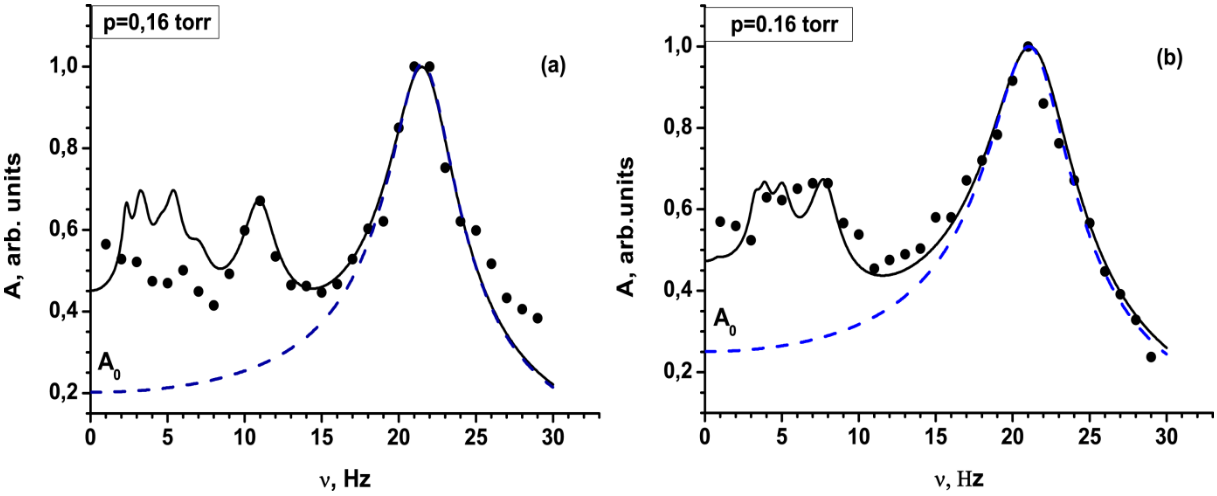

Fig. 1 – AFC obtained under the square wave current modulation with $\alpha = 3/8$ and $\alpha = 1/2$ at pressure p=0.16 torr

The amplitude spectrum is normalized to unity, the symbols represent experimental data, A_0 is the static zero-frequency offset, the solid line corresponds to approximation curve, described by equation (1). The dashed line is the approximation curve, which corresponds to the response function in the case of the sinusoidal driving force /4/.

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