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# Breathing-mode resonance of a complex plasma disk

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In complex plasma, dust motes float. Negatively-charged microparticles are suspended in the plasma sheath where the upward electrostatic force and downward gravitational forces balance. Monodisperse particles will often float in a monolayer above a horizontal electrode. With the addition of radial confinement, and in the strong-coupling regime, the particles form a two-dimensional circular crystal, which we call a complex plasma disk.

Normal mode phenomena are important in complex plasma physics as they provide a bridge linking theory to experiment. Large crystals exhibit continuum wave modes, such as dust acoustic waves [1][2], that are associated with unbounded systems and described by a dispersion relation. Single-particle oscillations in the vertical (*i.e.*, out-of-plane) direction can also be excited [3][4]. Between single particles and large crystals lie mesoscopic systems, which have a normal mode spectrum rather than a dispersion relation [5]-[7]. These systems have many degrees of freedom, yet are finite, and the boundaries play a large role in determining the modes. The complex plasma disk is one example of a mesoscopic system.

Normal mode frequencies can be calculated for a cold complex plasma disk using standard techniques [7]. Typically, the particle-particle interaction is assumed to be a shielded Coulomb force, and the radial potential well is taken to be parabolic. In general, the frequencies and particle motions for each mode depend sensitively on the number of particles $n$ and the particle arrangement. However, there are three special modes whose frequencies are independent of $n$ for a pure Coulomb interaction: spinning, sloshing and breathing [8]. The spinning mode is a rigid body rotation with zero frequency, the sloshing mode is a rigid body center-of-mass oscillation with a frequency $\omega_0$ that equals the single-particle oscillation frequency for the parabolic well, and the breathing mode is a longitudinal oscillation of the mean-square radius of the disk. For the unshielded Coulomb interaction (infinite Debye length), the breathing frequency $\omega_{br} = \sqrt{3}\ \omega_0$, and increases as the Debye length decreases. Both the Debye length and the particle charge can be determined from $\omega_{br}/\omega_0$ for a given $n$.

There are several ways in which the breathing frequency can be determined, including by a comparison between measured thermal motions and a *predicted* mode spectrum [5][6], or in a ringing experiment [5], which simultaneously excites many modes of the complex plasma disk. Ideally, we would like to perform a driven oscillator experiment, where a single-frequency driving force is applied and the steady-state oscillation amplitude is measured. The natural frequency and damping factor $\gamma$ can then determined by fitting the response to a resonance curve. However, performing such an experiment in a dissipative system with many degrees of freedom (*i.e.*, a complex plasma disk) using a arbitrary driving force may not work since the resonances lines are closely spaced and broadened by damping.

We have discovered a method [9] for driving *only* the breathing mode of a complex plasma disk. The driving force is created by amplitude-modulating the rf power sustaining the plasma (13.56 MHz) with a low-frequency sinusoidal signal. This creates a plasma density modulation that couples to the breathing mode, allowing us to measure the steady-state oscillation amplitude at a single frequency and thereby construct a resonance curve. Experiments were performed in the Dusty ONU experiment (D.ONU.T) using 10% and 20% amplitude modulation for a crystal of 125 MF resin microspheres (9.62 μm diameter) at a neutral pressure of 53 mtorr Ar. The average forward rf power was ≈ 11 W.

A time-lapse plot of the measured particle positions for 10% amplitude modulation at a driving frequency $\omega/2\pi = 4.00$ Hz, very near the measured breathing frequency $\omega_{br}/2\pi = 3.97$ Hz, is shown in Fig. 1. The crystal has an equilibrium radius of 2.6 mm, and is slightly elongated in *y*. The inner and outer circles indicate the calculated minimum and maximum radii of the oscillation. The streaks that represent the motion of the particles are nearly purely radial and increase in amplitude with radius, confirming this is the breathing mode. The driven breathing mode oscillation is robust. Particle motion remains coherent at resonance, indicating that the breathing mode is nonlinearly stable.

The dependence of the root-mean-square (rms) radial oscillation amplitude $r_{rms}$ for *each* particle as a function of distance from the center of mass is shown in Fig. 2. The dominant trend is a linear increase of $r_{rms}$ with $r$. Therefore, the crystal is expanding uniformly, and so behaves approximately as a continuous disk. The shell structure in the crystal is reflected by the grouping of data points around certain values of $r$.

The amplitude of the crystal response at the driving frequency $R_1(\omega)$ is shown in Fig. 3a for 10% and 20% amplitude modulation. The data is well fitted by the resonance curve for a driven, underdamped harmonic oscillation. For 10% modulation, the breathing frequency $\omega_{br}/2\pi = 3.97$ Hz, the amplitude $A = 23$ mm/s$^2$ and the damping factor $\gamma = 5.5$ s$^{-1}$, while for

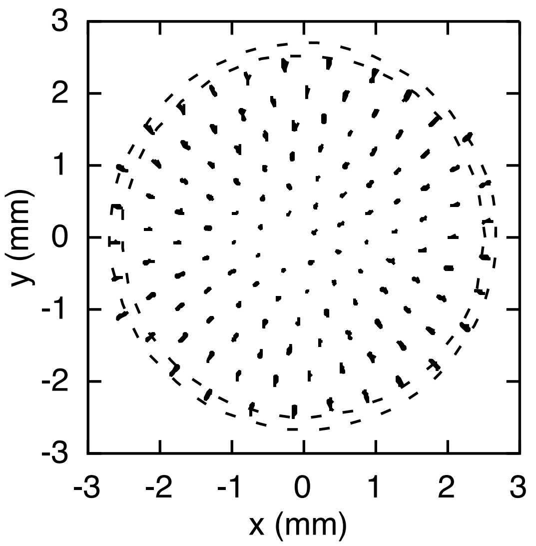


Fig. 1. Time history of particle positions.

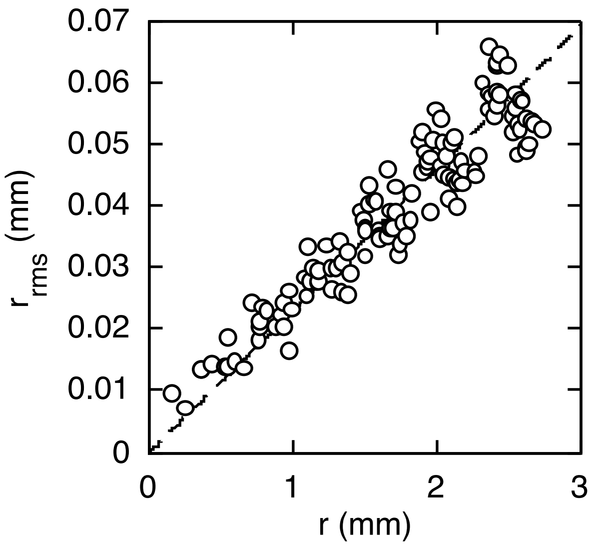


Fig. 2. Plot of the rms oscillation amplitude vs distance from the center of mass

20% modulation, $\omega_{br}/2\pi$ = 3.87 Hz, $A$ = 44 mm/s$^2$ and $\gamma$ = 5.7 s$^{-1}$. That is, the resonant frequency and damping constant are unchanged, while the driving force scales linearly with the modulation level. The quality factor Q = 2.2 and 2.1 for 10% and 20% modulation, respectively, is also unchanged. As discussed above, the measurement of a simple resonance curve for this system is somewhat surprising and we conclude that the applied sinusoidal plasma density modulation only couples strongly to the breathing mode. We believe this is the case because modulating the plasma density modulates the particle-particle spacing, causing the crystal to breathe without exciting other modes.

As shown in Fig. 3b, a resonance is also observed for the response at the second harmonic $R_2(\omega)$ at one-half of the fundamental resonant frequency, where the resonance curve is a reduced version of the curve in Fig. 3a. For 10% modulation, the frequency for amplitude resonance is $\omega_{br,2}/2\pi$ = 1.90 Hz, and the amplitude $A_2$ = 0.43 mm/s$^2$, while for 20% modulation $\omega_{br,2}/2\pi$ = 1.89 Hz and $A_2$ = 1.6 mm/s$^2$. The amplitude increases by a factor of four when the driving force is doubled, indicating a quadratic nonlinearity. Mode suppression of the second harmonic is observed at the fundamental resonance, providing further evidence for nonlinear behavior. The second harmonic resonance is well-fitted by driven damped harmonic oscillator theory for a *constant* driving force, implying that the plasma density modulation produces the second harmonic directly rather than through an interaction with the fundamental oscillation.

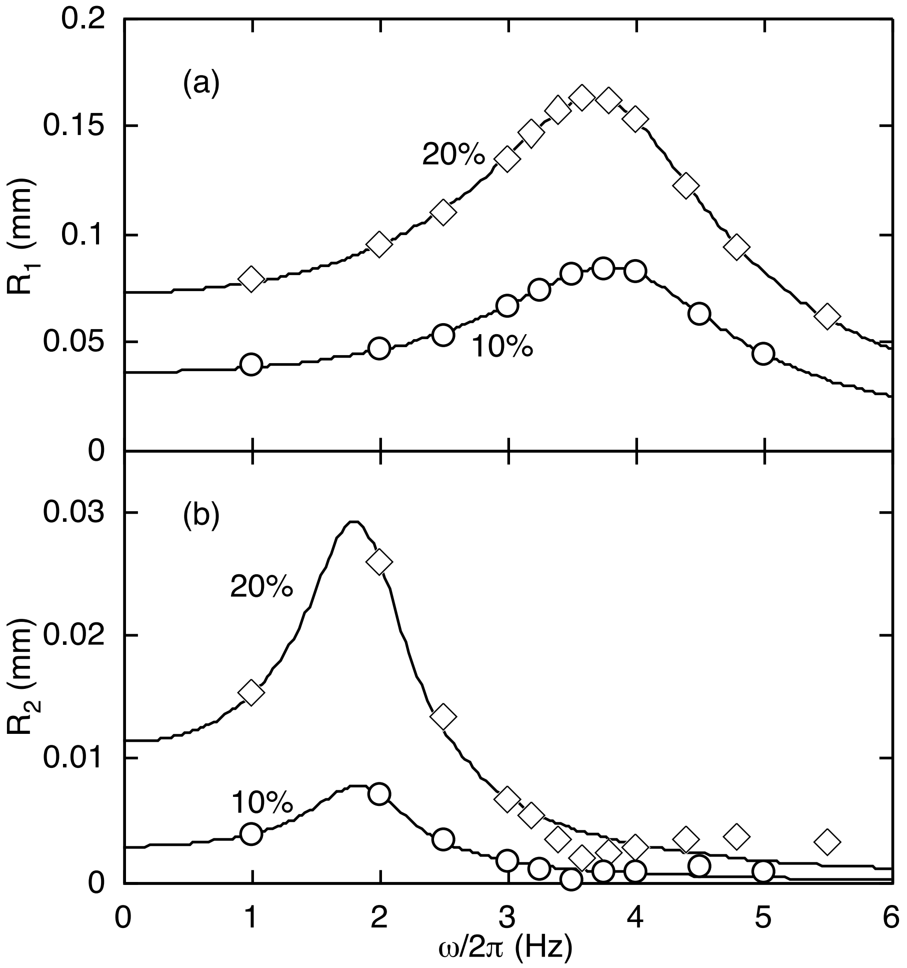


Figure 3. Response amplitude vs driving frequency for the fundamental and 2nd harmonics.

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