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Directional motion of dust particles at different gear structures in a plasma*

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Directional motion of dust particles in a dusty plasma ratchet is observed experimentally. The dusty plasma ratchet consists of two concentric gears with asymmetric sawtooth. It is found that the sawtooth number affects the directional motion of dust particles along the saw channel. With the increase of the sawtooth number, the particle velocity increases firstly and then decreases, and there is an optimum number of the sawtooth which could induce fast rotation of dust particles. The velocities of dust particles change as they are flowing along the saw channel. We also explore the force acting on the dust particle experimentally.

Keywords: dusty plasma, ratchet

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1. Introduction

Rectifying motion in random environments is a long standing problem. In the absence of any net macroscopic forces, asymmetric potentials can be used to induce a particle flow when subjected to external fluctuations.[1] Referred to as Brownian ratchet, its study has flourished as one of the most active and diverse fields such as physics,[2–5] chemistry,[6,7] and biology.[8,9] Symmetry breaking mechanisms are demanded for operation of Brownian ratchet. Three possibilities inducing the symmetry-breaking have been proposed:[1] (1) unbiased driving force, (2) asymmetric ratchet potential, and (3) collective effect. Experimental explores to these possibilities have been performed in several experiments, such as tunneling ratchet in a semiconductor nanostructure[10] and vortex ratchet in a superconductor.[4] As demonstrated in Ref. [5], asymmetric ratchet and unbiased driving force are two necessary conditions for operation of Brownian ratchet in one-dimensional pores of silicon membrane. Experimental investigation of ratchet effect in an easy way at the kinetic level is still highly sought until now.

Dusty plasma consists of electrons, ions, neutral gas atoms, and dust particles.[11–20] Due to the collection of electrons and ions from the plasma, these particles gain more than thousands of elementary charges and often become strongly coupled. Typical time scales of dynamical processes for the dust subsystem are in the range of 10–100 Hz. Therefore, micron-sized dust particles can be visualized individually and tracked easily in experiments at the kinetic level. This makes it an ideal model system for the study of phase transitions, strong coupling, and nonlinear waves phenomena, etc.[21–25]

In a recent experimental study, we designed a dusty plasma ratchet and realized the rectification of dust particles into directional motion in plasma environment.[26] We explored the fundamental mechanisms inducing the directional movement of dust particles: asymmetric ratchet potential and collective effect. In the previous experiments, we found that the sawtooth number on each gear could affect the directional movement of particles. The change of the sawtooth number modifies the degree of asymmetry of the ratchet potential. In the present study, we report the directional motion of dust particles in the saw channel with different sawtooth numbers in detail. Too many or too few sawtooth numbers will not cause the directional movement of dust particles. There exists an optimal sawtooth number which can give rise to fast motion of dust particles in the saw channel. We also explore the nonuniform motion of dust particles in the saw channel. Our results are helpful for understanding well the mechanisms of rectification of dust particles in the dusty plasma ratchet.

2. Experimental setup

The experiments are performed in a vacuum chamber filled with argon as shown by the schematic diagram in Fig. 1. The size of the vacuum chamber is 20 cm × 20 cm × 15 cm. The upper electrode is ITO glass plate and grounded, and the lower electrode is stainless steel plate connected to an RF power at a frequency of 13.56 MHz. As main control parameters, the gas pressure changes within the range of 10–40 Pa, and the power changes within the range of 15–40 W.

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Two asymmetric gears with the same number of sawtooth are placed concentrically on the lower electrode as indicated in Fig. 1. The sawtooth of gears have the same orientation as shown by the inset in Fig. 1. The two gears enclose a saw channel with varying width along the saw channel. Macroporous cross-linked polystyrene microspheres with a diameter of 23 μm and mass $m_d \approx 4.5\times10^{-12}$ kg are used as the dust particles. Once a plasma is generated, dust particles are dropped into the saw channel between the inner and outer gears. Electric field from the sheath of the sawtooth surface confines the dust particles within the saw channel. With the illumination from a flood lamp, the movements of dust particles are recorded by a camera placed on the top of the vacuum chamber. The trajectories and velocities of dust particles are obtained by using developed video processing programs.

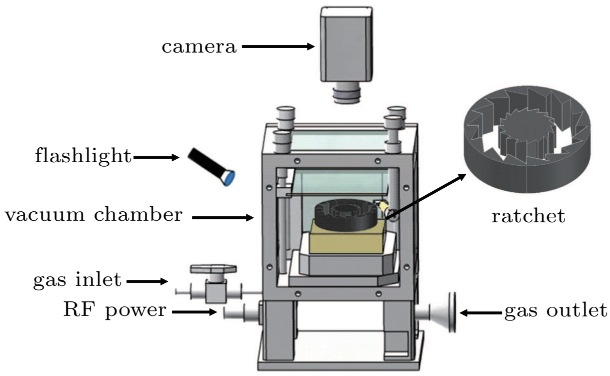

Fig. 1. Schematic diagram of the experimental setup. The upper right corner is a magnified view of the gears with asymmetric sawtooth. The depths of the sawtooth in the inner and outer gears are 3 mm and 4 mm, respectively. The radii of the inner and outer gears are 26 mm and 40 mm, respectively. The heights of the two gears are both 7 mm.

3. Experimental results

After dropped into the saw channel from one side, the charged dust particles flow along the saw channel due to the strong repulsive action among them. They form a dust particle chain after a transient about several seconds as shown in Fig. 2. Under appropriate experimental conditions, the dust particles could flow persistently as a whole along the saw channel. In order to describe conveniently the directional motions of dust particles along the saw channel, we use + and − to define the positive and negative directions of particle flow, respectively, as indicated in Fig. 2. Dust particles perform positive motion along the saw channel at 40 Pa and 25 W as shown in Fig. 2.

In order to explore the effect of the sawtooth number of gears on dust particle motion, we design a set of gears with the same radius, but different sawtooth numbers changing from $n = 28$ to $n = 72$. As we have shown that the number of the dust particles affects the average velocity of dust particles,[26] here we have to keep the number of dust particles as constant as possible after we replace the gears in different experiments. In the present work, the number of dust particles is set to $N_0 \approx 340$. In this case, the dust particles arrange themselves into a chain along the center of the saw channel as shown in Fig. 2. If the number of dropped dust particles exceeds N_0, we will decrease the gas pressure to several Pa in order to push up dust particles above the height of the gears. Some of the dust particles flow outside the saw channel until the number of dust particles approach 340.

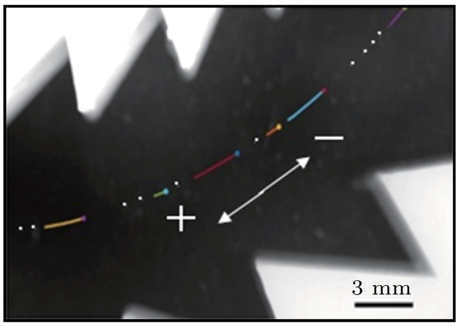

Fig. 2. Distribution of dust particles within several sawteeth along the saw channel. Colored lines indicate the trajectories of dust particles during 0.6 s. Circle on each trajectory marks the starting point of the trajectory. Gas pressure: 40 Pa, RF power: 25 W. Here + and − beside the white arrow define the motion directions. Particle brightness has been appropriately enhanced.

Figure 3 shows the dependence of the angular velocity of dust particles on the sawtooth number of gears at (30 Pa, 30 W). As can be seen, the angular velocity increases firstly with the sawtooth number until reaches a maximum about 0.52 rad/s at $n = 44$. This means that when $n < 44$, increasing the sawtooth number can enhance the flow of dust particles. When $n = 28$, the dust particles perform directional motions at a very slow velocity about 0.035 rad/s. It is believed that in the limitation case of $n \to 0$, the gears with asymmetrical sawtooth degenerate to circular rings without any asymmetry, which leads to zero flow of dust particles. The dust particles would perform random motions around their equilibrium positions in the saw channel.

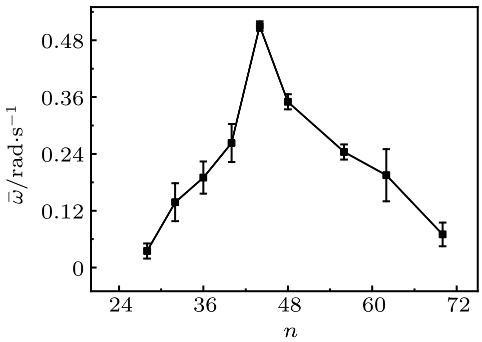

Fig. 3. Dependence of the angular velocity of dust particles on the sawtooth number of gears. Gas pressure: 30 Pa, RF power: 30 W. The error bar is caused by the difference of particle number and the deviation of image processing.

When the sawtooth number $n > 44$, the average angular velocity decreases with the sawtooth number. When $n = 70$, the average angular velocity reduces to one order of magnitude of the maximum. It is believed that in the limitation case of $n \to \infty$, the asymmetrical gears would also degenerate to circular rings. Therefore, the asymmetry of the system disappears in this case, which leads to zero flow of dust particles.

To further explore the effect of the sawtooth number on the rectification of dust particles, we consider the couple between the dust particles and the gears in the saw channel. As have been shown in Ref. [26], ratchet potential and collective effects are two keys to the rectification of dust particles. Along the saw channel, the ratchet potential is asymmetric and periodic with a ratchet length $L = 2\pi r/n$, here r is the radius of the circular trajectories dust particles following. The negatively-charged dust particles are separated well along the saw channel due to their strongly repulsive action with an average inter particle distance $d = 0.75$–0.98 mm. Then, one can obtain the number of dust particles within each ratchet well $N/n = L/d$, here N is the total number of dust particles. Too many or too few dust particles within each ratchet well lead to slow motion of dust particles. A peak appears at $L/d \approx 7$, which means that the optimal coupling between the dust particles and the gears is that each ratchet well accommodates $\sim$7 dust particles. The average angular velocity could reach 0.5 rad/s in this case.

Due to the periodic variation on the width of the saw channel, the angular velocity of the directional motion of dust particles changes as the dust particles are flowing along the center of the saw channel. Figure 2 shows several typical trajectories of dust particles during 0.6 s at 40 Pa and 25 W. It can be seen that the dust particles near the slot of the sawtooth have long trajectories which results from the faster motion of dust particles as they pass through the neck of the saw channel. In the following, we show the periodic change in the angular velocity when the dust particles flow along the saw channel.

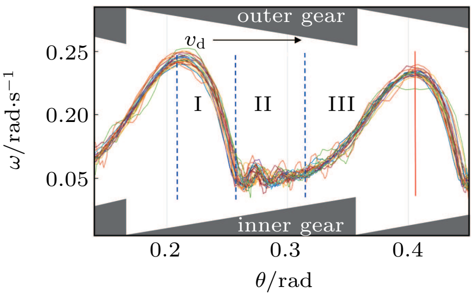

Fig. 4. Distribution of angular velocity at different angular positions in the saw channel. The colored curves represent the superposition of the distribution of angular velocity of 74 dust particles. Black arrow line indicates the motion direction of dust particles. Gas pressure: 40 Pa, RF power: 25 W.

Figure 4 shows the variations of angular velocity of dust particles along the saw channel. The angular velocities change within a range from 0.04 rad/s to 0.25 rad/s. The maximum of the angular velocity occurs near the slot of the sawtooth. We divide one period of the saw channel into three parts, i.e., I, II, III, as indicated in Fig. 4. After passing through the neck of the saw channel, the angular velocity of dust particle decreases in part I until reaching a minimum $\omega_{\min} \approx 0.04$ rad/s. When dust particle enters part II, it flows almost uniformly in the saw channel with the minimal angular velocity. Here the random motion of dust particle becomes obvious, especially in the radial direction, as shown in part II in Fig. 4. When dust particle enters part III, it is accelerated up to the maximum $\omega_{\max} \approx 0.25$ rad/s.

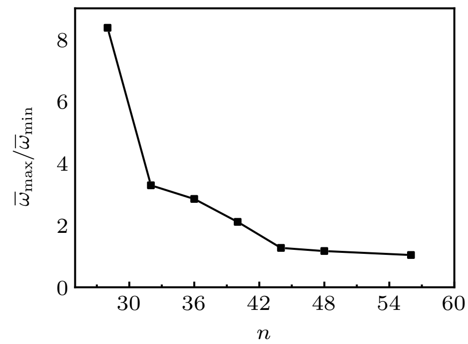

Fig. 5. Dependence of the ratio of the maximum to minimum angular velocities on the sawtooth number. Gas pressure: 30 Pa, RF power: 30 W.

Figure 5 shows the ratio of the maximum angular velocity to the minimum angular velocity of the dust particles in the saw channel for different sawtooth numbers. It can be seen that this ratio decreases as the number of sawtooth increases. When the sawtooth number is small, the maximum angular velocity is nearly 8 times larger than the minimum angular velocity. When the sawtooth number is more than $\sim$44, the ratio approaches to 1, which means that dust particles flow almost uniformly along the saw channel. This is induced by the reduction of the asymmetry of gears at the larger sawtooth number as illustrated above.

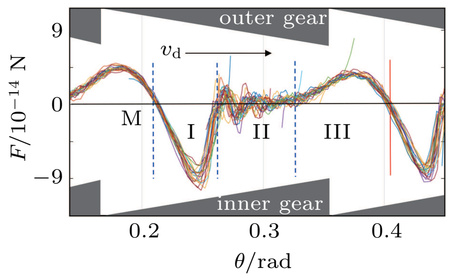

Fig. 6. Distribution of the force on the dust particle at different angular positions in the saw channel derived from Fig. 4. M indicates the stable stationary position of dust particle. Black arrow line indicates the motion direction of dust particles. Gas pressure: 40 Pa, RF power: 25 W.

We further explore the force acting on the dust particle. Based on Fig. 4, we perform integral of the velocity of dust particles and obtain the acceleration accordingly. Then, the force of dust particles can be acquired from the Newton second law as shown in Fig. 6. It shows that the force acting on the dust particle changes periodically as the dust particle traveling along the saw channel. Near the tip of the sawtooth, the force is positive and drives the dust particle forward passing through the narrow neck of the saw channel. When the dust particle enters part I, it suffers a negative force due to the block from the slanted side of the saw channel and performs decelerated motion. The point M indicates the stable stationary position of dust particle, at which $dF/d\theta$ is negative. In part Ⅱ, the force is small and the dust particle flows slowly along the saw channel. When the dust particle approaches the narrow neck of the saw channel once again, i.e., entering part Ⅲ, the force is positive and could reach a maximum of $\sim 4.5\times10^{-14}$ N.

Although the force is variable along the saw channel, its integral over one period of the saw channel is zero. Therefore, the dust particles would perform persistent flow along the saw channel. Our numerical simulations in Ref. [26] showed a clear physical picture of the directional movement of dust particles in the dusty plasma ratchet:[2] under a non-equilibrium driving force of ion drag ($\sim10^{-13}$ N) which could overcome the resistance of neutral gas ($\sim10^{-13}$ N), a large number of dust particles can perform directional motion along the periodic and asymmetrical ratchet potential. In this work, we measure that the resultant forces of dust particles are in the order of 10^{-14} N.

4. Conclusions

We have studied the effect of the sawtooth number on the average angular velocity of dust particles and explored the directional movement of dust particles in the saw channel. The change in the sawtooth number of gears affects the structure parameters of gears and then the coupling between the dust particle and the gears. The average angular velocity of the dust particles first increases and then decreases with the increasing sawtooth number. The distribution of angular velocity of dust particles is very nonuniform in the saw channel when the sawtooth number is less than 44. The distribution of the force acting on the dust particle is also nonuniform. Our results are important to finding optimal dust plasma ratchet for further control of the directional motion of dust particles in a plasma.

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