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Formation and evolution of vortices in a collisional strongly coupled dusty plasma

Sayanee Jana [a], Debabrata Banerjee [b,*], Nikhil Chakrabarti [a]

[a] Saha Institute of Nuclear Physics, a/AF Bidhannagar, Kolkata 700 064, India
[b] Institute for Plasma Research, Bhat, Gandhinagar 382428, India

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A B S T R A C T

Formation and evolution of vortices are studied in a collisional strongly coupled dusty plasma in the framework of a Generalized Hydrodynamic model (GH). Here we mainly present the nonlinear dynamical response of this strongly coupled system in presence of dust-neutral collisional drag. It is shown that the interplay between the nonlinear elastic stress and the dust-neutral collisional drag results in the generation of non-propagating monopole vortex for some duration before it starts to propagate like transverse shear wave. It is also found that the interaction between two unshielded monopole vortices having both same (co-rotating) and opposite (counter rotating) rotations result in the formation of two propagating dipole vortices of equal and unequal strength respectively. These results will provide some new understanding on the transport properties in such a strongly coupled system. The numerical simulation is carried out using a de-aliased doubly periodic pseudo-spectral code with Runge–Kutta–Gill time integrator.

1. Introduction

The formation of vortices and their evolution have been an important area of research in fluid dynamics and plasmas as they serve an important role in energy and particle transport in such medium. In nature, convection property of fluid particles generates vortices depending on the value of Reynolds number (inverse of kinetic viscosity). In presence of different free energy sources (like velocity shear, density gradient etc.), any small wavy disturbance can grow up due to different fluid instabilities like Kelvin–Helmholtz instability, Rayleigh–Taylor instability etc. These unstable modes finally converge nonlinearly into different vortex like structures preserving the balance between nonlinearity and dispersion or dissipation effects in fluids. Such vortices are mostly seen in the river current, ocean, high wind [1]. Like fluid media, vortices are also very often observed in space and astrophysical plasma [2,3]. Besides the fluid instabilities, other important driving mechanisms in case of space plasma vortices are different electro-magnetic phenomena like Alfvén wave, Drift wave, coupled drift–Alfvén wave. The structures such as two-dimensional vortex chains, dipolar and monopolar vortices etc. observed in the auroral plasma are well described by nonlinear drift–Alfvén theory in the article of Chmyrev et al. [4]. They have explained the generation of Alfvén vortices at the plasma sheet boundary layer region in presence of plasma inhomogeneities, and further reported that these vortices can transport trapped particles from this sheet region to the auroral ionospheric region. Our focus of this present article is to study formation and evolution of vortices in dusty plasma in strongly coupled regime. It is known that the dust particles are likely to be present in space and astrophysical plasma including the ionosphere and magnetosphere of Earth [5], planetary rings of Saturn and Jupiter [6], interstellar clouds, interplanetary space, solar wind etc. [7]. The dust vortices studied in this present article are expected to be present in these regions of space dusty plasma specially white dwarf matter, interiors of heavy planets which may have suitable parameter regime of strongly coupled dusty plasma [7,8].

Thus experimental and theoretical research in the field of formation, transport and interaction of different vortices, is essential to understand the nonlinear structures in fluids [9] and plasmas [10]. Theoretical and numerical studies on the Euler vortex equation fruitfully represent experimental and natural phenomena of formation and interaction of vortices in hydrodynamical fluids. Monopole vortices and dipole vortices, which occur mostly in nature, are also well known solutions of the Euler equation. Using spectral method, Rasmussen et al. [11] studied generation of lamb dipole by solving the Euler equation from different localized structures and their decay in presence of viscosity. The phenomena of

* Corresponding author. Present address: Department of Modern Physics, University of Science and Technology of China, Hefei, Anhui 230026, China.
E-mail address: debu@ustc.edu.cn (D. Banerjee).

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merzing of two co-rotating monopole vortices [12] and dipole formation from the interaction between two counter rotating vortices [13] are crucial in decay turbulence and inverse cascading.

A dusty plasma, commonly known as complex plasma, consists of electrons, ions, neutral particles and micron sized dust particles. At low temperature, the average inter-particle potential energy of strongly coupled dust particles becomes larger than the average kinetic energy of each particle which causes the dust particles to be strongly coupled to each other. This coupling strength can be characterized by the coulomb coupling parameter [14,15] $\Gamma = q_d^2/(k_B T_d a)$, the ratio of the average potential energy to the average kinetic energy per particle, where q_d, a, T_d and k_B are the charge on the dust particle, the average inter particle distance, the temperature of the dust component and the Boltzman constant respectively. The average inter particle a can be characterized as the Wigner–Seitz radius $a = (3/4\pi n_d)^{1/3}$, where n_d is the dust number density. In the regime where Γ varies from 1 to Γ_c ($\sim$170, a critical value beyond which the system becomes crystalline), both viscosity and elasticity are equally important and this property is known as visco-elasticity [8,16,17]. In this intermediate coupling regime the system behaves as a viscoelastic media and its dynamics is provided by the Generalized Hydrodynamic model (GH) that incorporates the Maxwell's relaxation parameter τ_m to mimic this behavior [18]. It has been shown theoretically as well as experimentally that this viscoelastic system can support transverse shear wave because of its elastic property [8,16,17]. In nonlinear regime, it has been shown theoretically that this strongly coupled dusty plasma system can support vortex like structures depending on the various parametric conditions [19–22]. In such system the effect of elasticity on vortices makes them quite different from viscous fluid. Recent molecular dynamic simulation has shown formation of tripole and dipole vortices from the perturbed shielded Gaussian vortex [23].

In above mentioned references on dust vortices [19–23], none has taken consideration of dust-neutral collisional drag (i.e. friction force exerted on the dust particles due to presence of the neutral gas in complex plasma, known as Epstein drag [24]). But, if one desire to model experimental situation properly, should take into account the effect of collisional drag however small it is. However, theoretical studies in presence of Epstein drag have shown the significant damping effect on the properties of plasma waves [25–27]. For long wavelength dust acoustic wave, it has been reported that mostly damping is provided by the dust-neutral collisional drag [27]. For large pressure, it has also been reported that flow related instabilities are effectively damped by collisions between the dust and neutral particles [28]. Non-Newtonian behavior of complex plasma has been experimentally studied in presence of high value of dust-neutral collisional drag [29]. Thus the dusty plasma can act as a highly dissipative system in presence of dust-neutral collisional drag. It is, therefore, both interesting and important to study the effect of dust-neutral collisional drag in the context of the dust vortex dynamics in the frame work of the Generalized Hydrodynamic model (GH). In microgravity experiments, different types of dust vortices have been observed in the cloud of fine dust particles. Experiments carried out in the laboratory rf (radio-frequency) plasma have reported the formation of dust vortices at the wake flow regime of dust particles behind voids [30]. Mitic et al. have observed vortex like structures of convective dust clouds due to the phenomena of thermal creep in their complex plasma experiment [31]. Bockwoldt et al. have explained in experimental and numerical studies that stable dust vortices are generated due to the balance between the driving torques from charge gradients and ion drag and the loss of torque by friction with the neutral gas [32]. They have also explained that charge gradient alongwith ion drag force is essential for the generation of quadrupole vortices. The change in dust vortex structure and possible breaking into small vortices with decreasing radio-frequency (rf) power has been observed in experiment by Morfill et al. [33]. In simulation, it has been concluded that thermophoretic force has no driving role for the generation of dust vortices in microgravity [34]. Recently, Schwabe et al. have studied the properties of dust vortices in light of turbulence and reported that velocity structure function scaling is very close to the prediction by Kolmogorov theory [35]. Agarwal et al. have observed spontaneous rotation of a strongly coupled dusty plasma cloud in the absence of any external magnetic field induced by charge gradients perpendicular to gravity [36]. Ratynskaia et al., have studied visco elastic vortical fluid motion in strongly coupled monolayer dusty plasma observed in a capacitively coupled radio-frequency (rf) plasma experiment, and reported the importance of dust-neutral collisional drag for studying long time scale and large spatial scale vortical fluid flows [37]. In a recent article, the dynamical change of the phenomena of vortex merging has been studied numerically by varying the strong coupling parameter ranging from hydrodynamic to strongly coupled limit in the strongly coupled dusty plasma in the framework of the Generalized Hydrodynamic model (GH) without considering dust-neutral collisional drag [38]. So, it is very interesting to study the effect of both elastic stress arising due to the strong coupling effect and dust-neutral collisional drag on the vortex phenomenon in the strongly coupled dusty plasma.

In this article, we have studied an important phenomenon of vortex formation and its evolution for different well known initial structures in a strongly coupled dusty plasma in the framework of the Generalized Hydrodynamic model (GH) modified by dust-neutral collisional drag. Specifically, we have observed how the interplay between the nonlinear elastic stress and the dust-neutral collisional drag determines the dynamics of the vortices in such a strongly coupled system. All the studies have been done by numerically integrating Generalized Hydrodynamic equation (GH) after transforming into Fourier space using the doubly periodic pseudo-spectral simulation method. In this work we find two interesting aspects of vortex evolution which are as follows: 1) a sensitive balance between the nonlinear elastic stress and the dust-neutral collisional drag results in the generation of non-propagating monopole vortex before it starts to propagate like shear wave and 2) the interaction between two unshielded monopole Gaussian vortices having both same (co-rotating) and opposite (counter rotating) rotations produces two propagating dipole vortices of equal and unequal strength respectively when there is a sensitive balance between the nonlinear elastic stress and the dust-neutral collisional drag.

2. Basic equations

In this present work, we consider a strongly coupled dusty plasma which is a collection of electrons, ions and neutral particles together with negatively charged massive dust particles. The dust particles are strongly coupled to each other due to their larger electric charges than the electrons and ions which remain weakly coupled. As we are interested in the low frequency response ($\omega \ll k v_{th\ e(i)}$; where $k v_{th\ e(i)}$ is the thermal velocity of the electrons (ions)) of this system so the electrons and ions inertia can be neglected compared to the massive dust particle motion and their dynamics are treated through the Boltzmann relation. These are given by

$$0 = -n_e e\mathbf{E} - \nabla p_e \quad \Rightarrow n_e = n_{e0} \exp\left(\frac{e\phi}{T_e}\right), \tag{1}$$

$$0 = n_i e\mathbf{E} - \nabla p_i \quad \Rightarrow n_i = n_{i0} \exp\left(-\frac{e\phi}{T_i}\right), \tag{2}$$