Chapter 3

# Sound Waves in Complex (Dusty) Plasmas

Aamir Shahzad, Muhammad Asif Shakoori,
Maogang He and Sajid Bashir

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.71203

**Abstract**

Wave properties of strongly coupled complex dusty (SCCD) plasmas evaluated using the equilibrium molecular dynamics (EMD) simulation technique. In this work, the plasma normalized longitudinal current correlation function $C_L(k,t)$ and transverse current $C_T(k,t)$ are calculated for a large range of plasma parameters of Coulomb coupling parameter ($\Gamma$) and screening strength ($\kappa$) with varying wave's number ($k$). In EMD simulations, we have analysed different modes of wave propagation in SCCD plasmas with increasing and decreasing sequences of different combinations of plasmas parameters ($\kappa$, $\Gamma$) at varying simulation time step ($\Delta t$). Our simulation results show that the fluctuation of waves increases with an increase of $\Gamma$ and decreases with increasing $\kappa$. Additional test shows that the presented results for waves are slightly dependent on number of particles ($N$). The amplitude and time period of $C_L(k,t)$ and $C_T(k,t)$ also depend on different influenced parameters of $\kappa$, $\Gamma$, $k$ and $N$. The new results obtained through the presented EMD method for complex dusty plasma discussed and compared with earlier simulation results based on different numerical methods. It is demonstrated that the presented model is the best tool for estimating the behaviour of waves in strongly coupled complex system (dusty plasmas) over a suitable range of parameters.

**Keywords:** wave properties, plasma parameter, current correlation function, dynamic structure factor, strongly coupled complex (dusty) plasmas, equilibrium molecular dynamics

## 1. Introduction

Transport properties of complex dusty plasma have been very actively investigated in the laboratory and by computer simulations, and wave properties have played a dominated role in both system monitoring and optimization. Waves in complex system have a dynamical role for understanding the behaviours of individual particles in different applications, for example, instabilities and wave propagation during flow. The subject of complex liquids or dusty plasmas containing micron-size charged condensed particles has recently been actively investigated in the physics and chemistry of plasmas, ionized gases, and the space environment, environmental sciences, semiconductor plasma processing industries, nuclear energy generation and materials research. Dust in atmosphere and in the entire universe is in different shapes and sizes. Mostly, it is in solid form and also in liquid and gaseous forms. Dust particle coexists with plasma and then forms dusty (complex) plasma. In the plasma when an electron is displaced from their equilibrium position, the electrostatic forces due to ions pull the electron back. Due to small mass of electron, overshoot the ions and oscillation in plasma is started.

### 1.1. Plasma

There are four states of matter: liquid, solid, gas and plasma. The Irving Langmuir, an American physicist, defines plasma first time as "plasma is a quasi-neutral gas of the charged particles that show collective behaviors." He received Noble prize in 1927 first time using the term "plasma" [1]. The quasi neutral means "when the number of ions is equal to the number of electrons then gas becomes electrically neutral ($ni \approx ne$)". Collective behaviour means that charged particle collides with each other due to electric field and coulomb potential. Applications of plasma in industries, science and technology and in our daily life are very significant [2, 3].

#### *1.1.1. History of plasma*

In 1922, the term plasma is used and defined by an American scientist Irving Langmuir. In 1930, a few isolated researchers, each motivated by some specific practical problems, began the study of what is now called plasma physics. In 1940, Hanes Alfven developed theory of hydrodynamic waves and gives the future prospectus of waves in astrophysical plasma (now called Alfven's waves). In 1950, research on magnetic fusion energy was started based on plasma physics in the USA, Soviet and Britain. The end decade of 1960 Russian Tokomak configuration empirically developed and created plasma with different parameters. In 1970 and 1980, the performance of tokomak was improved at the end of twentieth century and fusion break-even nearly achieved in tokomak. In the 1980s, many new applications of plasma in different fields of science and technology appeared. In the 1990s, study on dusty plasma was started (when the dust particles are immersed in plasma, they change the properties of plasma, which is known as dusty plasma) [4, 5].

#### *1.1.2. Types of plasma*

Plasma classified on the basis of temperature of electrons, ions and degree of ionization as well as density.

#### *1.1.3. Cold plasma*

$T_i$, $T_e$ and $T_g$ are the temperatures of ions, electron and gas respectively, if the plasmas satisfy $T_e >> T_i >> T_g$ condition is called cold plasma. The pressure of the cold plasma is low than

http://dx.doi.org/10.5772/intechopen.71203

collisions between electrons, ions and gases molecule that are not frequent. In this plasma, non-thermal symmetry between energies of gas molecules and electrons are not existed. Temperature of electrons is higher than ions and has greater energy than ions. Similarly, ions have greater energy than gas molecules. In this type of plasma, the effect of magnetic field is very weak and also can be ignored; only charge particles are affected by electric field. It is created in the laboratory on positive column of the glow discharge tube. Applications of cold plasma in food processing, sterilization of tooth, hand and self-decontaminating filter. It is used as a convenient descriptor to distinguish one-atmosphere. Examples of cold plasma are fluorescent lamps and neon signs [6].

*1.1.4. Ultracold plasma*

If the plasma having very low temperature approximately 100 mK to 10 μK, density $2\times10^{9}cm^{3}$, interaction between particles is strong and the thermal energy of the particles is low compared with Coulomb energy between interacting particles known as ultracold plasma. It is created by pulsed lasers, laser-cooled atoms and photo ionization [7].

*1.1.5. Hot plasma*

If the plasmas have very high temperature, the collision between interacting particles is very frequent also thermal equilibrium obtains, if plasma satisfies $T_e \cong T_{i,}$ this condition is known as hot plasma or thermal plasma. It is created in laboratory with high gas pressure in the discharge tube. Hot plasma acquired local thermodynamic equilibrium (LTE). Examples of hot plasma are atmospheric arcs, sparks and flame. In the hot plasma, the thermal equilibrium occurs between the gas molecules and electrons when electron collides with the gas molecules at a high pressure in the discharge tube.

*1.1.6. Ideal plasma*

It is defined by a plasma parameter which is known as Coulomb coupling and denoted by $\Gamma = \frac{P.E}{K.E}$. Whenever, $\Gamma< 1$, then that plasma is called ideal plasma. In ideal plasma, the kinetic energy (KE) of the plasma is greater than potential energy (PE) at low density and high temperature. In the ideal plasma, the value of Coulomb coupling is negligible. Due to low density, the collisions between particles are less, and ideal plasma does not have a specific structure [8, 9].

*1.1.7. Non-ideal complex (dusty) plasma*

When dust particles are immersed in the plasma, then the properties of plasma become complex known as complex (dusty) plasma. The dust particles are charged and much larger than electrons, ions and neutral atoms, and their size varies from millimetre to nanometre. The properties of dust particles are investigated in different fields of research such as plasma physics, plasma chemistry, ionized gases, material research and astrophysics and also in space physics. Dust particle changes different properties of plasma dominate in current carrier, form liquid and crystalline states. Comets, exposed dusty surfaces, planetary rings and zodiacal dust cloud are the examples of dusty plasma [10–12].

### 1.2. Dust particle in plasma

Dust in atmosphere and in the entire universe is in different shapes and sizes. Mostly, it is in solid form and also presents in liquid and gaseous forms. If dust particle coexists with plasma, it forms dusty (complex) plasma. Dust particle acquires charge and is affected by electric and magnetic fields. Temperature on the dust particle is approximately 10 K, and electric potential varies from 1 to 10 V is mostly negatively potential. Charge on dust particle depends on the flow of electrons and ions. It can be grown or inserted in low-temperature plasma at low degree of ionization in the laboratory. It becomes a dominant component of dusty plasma for transports of energy, momentum and mass. In these days, dusty plasma becomes more significant in the field of research of science and technology by investigating its transport properties in the laboratory. Currently, complex plasma becomes more interesting field of research. The major ratio of plasma in the universe is dusty plasma. It is a huge occurrence in magneto and ionosphere of earth, atmosphere of stars, sun, solar wind, galaxies cosmic radiations, planetary rings comet tails and nebulae. Dusty plasma also known as complex plasma has electrons, ions, neutral and dust particles components [12].

#### *1.2.1. Charge on dust particle*

Dust particles in plasma gain the electric charge, which they obtained in the plasma. The charge on dust particle can range from zero to hundreds of thousands of electrons depending on the size and shape of the dust particle. When a dust grain immersed in an ionized medium, soon it gains a charge when its surface is contact with plasma. This is valid for small floating objects like dust particles, also for electrode surfaces and macroscopic objects inserted into the discharge tube. This charge determines by balancing positive ion and the electron current. These currents must be equal in a steady state. Due to high mobility of the electrons as compared to ions, the surface collects negative charges, which attracts positive ions and repel the electrons until an immobile state is reached. Therefore, by equating fluxes between electrons and ions, the charge on particle can be obtained. This charge is responsible for confinement and long lifetimes of particles in plasmas. Due to interactions between these particles, waves, instabilities and other collective phenomena are produced.

#### *1.2.2. Size of dust particle*

Dust particles are much larger than electrons and ions, and its size varies from $10^{-3}$ m to $10^{-9}$ m. A typically used particle may have a diameter of 3.50±0.05 μm and a mass ~$3\times10^{-11}$ kg. Such particles are named mono disperse. It has any shape, mostly spherical, and also easily observed in laboratory without any microscope. It is made by conducting or dielectric material [12, 13].

#### *1.2.3. Nature of dust particle*

Dust particles that collect the plasma particles such as electrons and ions on their surface become an interacting particle. In the dusty plasma energy, momentum and mass are transferred through dust particle. Dust particle may be in liquid, solid and gaseous forms.

### 1.3. Application of plasma in daily life

Plasma is widely used in the field of science, technology and in our daily life. Plasma science also affects human life in different fields and ways. It plays a very important role in the sterilizing of medical instruments, laser, developments of fusion energy, intense particle beams, plasma processing, lightening, development fusion energy controlling, high-power energy sources, high-power radiations sources and water purification plant [3]. X-ray and ultraviolet electron beams and radiations, which are emitted by plasma-centered sources, have a diversity of applications in different fields.

#### *1.3.1. Application of plasma in textiles*

In textile industries, plasma used for surface treatment shows a large number of advantages. Different plasma treatments were used to modify the surface of fabrics, such as cold plasma treatments, which modify the large and reliable systems in fabrics. Three effects are found on the textile surfaces during plasma treatments: (1) cleaning effect, (2) increase of micro roughness and (3) produce deliquescent surfaces. The plasma polymerization is a process in which solid polymeric materials are deposited on textile substrate with required properties; currently, this technique is under development, and in this technique only upper surface is modified. This treatment also has optimistic effects on printing and dying of wool and has proved to be successful in shrink-resist. Improvement of surface wetting technique in artificial polymers is done with treatment in oxygen-, air- and $NH_3$ plasma. Hydrophilic treatment used as a dirt-repellent and antistatic finish [Sparavigna, 2008]. Plasma treatment is environmental friendly in which only upper layer of surface is modified without changing its bulk properties. Vacuum plasma is used on a small scale as is used in reel-to-reel machinery at the industrial scale; it plays a vital role to enhance a number of properties, including liquid repellency, the specific surface functionality and improved wet ability.

#### *1.3.2. Application of plasma in industry*

The surfaces of optics and contact lenses can be cleaned by plasma treatment. In this process, thin layer of the organic impurity is removed almost from all surfaces. Plasmas are used for the manufacturing of semiconductor chips in discharge tube, and the dust particles are essentially formed from the reactive gases used for the creation of plasmas. These dust particles are used for the manufacturing of semiconductor chips and give the significant results for the conduction of electric current. In the aerospace industries, plasma treatment of composite and polymer materials are commonly used. This treatment has advantages in adhesive and cleaning bonding of the dissimilar materials. In the automotive industries, adhesion of the exterior and interior parts is increased by the plasma treatment apparatus and plasma treatment procedures without any heat effect that commonly facing with flames. The Henniker is well known as a great leader in this field because he controlled plasma systems with low cost for almost in every common automotive development mission [2, 3, 11].

## 1.4. Waves in plasma

### *1.4.1. Plasma oscillation*

In the plasma, when an electron is displaced from their equilibrium position, the electrostatic forces due to ions pull the electron back. Due to small mass of electron, overshoot the ions and oscillation in plasma are started. The plasma oscillation leads to plasma frequency which is denoted by $\omega_{pe}$. When the amplitude of oscillation is small, then oscillation forms a sinusoidal waveform. Mathematically, oscillation is represented as:

$$n = \bar{n} \exp[i(k \,.\, r - \omega t)] \qquad (1)$$

where $n$ is the density, $\bar{n}$ is the constant that tells about the amplitude of waves and $k$ is propagation constant that describes the direction of waves and $t$ is the time. The propagation constant in Cartesian coordinates

$$k \,.\, r = k_x x + k_y y + k_y y \qquad (2)$$

The phase velocity is $\frac{dx}{dt} = \frac{\omega}{k} = v_\phi$ that gives the direction of waves negatively or positively. Sometimes the phase velocity in plasma exceeds the velocity of light $c$. The group velocity is $v_g = \frac{dw}{dk}$ and plasma frequency is $\omega_{pe} = \left(\frac{n_o e^2}{\varepsilon_o m}\right)^{\frac{1}{2}}$ that depends upon the density of plasma and does not depend on $k$.

### *1.4.2. Classification of waves in plasma*

In this chapter, we classified plasma waves with respect to direction of motion of charge particles (electron, ion), which are perpendicular or parallel to the direction of propagation. The longitudinal waves consist of electrostatic (ion and electron) waves and transverse wave consists of electromagnetic (ion and electron) waves, mostly transverse component and sometime longitudinal component also.

## 1.5. Electron waves (electrostatic)

### *1.5.1. Plasma oscillation*

Plasma oscillation, also known as Irving Langmuir waves, is discovered by American scientists Irving Langmuir and Lewi Tonks in 1920, and the frequency of plasma oscillation is high due to low electron density in the conducting materials such as metal and plasma. It is found in interstellar gas clouds and earth atmosphere. Mathematically, it is written as $\omega^2 = \omega_p^2 + \frac{3}{2} k^2 v_{th}^2$.

### *1.5.2. Upper hybrid oscillation*

The upper hybrid oscillation is a resonance phenomenon in plasma which the electric field perpendicular to the magnetic field and waves propagates across the static magnetic field: $\omega^2 = \omega_p^2 + \omega_c^2 = \omega_h^2$.

http://dx.doi.org/10.5772/intechopen.71203

### 1.6. Ions waves (electrostatic)

#### *1.6.1. Acoustic waves*

It is a type of longitudinal waves in magnetized plasma that propagates due to compression mode and its direction along the magnetic field lines. The particle velocity, sound pressure, sound intensity and particle displacement are the important quantities of acoustic waves. It exhibits the interference, diffraction and reflection phenomenon. In general, ion acoustic wave formula is [1, 14], $\omega^2 = k^2 v_s^2 = k^2 \frac{\gamma_e KT_e + \gamma_i KT_i}{M}$.

## 2. EMD model for correlation relations and numerical technique

In this section, we introduce the molecular dynamic simulation technique and its theoretical background that was needed in this work. We introduced a system of mathematical model that used and applied in the computer simulations and also explained steps for molecular dynamics simulation codes. In addition, it also explains the simulation parameters and techniques. Yukawa potential was first time proposed by a scientist Hideki Yukawa in 1930. Through this potential, charged particles do interact, which is defined as

$$\phi(|r|) = \frac{Q^2}{4\pi\varepsilon_o} \frac{e^{-|r|/\lambda_D}}{|r|} \tag{3}$$

where $Q$ is the charge on dust particle interacts with other charge particle, $\varepsilon_0$ is the permittivity of free space, r is the distance of interacting particle and $\lambda_D$ is Debye screening length.

### 2.1. Current correlation functions

The particle current or momentum current for single atomic (molecule) species in MD unit is given as:

$$\pi(r, t) = \sum_j v_j \delta\left(r - r_j(t)\right) \tag{4}$$

where $v_j$ and $r_j$ are the velocity and position of $j$th particle. By using the Fourier transformation, Eq. (4) should be written as:

$$\pi(k, t) = \sum_j v_j e^{-ik.r_j(t)} \tag{5}$$

The correlation function of the current vector component is defined as:

$$C_{\alpha\beta}(k, t) = \frac{k^2}{N_m}\left( \pi_\alpha(k, t)\, \pi_\beta(-k, 0)\right) \tag{6}$$

For the isotropic fluid under the consideration of symmetry, Eq. (6) can be expressed in terms of longitudinal current correlation and transverse current correlation in the relative direction of $k$, where $k$ is the wave vector.

$$C_{\alpha\beta}(k, t) = \frac{k_\alpha k_\beta}{k^2} C_L(k, t) + \left(\delta_{\alpha\beta} - \frac{k_{\alpha\beta}}{k^2}\right) C_T(k, t) \tag{7}$$

By setting $k = k\hat{z}$, we obtain longitudinal and transverse current functions in X, Y and Z direction relative to the $k$ and $-k$.

### 2.2. Normalized longitudinal current correlation function $C_L(k,t)$

Eq. (7) split into longitudinal current and transverse current by using the Fourier transformation as:

$$C_L(k, t) = \frac{k^2}{N_m} \langle \pi_z(k, t)\, \pi_z(-k, 0) \rangle \tag{8}$$

Inserting the value of $\pi_z$ in Eq. (8), we have

$$C_L(k, t) = \frac{k^2}{N_m} \left\langle \Sigma\, v_i\, e^{-ik.z_j(t)}(k, t) \Sigma v_j\, e^{-ik.Z}(k, t) \right\rangle \tag{9}$$

Longitudinal current correlation function explains the direction of propagates along Z-axis in the positive and negative directions of Z-axis with wave number. This equation also specifies about longitudinal motion of charge particle.

### 2.3. Time-dependent normalized transverse current correlation $C_T(k,t)$

Using the Fourier transformation for Eq. (7), the transverse current correlation is defined as:

$$C_T(k, t) = \frac{k^2}{2\, N_m} \left\langle \pi_x(k, t)\, \pi_x(-k, 0) + \pi_y(k, t)\, \pi_y(-k, t) \right\rangle \tag{10}$$

where

$$\pi_x(k, t) = \sum_j v_j\, e^{-ik.x_j(t)} \tag{11}$$

$$\pi_y(k, t) = \sum_j v_j\, e^{-ik.y_j(t)} \tag{12}$$

Eq. (12) states about the directions of propagation of electromagnetic waves with respect to wave number along the positive and negative X- and Y-axes. The transverse current correlations also describe us about transverse motion of charge particle in complex system or complex (dusty) plasma [15–17].

### 2.4. Parameters and simulation techniques

In this section, we select a system of choice having number of particles $N$ = 500–4000: these existing particles in a cube volume ($V$) interact with each other by pairwise Yukawa potential given in Eq. (3). In this chapter, the EMD simulation technique has been used to investigate the longitudinal current correlation and transverse current correlation that are given in Eqs. (9) and (10), respectively. The dimensions of simulation box are chosen as $L_{x,}$ $L_{Y,}$ $L_Z$. The periodic

http://dx.doi.org/10.5772/intechopen.71203

boundary condition is used to minimize the surface size effect and applied to the simulation box. In our case, the main calculations are performed for $N = 500$ particles at $\kappa = 1.4$, 2, 3 and 4 with plasma coupling parameters $\Gamma$ (temperature of the Yukawa system) varies from 1 to 300 and waves numbers $k = 0$, 1, 2 and 3. The simulation time step is taken as $\Delta t = 0.005/\omega_p$ that allows to compute the important data for sufficient long simulation run. The EMD method is reported for the current correlation of SCCD plasma over reasonable domain of plasma parameters of Debye screening ($1 \leq \kappa \leq 4$) and Coulomb coupling ($1 \leq \Gamma \leq 300$). Particle velocity thermostat is used to control the temperature of systems. The reported simulations are performed between $5.0 \times 10^5/\omega_p$ and $2.0 \times 10^5/\omega_p$ time units in the series of data recording of correlation functions [16, 17].

## 3. EMD simulation results

### 3.1. Time-dependent longitudinal current correlation function $C_L(k,t)$, at $\kappa = 1.4$

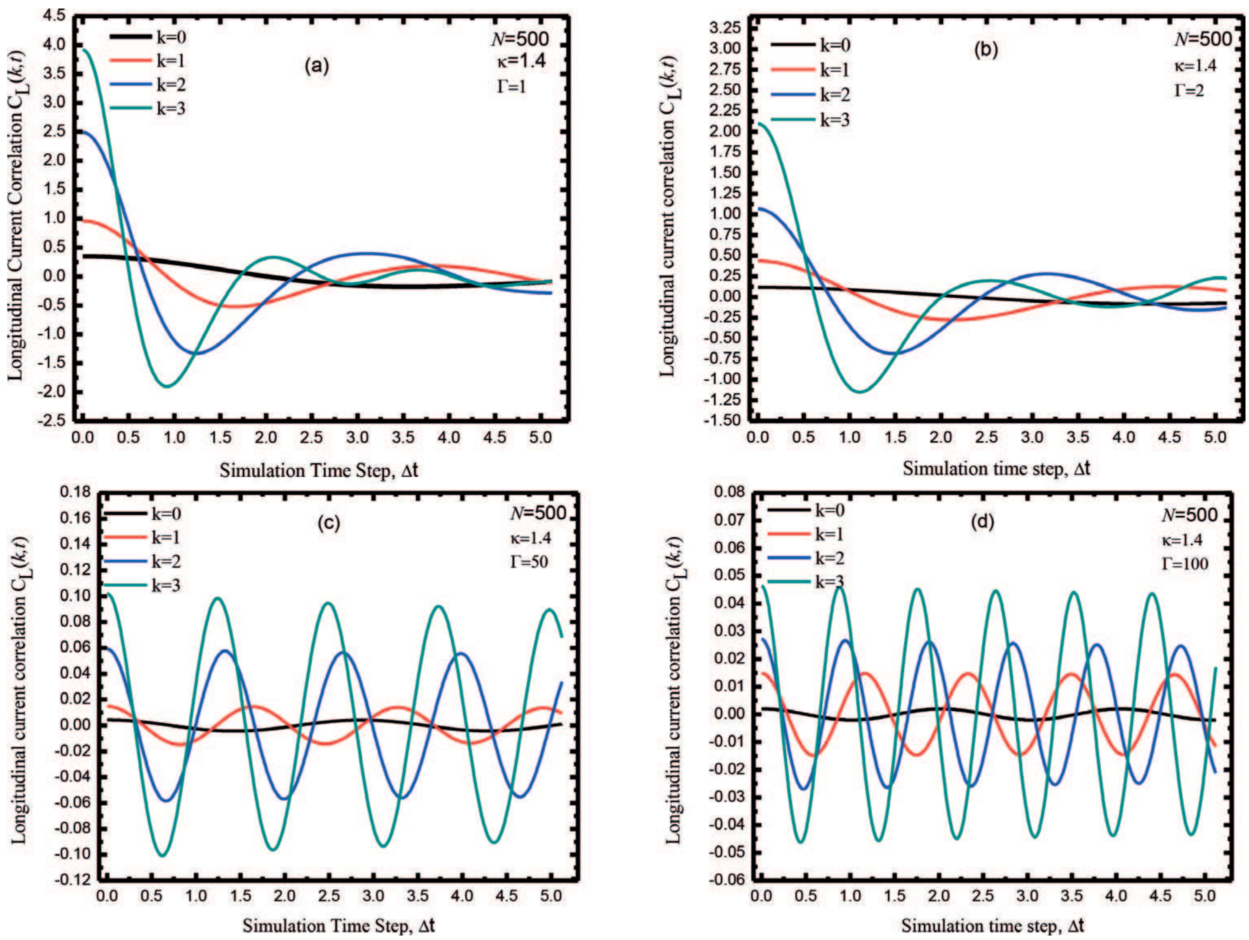


**Figure 1.** Variation of $C_L(k,t)$ as a function of simulation time step ($\Delta t$) of strongly coupled complex plasma at $\kappa = 1.4$, $N = 500$, waves number $k = 0$, 1, 2 and 3 for (a) $\Gamma = 1$, (b) $\Gamma = 2$, (c) $\Gamma = 50$ and (d) $\Gamma = 100$.

### 3.2. Time-dependent longitudinal current correlation function $C_L(k,t)$ at $\kappa = 2$

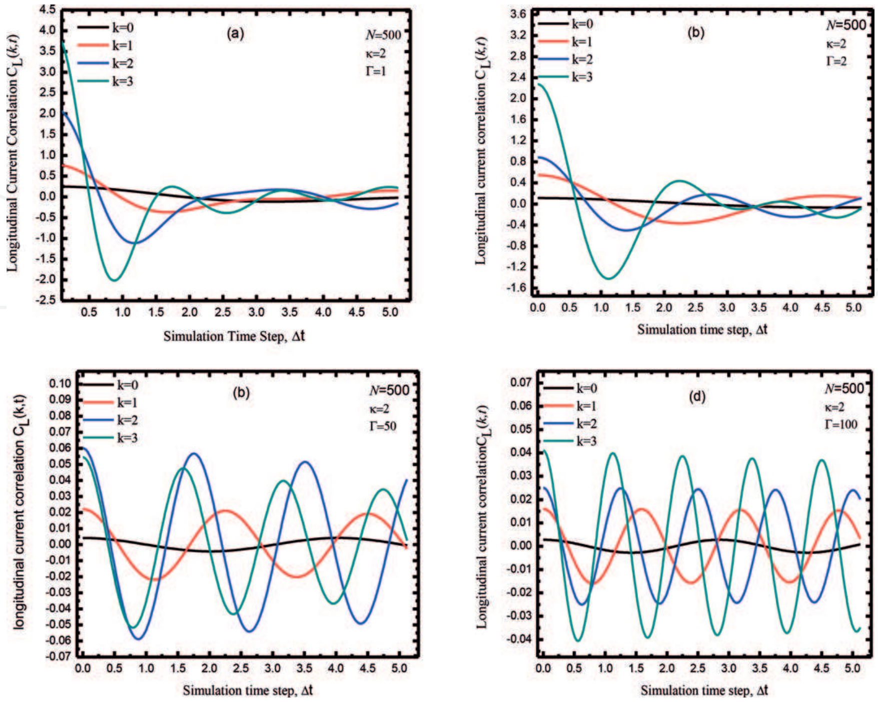


**Figure 2.** Variation of $C_L(k,t)$ as a function of simulation time step ($\Delta t$) of strongly coupled complex plasma at $\kappa$ =2, $N$ = 500, waves number $k$ = 0, 1, 2 and 3 for (a) Γ =1, (b) Γ =2, (c) Γ =50 and (d) Γ =100.

### 3.3. Time-dependent longitudinal current correlation function $C_L(k,t)$ at $\kappa = 3$

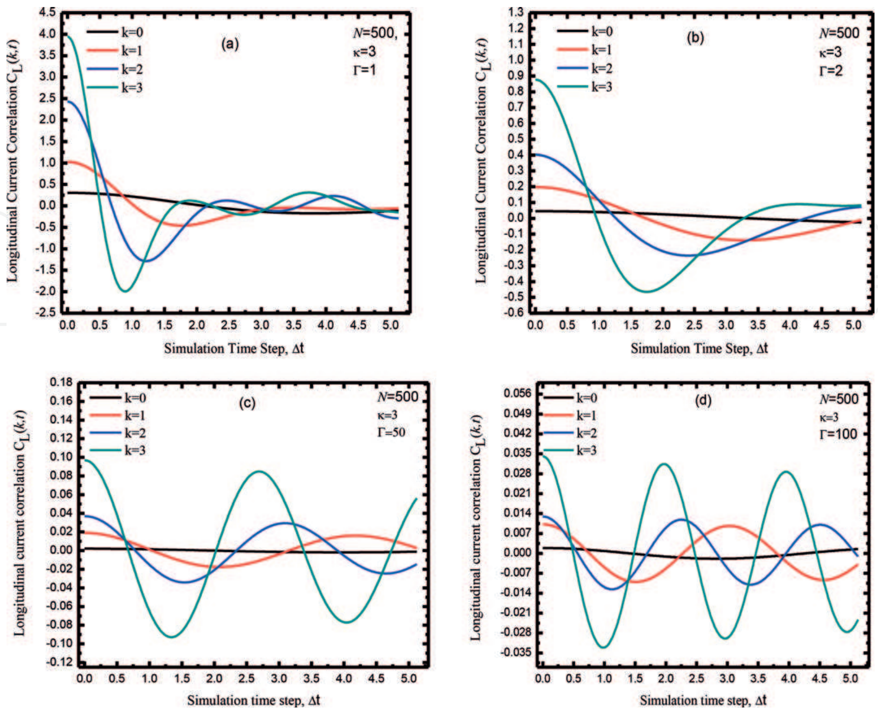


**Figure 3.** Variation of $C_L(k,t)$ as a function of simulation time step ($\Delta t$) of strongly coupled complex plasma at $\kappa$ =3, $N$ = 500, waves number $k$ = 0, 1, 2 and 3 for (a) Γ =1, (b) Γ =2, (c) Γ =50 and (d) Γ =100.

To illustrate the behaviour of correlation function of SCCD plasma using EMDS, the time-dependent normalized longitudinal current correlation ($C_L(k,t)$ from Eq. (9) spectra is plotted against simulation time step ($\Delta t$), as shown in **Figures 1–3**, for waves number ($k$ = 0, 1, 2 and 3), plasma parameter (Coulomb coupling) $\Gamma$ = 1, 2, 50 and 100 and for screening parameter ($\kappa$ = 1.4, 2 and 3), respectively. It is observed from four panels of **Figure 1** that the wavelength decreases and amplitude of longitudinal current increases with increasing waves numbers ($k$), as $C_{L=}$ 0.2875, 0.9220, 2.5143 and 3.7139 for waves numbers $k$ **=** 0, 1, 2 and 3, respectively, at same values of $\Gamma$ =1 and $\kappa$ =1.4. It has been shown that the value of $C_L(k,t)$ decreases with increasing of $\Gamma$ as $C_L(k,t)$ = 0.2875 (0.9220), 0.1179 (0.4369), 0.0044 (0.0148) and 0.0020 (0.0148) for $\Gamma$ =1, 2, 50 and 100, respectively, at $k$ = 0 (1) and for $\kappa$ =1.4. In case of wave number $k$ = 2(3), the value of $C_L$ is 2.5142(3.7139), 1.0661(2.0954), 0.0591(0.1020) and 0.0271(0.0463), respectively. The fluctuation of sound waves in SCCD plasma is observed from **Figures 1–3** that increases with decreasing the plasma temperature, and it is noted that the amplitude, fluctuation and wavelength for simulation time step ($\Delta t$) of longitudinal current correlation in SCCD plasma gradually decrease with increasing of $\kappa$. We have noted from simulation results that the propagation of sound waves in dusty plasma is frequently propagated at higher value of Γ =50 and 100 and at lower value of $\kappa$ =1.4 and 2.

### 3.4. Time-dependent transverse current correlation function $C_T(k,t)$, $\kappa$ = 1.4

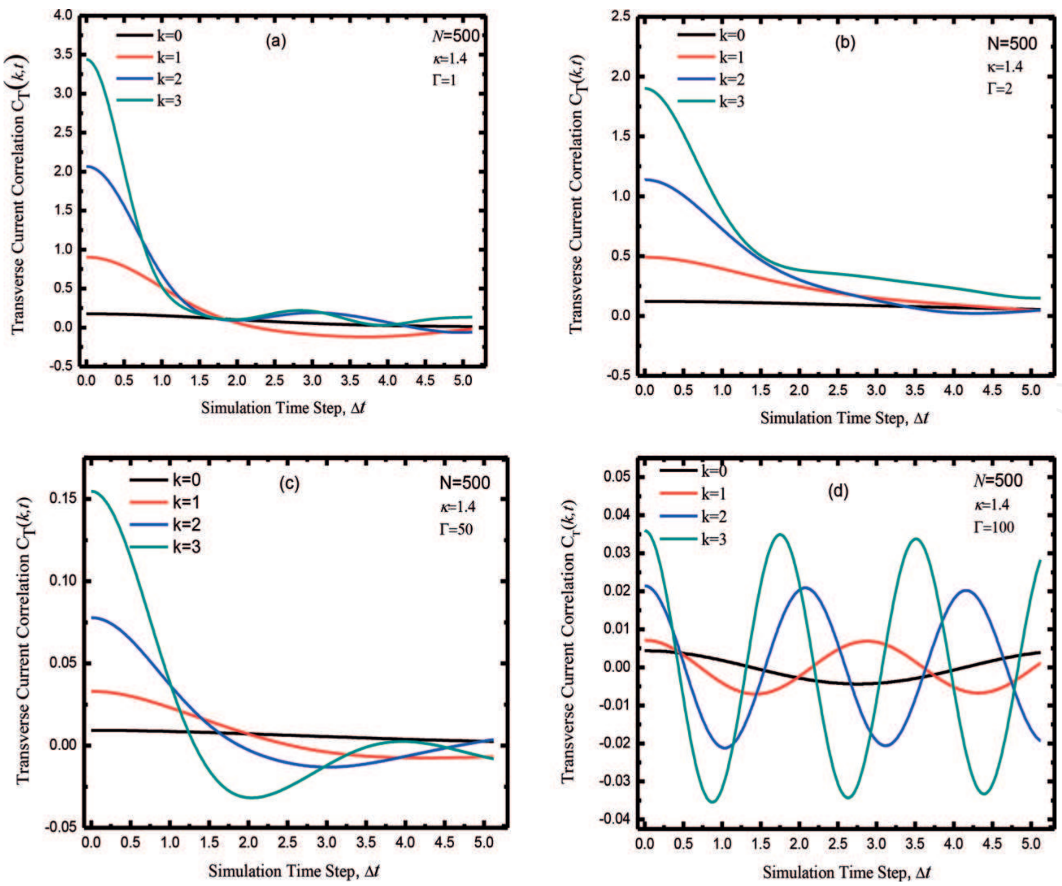


**Figure 4.** Variation of $C_T(k,t)$ as a function of simulation time step ($\Delta t$) of strongly coupled complex plasma at $\kappa$ =1, $N$ = 500, waves number $k$ = 0, 1, 2 and 3 for (a) Γ =1, (b) Γ =2, (c) Γ =50 and (d) Γ =100.

### 3.5. Time-dependent transverse current correlation function $C_T(k,t)$, $\kappa = 2$

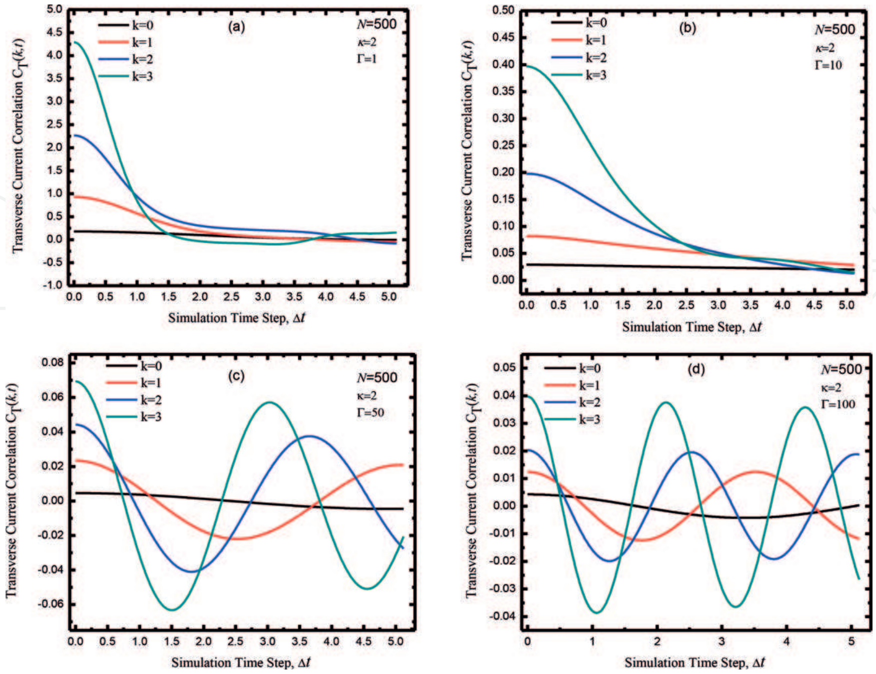


**Figure 5.** Variation of $C_T(k,t)$ as a function of simulation time step ($\Delta t$) of strongly coupled complex plasma at $\kappa$ =2, $N$ = 500, waves number $k$ = 0, 1, 2 and 3 for (a) Γ =1, (b) Γ =2, (c) Γ =50 and (d) Γ =100.

### 3.6. Time-dependent transverse current correlation function $C_T(k,t)$, $\kappa = 4$

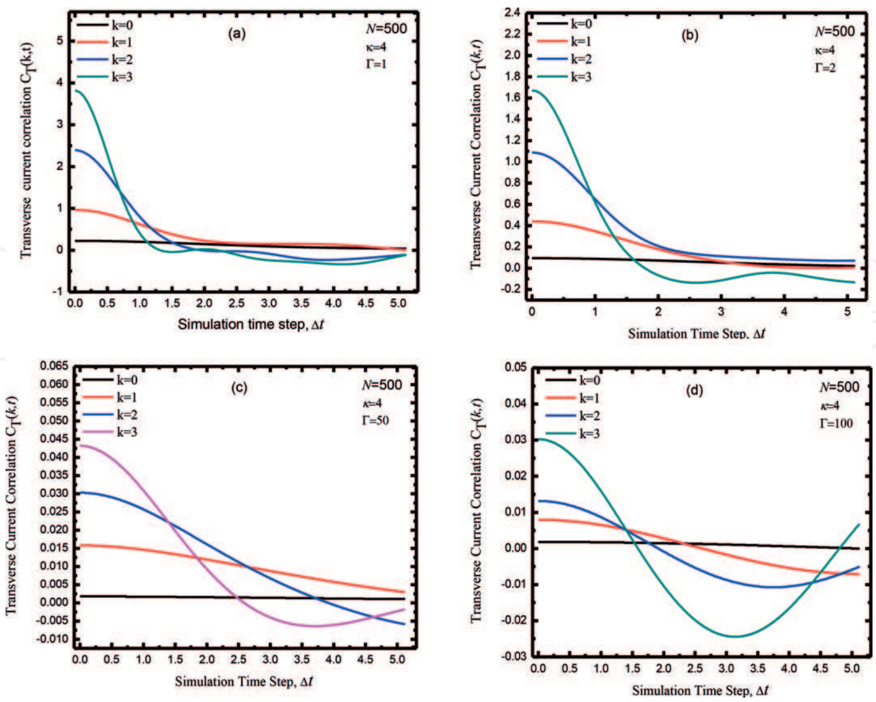


**Figure 6.** Variation of $C_T(k,t)$ as a function of simulation time step ($\Delta t$) of strongly coupled complex plasma at $\kappa$ =4, $N$ = 500, waves number $k$ = 0, 1, 2 and 3 for (a) Γ =1, (b) Γ =2, (c) Γ =50 and (d) Γ =100.

**Figures 4–6** demonstrate that the simulation results are obtained for $C_T(k,t)$ of SCCD plasma using EMD simulation at $k$ = 0, 1, 2 and 3, Γ =1, 2, 50 and 100 and κ =1.4, 2 and 4, respectively, at $N$ = 500. The presented simulation results of $C_T(k,t)$ spectra are compared with increasing and decreasing sequence of Γ, κ and $k$. It is noted that the fluctuation, wavelength and amplitude of $C_T(k,t)$ (transverse or shear waves) in complex (dusty) plasma immediately depend on plasma temperature, Coulomb coupling and system size. We have observed from simulation results of transverse waves in dusty plasma that wavelength of these waves decreases with increasing wave number, plasma parameters, Coulomb coupling and number of particles. The amplitude of $C_T(k,t)$ increases with increasing wave number as $C_T$ = 0.2655, 0.9679, 2.0914 and 3.8960 for $k$ = 0, 1, 2, and 3, respectively, at κ =1.4 shown in **Figure 4(a)** and decreases with increasing Γ as for $k$ = 0(1), $C_T$ = 0.2655(0.9679), 0.1395(0.5607), 0.0074(0.0197) and 0.0040(0.0081) and for the case $k$ = 2(3), $C_T$ = 2.0914(3.8960), 1.0590(1.8826), 0.0537(0.0929) and 0.0259(0.0366) at Γ =1, 2, 50 and 100, respectively, shown in four panels of **Figures 4** at κ =1.4 and $N$ = *500*. We have observed from 12 simulated results, which are displayed in **Figures 4–6**, that fluctuations in $C_T(k,t)$ increase with decreasing plasma temperature and decrease with increasing κ, $N$. We have concluded from 24 simulated results that amplitude and wavelength of transverse waves in SCCD plasma are directly proportional to the plasma temperature and inversely proportional to the screening strength. Shear waves are frequently propagated at higher value of Γ.

## 4. Summary

The EMD simulation method is used to investigate the $C_L(k,t)$ and $C_T(k,t)$ for SCCD plasma over a wide range of plasma parameters κ, Γ, $N$ and $k$ (wave number). The first involvement of presented simulation is that it delivers and understands the propagation of waves in SCCD plasma. In general, the amplitude and frequency of waves with different modes are analysed. The presented simulation specifies that the waves are frequently propagated at intermediate and high value of Γ. These investigations show that the values of frequency and amplitude depend on Γ, κ, $N$ and $k$. The EMD simulation investigation shows the plasma wave behaviors that are observed at low and intermediate values of Γ and does not show at higher value of Γ and at lower value of κ =1.4. It has been shown that the presented EMD method and earlier EMD techniques have comparable performance over the wide range of plasma points, both yielding reasonable results for correlation parameters. New simulations yield more reliable and excellent data for the $C_L(k,t)$ and $C_T(k,t)$ for a wider range of κ (= 1, 4) and Γ (= 1, 100), respectively. The existing simulation delivers more reliable data for the existence of waves and dynamical structure in SCCD plasma. These simulation results show that in the absence of structure in dusty plasma, the shear wave does not support. The sound wave frequently propagates at medium and higher values of Γ in SCCD plasma. It is suggested that the presented EMD technique based on the Ewald summation described here can be used to explore other ionic and dipolar materials. It is very interesting to note what other types of interaction potentials support correction parameters of strongly coupled plasmas and how its strengths depend on the range of new interaction potentials.

## Acknowledgements

The authors thank Z. Donkó (Hungarian Academy of Sciences) for providing his thermal conductivity data of Yukawa Liquids for the comparisons of our simulation results and useful discussions. We are grateful to the National High Performance Computing Center of Xian Jiaotong University and National Advanced Computing Center of National Center of Physics (NCP), Pakistan, for allocating computer time to test and run our MD code.

## Abbreviations

| | |
|---|---|
| NICDPs | non-ideal complex (dusty) plasmas |
| EMD | equilibrium molecular dynamics |
| Γ | Coulomb coupling |
| $\kappa$ | Debye screening length |
| $C_T(k,t)$ | transverse current correlation function |
| MD | molecular dynamics |
| LTE | local thermodynamic equilibrium |
| SCP | strongly coupled plasma |
| PBCs | periodic boundary conditions |
| $C_L(k,t)$ | longitudinal current correlation function |

## Author details

Aamir Shahzad[1,2]*, Muhammad Asif Shakoori[1], Maogang He[2] and Sajid Bashir[3]

Address all correspondence to: aamirshahzad_8@hotmail.com

1 Department of Physics, Government College University Faisalabad (GCUF), Faisalabad, Pakistan

2 Key Laboratory of Thermo-Fluid Science and Engineering, Ministry of Education (MOE), Xi'an Jiaotong University, Xi'an, PR China

3 Punjab Institute of Nuclear Medicine Faisalabad, Faisalabad, Pakistan

## References

[1] Chen FF. Introduction to Plasma Physics and Controlled Fusion. 2nd ed. New York: Springer-Verlag. 2006; 200 p. ISBN: 9780521825689

[2] Shahzad A, He M-G. Thermal conductivity calculation of complex (dusty) plasmas. Physics of Plasmas. 2012;**19**(8):083707. DOI: 10.1063/1.4748526

[3] Shahzad A, He M-G. Computer Simulation of Complex Plasmas: Molecular Modeling and Elementary Processes in Complex Plasmas. 1st ed. Saarbrücken, Germany: Scholar's Press; 2014; 170 p

[4] Bellan PM. Fundamentals of Plasma Physics. 1st ed. Cambridge, UK: Cambridge University Press; 2008; ISBN: 9780521528009

[5] Shahzad A, He M-G. Thermal conductivity of three-dimensional Yukawa liquids (dusty plasmas). Contributions to Plasma Physics. 2012;**52**(8):667. DOI: 10.1002/ctpp.201200002

[6] Killian T, Pattard T, Pohl T, Rost J. Ultracold neutral plasmas. Physics Reports. 2007;**449**:77. DOI: 10.1016/j.physrep.2007.04.007

[7] Killian TC, Kulin S, Bergeson SD, Orozco LA, Orzel C, Rolston SL. Creation of an ultracold neutral plasma. Physical Review Letters. 1999;**83**(23):4776. DOI: 10.1103/phyRevLett. 83.4776

[8] Boulos MI, Fauchais P, Pfender E. Thermal Plasmas: Fundamentals and Applications. Vol. 8, New York: Springer Science & Business Media; 2013. DOI: 10.1007/978-1-1337-1

[9] Shahzad A, He M-G. Thermal Conductivity and Non-Newtonian Behavior of Complex Plasma Liquids, chapter from book of Thermoelectrics for Power Generation—A Look at Trends in the Technology" InTech. 2016; 305 p. DOI: 10.5772/65563

[10] Fortov VE, Vaulina OS, Lisin EA, Gavrikov AV, Petrov OF. Analysis of pair interparticle interaction in nonideal dissipative systems. Journal of Experimental and Theoretical Physics. 2010;**110**:662-674. DOI: 10.1134/S1063776110040138

[11] Shahzad A, He M-G. Thermodynamic characteristics of dusty plasma studied by using molecular dynamics simulation. Plasma Science and Technology. 2012;**14**(9):771-777. DOI: 10.1088/1009-0630/14/9/01

[12] Shahzad A, He M-G. Interaction contributions in thermal conductivity of three dimensional complex liquids. In: Liejin GUO, editor. AIP Conf. Proc; 26-30-10-2012; Xi'an, China. USA: AIP. 2013; p. 173-180. DOI: 10.1063/1.4816866

[13] Shukla PK, Mamun AA. Introduction to Dusty Plasma Physics. CRC Press; 2015 97807 50306539 – CAT#IP391

[14] Donko Z, Kalman GJ, Hartmann P. Dynamical correlations and collective excitations of Yukawa liquids. Journal of Physics: Condensed Matter. 2008;**20**(41):413101. DOI: 10.1088/0953-8984/20/41/413101

[15] Rapaport DC. The Art of Molecular Dynamics Simulation. New York: Cambridge University Press; 2004; 250 p. DOI: 9780521825689

[16] Shahzad A, He M-G. Homogenous nonequilibrium molecular dynamics evaluations of thermal conductivity 2D Yukawa liquids. International Journal of Thermophysics. 2015;**36**(10-11):2565. DOI: 10.1007/s10765-014-1671-8

[17] Shahzad A, He M-G. Calculations of thermal conductivity of complex (dusty) plasmas using homogenous nonequilibrium molecular simulations. Radiation Effects and Defects in Solids. 2015;**170**(9):758-770. DOI: 10.1080/10420150.2015.1108316

IntechOpen