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Propagation of surface waves in semi-bounded quantum collisional plasmas with electron exchange-correlation effects

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Abstract

The propagation of surface waves in semi-bounded quantum collisional plasmas are investigated by taking into account the quantum Bohm potential, Fermi statistical pressure, electron exchange-correlation effects and collisional effects. The modified quantum hydrodynamic model in conjunction with Maxwell equations are used to obtain the new general dispersion relations of surface waves, and the dispersion relations are discussed in some special cases of interest. It is indicated that the wave frequency spectrum can be down-shifted due to the electron exchange-correlation effects. It is also shown that the growth rate of surface waves instability can be enhanced by increasing the collisional frequency, especially in the short wavelength region. The corresponding results can be helpful for identifying surface waves which transport in intense metallic plasmas.

Keywords: surface wave, quantum plasmas, exchange-correlation effects, collisional effect

(Some figures may appear in colour only in the online journal)

1. Introduction

The interest to investigate quantum plasmas have attracted considerable attention in recent years. In the traditional research of plasma physics, most of the studies focused on the high-temperature and low-density plasma, and the quantum effects can be safely ignored. However, when the electron density reaches 10^{23}–10^{30} cm^{-3} in high energy dense plasmas, the plasmas are degenerate and the distribution function follows the Fermi–Dirac for the electrons. The degeneracy of electrons makes us to consider the quantum Bohm potential and Fermi statistical pressure, so the quantum effects in high-energy dense plasma becomes important, and cannot be simply ignored. One knows that at room temperature and standard metal densities, the electron gas is also quantum plasma, as discussed by Manfredi [1]. Quantum plasmas have a wide range of research area in high-density astrophysical systems such as in the interior of Jupiter, white dwarfs, high-density neutron stars, and in miniature semiconductor devices [2, 3]. Meanwhile, quantum plasmas are also widely studied in high-density laser plasma [4], ultra-small electronic equipment [5], and in dusty plasmas [6].

Waves in quantum plasmas are very plentiful, through the study of the characteristics of waves, one can understand the properties of quantum plasmas. In recent years, many scientists have carried out extensive research on wave phenomena in quantum plasmas. Ren *et al* studied the dispersion relation of electrostatic drift waves with the presence of an equilibrium magnetic field inhomogeneity and found a new purely quantum branch [7]. The elliptically polarized extra-ordinary electromagnetic waves in superdense magnetized quantum plasmas with electron spin-1/2 effects were studied in 2012, and the results indicated that the electron spin-1/2 effects can reduce the transport of energy in quantum plasma systems [8]. Electrostatic solitary waves in quantum plasmas with relativistically degenerate electrons were discussed by

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Masood *et al* a nonlinear Korteweg–de Vries equation was derived using the small amplitude expansion method, and the results shown that the increasing number density increases the amplitude but decreases the width of the ion acoustic solitary wave with relativistically degenerate electrons [9]. The propagation of surface waves in spin-$1/2$ magnetized quantum plasmas with and without collisional effects have been presented by some authors, respectively [10, 11]. Especially, the surface waves, which propagate along the interface between two different media, are widely discussed in many theories and experiments in recent years. Surface waves may be important in connection with plasma diagnostics by laser light scattering of the particles or by examining the wave dispersion properties. In addition, surface waves are relevant to laser fusion and astrophysical problems in the magnetosphere. Furthermore, because of electromagnetic-energy localization near the boundary, surface waves could be preferable for use in solid-state and gaseous-plasma electronics, owing to the comparative simplicity of excitation and removal of energy and the convenience of interaction with electron beams and external electromagnetic fields [12]. For these reasons, it is of interest to study surface waves which can exist on the boundary separating two dielectric media.

Surface waves in quantum plasmas have been investigated in a number of papers. The quantum effects on the Langmuir oscillation of a semi-bounded quantum plasma was investigated by Chang and Jung [13]. Moradi studied the surface electrostatic oscillation in the semi-bounded quantum plasma under the existence of quantum effects, and the numerical results revealed that the plasmon energy is significantly changed by the very slow nonlocal variation [14]. The propagation of high frequency electrostatic waves propagation in a dense and semi-bounded quantum plasmas was studied by Lee *et al* and the results showed that the quantum effects enhanced the frequency of the wave especially in the high wave number [15]. In 2016, Choudhury *et al* studied the nature of solitary waves in a quantum semiconductor plasma by taking into account the quantum Bohm potential, Fermi statistical pressure and electron exchange-correlation effects [16]. For the collisionless approximation in quantum plasmas, it is generally agreed that the quantum coupling parameter $g_Q \ll 1$, where g_Q is the ratio of the interaction energy to the average kinetic energy [1]. For example, dense plasmas produced by a strong laser, its quantum coupling parameters is $g_Q \approx 0.15 < 1$, so there is no need to consider the collisional effects. On the contrary, it is known that quantum coupling parameter in metallic plasmas may be much greater than one, so the collision lengths may be larger than the Fermi lengths. Thus, the binary collisions have a considerable effect on the dynamics of plasma particles. When $g_Q \gg 1$, the collisional effects will have a considerable influence and cannot be ignored, the quantum plasmas are assumed to be collisional or strongly coupled. Khorashadizadeh *et al* [17]. investigated the propagation of surface waves in the quantum plasma semi-bounded by considering the collisional effects, and found that the surface waves can be unstable when the collisional effects are included. It is also shown that the quantum effects and collisional effects can enhance the growth rate of instability.

The interactions between electrons in quantum plasmas can be separated into Hartree term due to the electron exchange-correlation term, especially, when the electron density is relatively high and the temperature is low, the electron exchange-correlation effects should be significant. The including of additional exchange-correlation term which is somehow retrievable from the density functional theory (DFT) in the momentum equation gives rise to an additional force on electrons. The electron exchange-correlation term depends on the number density of the system. Therefore, in quantum plasmas with low electron temperature and high electron density, the influence of the exchange-correlation effect becomes important and its effects cannot be ignored. This effect is a complicated function of the electron density which can be derived through the adiabatic local-density approximation, as discussed by Crouseilles [18]. Ma *et al* considered wave excitation in a bounded quantum plasma with the effect of electron exchange-correlation potential and found that the electron exchange-correlation effects have a significant effect on the collective mode at high and low frequency limits [19]. Khan *et al* explored in detail the electrostatic electron plasma oscillations in single-walled carbon nanotubes including the electron exchange-correlation effects, and they found that the quantum effects and the exchange-correlations effects have significant impact on the wave. The frequency of wave was influenced by variation in azimuthally index and radius of the nanotubes [20]. Lazar *et al* studied the dispersion of surface waves on a quantum electron plasma semi-bounded, and the results showed that the electrostatic surface waves were significantly affected by the quantum effects [21]. In this work, we will further study the propagation properties of surface waves in semi-bounded quantum collisional plasmas, combining the quantum effects, electron exchange-correlation effects and collisional effects.

2. Theoretical model and dispersion relations

In this paper, the propagation properties of surface waves in the semi-bounded quantum plasmas will be analyzed and studied by using the quantum hydrodynamic model and Maxwell equations. The dynamics of the electron is governed by the continuity and momentum equations as follows

$$\frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \boldsymbol{v}) = 0, \tag{1}$$

$$\frac{\partial \boldsymbol{v}}{\partial t} = -\frac{e}{m_e}\boldsymbol{E} - \frac{1}{m_e n_e}\nabla P_e + \frac{\hbar^2}{2m_e^2}\nabla\left(\frac{\nabla^2\sqrt{n_e}}{\sqrt{n_e}}\right) - \frac{1}{m_e}\nabla V_{xc} - \nu\boldsymbol{v}, \tag{2}$$

where $\boldsymbol{v}$ is the electron fluid velocity, n_e and n_{e0} represent the perturbed and equilibrium electron number density, $\boldsymbol{E}$ is the electric field, $P_e = m_e v_{\mathrm{Fe}}^2 n_e^3/3n_{e0}^2$, v_{Fe} is the Fermi velocity which is given by $\sqrt{2k_{\mathrm{B}}T_{\mathrm{Fe}}/m_e}$, T_{Fe} is the Fermi temperature, k_{B} is the Boltzmann constant, m_e is the electron mass, e is the electron charge, $\hbar = h/2\pi$ is the Planck's constant divided by 2π. ν is the effective collision frequency for momentum transfer. The third term in the right-hand side of equation (2) is the quantum force due to the so-called quantum Bohm potential. The fourth term in the right-hand side of equation (2) is associated with the electron exchange-correlation potential, and the general framework that produces the exchange-correlation potential is the DFT [18, 22], it is a complicated function of the electron density which is given by

$$V_{xc} = -0.985\frac{n_e^{1/3}e^2}{\varepsilon}\left[1 + \frac{0.034}{n_e^{1/3}a_{\mathrm{B}}}\ln(1 + 18.376n_e^{1/3}a_{\mathrm{B}})\right] \tag{3}$$

where $a_{\mathrm{B}} = \varepsilon\hbar^2/m_e e^2$ is the Bohr radius and ε is the effective dielectric permeability of the material. The last term in the right-hand side of equation (2) is collisional term.

The electromagnetic fields are coupled by the linearized Maxwell equations

$$\nabla \times \boldsymbol{E} = -\frac{1}{c}\frac{\partial \boldsymbol{B}}{\partial t}, \tag{4}$$

$$\nabla \times \boldsymbol{B} = \frac{1}{c}\frac{\partial \boldsymbol{E}}{\partial t} - \frac{4\pi n_e e}{c}\boldsymbol{v}, \tag{5}$$

$$\nabla \cdot \boldsymbol{B} = 0, \tag{6}$$

$$\nabla \cdot \boldsymbol{E} = -4\pi e n_e. \tag{7}$$

The quantum Bohm potential, Fermi statistical pressure, electron exchange-correlation effects and collisional effects are considered together in the momentum equation (2). The linearized equations can be obtained from equations (1) and (2)

$$\frac{\partial n_e}{\partial t} + n_{e0}\nabla \cdot \boldsymbol{v} = 0, \tag{8}$$

$$\frac{\partial \boldsymbol{v}}{\partial t} = -\frac{e}{m_e}\boldsymbol{E} - \frac{3\alpha^2 - \gamma - 2\lambda}{3n_{e0}}\nabla n_e + \frac{\beta^2}{n_{e0}}\nabla\nabla^2 n_e - \nu\boldsymbol{v}, \tag{9}$$

where $\alpha = v_{\mathrm{Fe}}$, $\gamma = 0.985e^2 n_{e0}^{1/3}/m_e\varepsilon$, $\lambda = 0.308e^2 n_{e0}^{1/3}/(1 + 18.376n_{e0}^{1/3}a_{\mathrm{B}})m_e\varepsilon$ and $\beta = \hbar/2m_e$ are the corresponding auxiliary quantities. It is necessary to mention that the γ and λ are new parameters, due to the added potential, measuring the electron exchange-correlation effects, respectively.

Considering the surface waves propagate along the plasma-vacuum interface and the wave vector is parallel to the surface, and the quantum plasmas are assumed to fill with the semi-bounded, $x > 0$, which is bounded with vacuum. We suppose that each quantity φ can be written as $\varphi(x)\exp(\mathrm{i}k_y y - \mathrm{i}\omega t)$, where k_y is component of the wave vector along y axis and ω is the frequency of surface waves. The perturbation equation of electron density can be derived from equations (7)–(9)

$$\left(\frac{\mathrm{d}^2}{\mathrm{d}x^2} - q_E^2\right)n_e(x) = 0, \tag{10}$$

where $q_E^2 = k_y^2 + \frac{3(\omega_{pe}^2 - \omega^2 - \mathrm{i}\omega\nu)}{3\alpha^2 - \gamma - 2\lambda + 3\beta^2 k_y^2}$, $\omega_{pe}^2 = 4\pi n_0 e^2/m_e$, and the very slow nonlocal variations are ignored, i.e. $k_y^{-2}(\partial^4/\partial x^4) \ll \partial^2/\partial x^2 \ll k_y^2$, therefore, the solution of equation (10) in the plasma medium can be written as

$$n_p(x) = A\exp(-q_E x), \quad x > 0, \tag{11}$$

where A is a constant. In addition, by combining the equations (2), (4) and (5), one can yield the wave equation of the magnetic field

$$\left(\frac{\mathrm{d}^2}{\mathrm{d}x^2} - q_M^2\right)\boldsymbol{B}(x) = 0, \tag{12}$$

where $q_M^2 = k_y^2 + \frac{\omega_{pe}^2\left(\frac{\omega}{\mathrm{i}\nu + \omega}\right) - \omega^2}{c^2}$.

The solution of the equation (12) in the vacuum region ($x < 0$) is

$$\boldsymbol{B}_v(x) = \mathbf{C}_1\exp(-q_v x), \tag{13}$$

where $q_v^2 = k_y^2 - \omega^2/c^2$, and the solution of the equation (12) in the plasma region ($x > 0$) is

$$\boldsymbol{B}_p(x) = \mathbf{C}_2\exp(-q_M x) \tag{14}$$

$\mathbf{C}_1$ and $\mathbf{C}_2$ are constant vectors. Using the Maxwell equations again, one can find that the electric field of surface waves in the vacuum and plasma regions can be expressed as follows

$$\boldsymbol{E}_v(x) = \mathbf{D}_v\exp(q_v x),\ x < 0 \tag{15}$$

$$\begin{aligned}\boldsymbol{E}_p(x) = \mathbf{D}_p\exp(-q_M x) &+ \frac{4\pi eA\exp(-q_E x)}{(\mathrm{i}\nu\omega + \omega^2) - \omega_{pe}^2}\\ &\times\left[\frac{3\alpha^2 - \gamma - 2\lambda}{3} - \beta^2(q_E^2 - k_y^2)\right]\\ &\times(-q_E\boldsymbol{e}_{\mathbf{x}} + \mathrm{i}k_y\boldsymbol{e}_y),\ x > 0\end{aligned} \tag{16}$$

where $\mathbf{D}_v$ and $\mathbf{D}_p$ are constant vectors.

In order to obtain the general dispersion relation of surface waves, we consider the appropriate boundary conditions in the interface plane, that is, (a) the tangential component of $\boldsymbol{E}$ and $\boldsymbol{B}$ are continuous at $x = 0$, (b) the normal component of the displacement vector is continuous in the interface, (c) the velocity components will vanish for electrons, i.e. $v_x = 0$ at $x = 0$.

Here, by using Maxwell equations and the velocity components vanish for electrons in the interface plane, i.e. $v_x = 0$ at $x = 0$, one can see that

$$\mathrm{i}k_y\frac{\partial E_y}{\partial x} = -q_v^2 E_x. \tag{17}$$

By substituting equations (15) and (16) into (17), one can therefore obtain

$$D_{px} = \frac{4\pi eA}{\omega_{pe}^2 - (\omega^2 + \mathrm{i}\nu\omega)}\left(k_y^2\frac{q_E - q_v}{q_M q_v + q_v^2} - q_E\right)Q^2. \tag{18}$$

Similarly, by introducing the boundary conditions at $x = 0$, and from equation (9), one can also derive

$$D_{px} = 4\pi eAq_E\left(\frac{1}{\omega_{pe}^2} - \frac{1}{\omega_{pe}^2 - (\omega^2 + \mathrm{i}\nu\omega)}\right)Q^2, \tag{19}$$

where $Q^2 = \frac{3\alpha^2 - \gamma - 2\lambda}{3} - \beta^2(q_E^2 - k_y^2)$. Using the above expression in equations (18) and (19), one can see that

$$\begin{aligned}&\omega_{pe}^2(k_y^2 q_M + q_M q_v q_E + q_E q_v^2 - k_y^2 q_E)\\&\quad = q_E q_v (q_M + q_v)(\omega^2 + \mathrm{i}\nu\omega).\end{aligned} \tag{20}$$

Equation (20) is a general dispersion relation for the surface waves on semi-bounded quantum plasmas by considering quantum Bohm potential, Fermi statistical pressure, electron exchange-correlation effects and collisional effects, and the appropriate boundary conditions were also considered here.

3. Analysis of the dispersion relation in different cases

In section 2, the general dispersion equation is derived and now we concentrate on the electrostatic surface waves because the transverse electromagnetic component of the surface waves is not affected by the quantum effects, as mentioned in the previous literature [23]. Assuming the electrostatic limit condition, $c \to \infty$, and the overcritical dense condition, i.e. $k_y^2 v_{\mathrm{Fe}}^2 + \hbar^2 k_y^4/4m^2 \ll |\omega_{pe}^2 - \omega^2 - \mathrm{i}\nu\omega|$, one can derive the general dispersion relation in the following form

$$\begin{aligned}\omega^2 + \mathrm{i}\nu\omega = \frac{\omega_{pe}^2}{2}\Bigg[1 + \frac{k_y}{\sqrt{\omega_{pe}^2 - \omega^2 - \mathrm{i}\nu\omega}}\\ \times\sqrt{\alpha^2 - \frac{\gamma}{3} - \frac{2\lambda}{3} + \beta^2 k_y^2}\Bigg].\end{aligned} \tag{21}$$

Solving equation (21), by taking into account the condition $\nu^2/\omega^2 \ll 1$, whence we find that

$$\begin{aligned}\omega = -\mathrm{i}\frac{\nu}{2} \pm \frac{\omega_{pe}}{\sqrt{2}}\Bigg[1 + \frac{1 + \mathrm{i}\sqrt{2}\,\nu/\omega_{pe}}{\sqrt{2}}\frac{k_y}{\omega_{pe}}\\ \times\sqrt{\alpha^2 - \frac{\gamma}{3} - \frac{2\lambda}{3} + \beta^2 k_y^2}\Bigg]\end{aligned} \tag{22}$$

therefore, we can obtain the imaginary part of equation (22) as

$$\mathrm{Im}(\omega) = \nu\left[-\frac{1}{2} + \frac{k_y}{\sqrt{2}\,\omega_{pe}}\sqrt{\alpha^2 - \frac{\gamma}{3} - \frac{2\lambda}{3} + \beta^2 k_y^2}\right]. \tag{23}$$

If we neglect the collision term ($\nu = 0$) in equation (22), the dispersion relation of surface waves can be rewritten as

$$\omega = \frac{\omega_{pe}}{\sqrt{2}}\left[1 + \frac{k_y}{\sqrt{2}\,\omega_{pe}}\sqrt{\alpha^2 - \frac{\gamma}{3} - \frac{2\lambda}{3} + \beta^2 k_y^2}\right] \tag{24}$$

this dispersion relation is similar to the expression derived by Niknam *et al* [23].

If we simply ignore the electron exchange-correlation effects in equation (22), one can also obtain the new dispersion relation as follows

$$\omega = -\mathrm{i}\frac{\nu}{2} \pm \frac{\omega_{pe}}{\sqrt{2}}\left[1 + \frac{1 + \mathrm{i}\sqrt{2}\,\nu/\omega_{pe}}{\sqrt{2}} \cdot \frac{k_y}{\omega_{pe}}\sqrt{\alpha^2 + \beta^2 k_y^2}\right] \tag{25}$$

this result is consistent with the work which has been obtained in [17].

Meanwhile, without the electron exchange-correlation effects and the collisional effects, we recover from equation (22) the dispersion relation in the following

$$\omega = \frac{\omega_{pe}}{\sqrt{2}}\left[1 + \frac{1}{\sqrt{2}}\frac{k_y}{\omega_{pe}}\sqrt{\alpha^2 + \beta^2 k_y^2}\right] \tag{26}$$

this is just the same result presented by Lazar *et al* [21]. Furthermore, without the quantum effects due to the quantum Bohm potential and the Fermi statistical pressure, equation (26) can give the frequency of surface plasmons $\omega = \omega_{pe}/\sqrt{2}$ [24].

In order to simplify the formulation, we introduce the dimensionless quantity parameter as $\Omega = \omega/\omega_{pe}$, $K = k_y v_{\mathrm{Fe}}/\omega_{pe}$, $\Gamma = \gamma/3v_{\mathrm{Fe}}^2$, $\Lambda = 2\lambda/3v_{\mathrm{Fe}}^2$, $H = \hbar\omega_{pe}/2m_e v_{\mathrm{Fe}}^2$ (the plasmonic coupling parameter), $\Theta = \nu/\omega_{pe}$, equation (22) can also be expressed in the following

$$\begin{aligned}\Omega = -\mathrm{i}\frac{\Theta}{2} \pm \frac{1}{\sqrt{2}}\\ \times\left[1 + \frac{1 + \mathrm{i}\sqrt{2}\,\Theta}{\sqrt{2}}K\sqrt{1 - \Gamma - \Lambda + H^2K^2}\right]\end{aligned} \tag{27}$$

thus, we can separate the real and imaginary parts of the frequency spectrum in equation (27) as follows

$$\mathrm{Re}(\Omega) = \frac{1}{\sqrt{2}}\left[1 + \frac{K}{\sqrt{2}}\sqrt{1 - \Gamma - \Lambda + H^2K^2}\right], \tag{28}$$

$$\mathrm{Im}(\Omega) = \Theta\left[-\frac{1}{2} + \frac{K}{\sqrt{2}}\sqrt{1 - \Gamma - \Lambda + H^2K^2}\right]. \tag{29}$$

One can see from equations (28) and (29) that the real and imaginary parts of the frequency are related to three effects, that is: (a) quantum effects (including the quantum Bohm potential and the Fermi statistical pressure), (b) electron exchange-correlation effects and (c) collisional effects. Next, in order to show these effects on the dispersion properties of surface waves, we plot the real and imaginary parts of the frequency versus the normalized wavenumber K. Here , we consider the parameters of electrons in metal at room temperature, and the typical parameters are $n_{e0} = 5.9 \times 10^{28}\ \mathrm{m}^{-3}$, $\omega_{pe} = 1.37 \times 10^{16}\ \mathrm{s}^{-1}$, $v_{\mathrm{Fe}} = 1.4 \times 10^6\ \mathrm{m\ s}^{-1}$, $T_{\mathrm{Fe}} = 5.53$ eV, and $T = 0.026$ eV, respectively. The quantum coupling parameter $g_Q \simeq 12.7 \gg 1$, the degeneracy parameter $\chi = 213 \gg 1$. The magnitudes of the quantum coupling parameter and the degeneracy parameter indicated that the metallic plasma is a quantum collisional plasma. For better comparison and clarity, the results of Khorashadizadeh *et al* [17] are included in figures 1 and 2, which are depicted by the red dotted line.

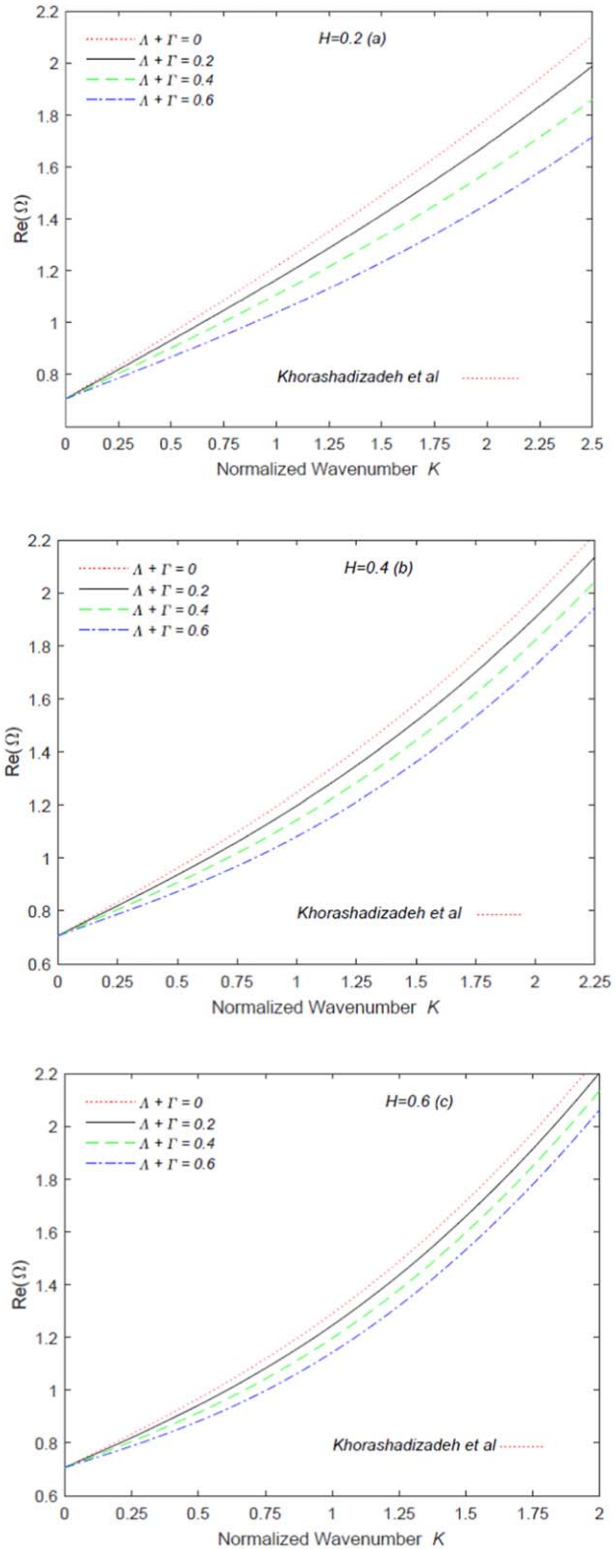

Figure 1. The normalized real frequency of the surface waves $\mathrm{Re}(\Omega)$ with respect to the normalized wavenumber $K = k_y v_{\mathrm{Fe}}/\omega_{pe}$ in quantum plasmas with the electron exchange-correlation effects, for (a) $H = 0.2$, (b) $H = 0.4$, and (c) $H = 0.6$. Each figures are plotted for different values of parameter $\Lambda + \Gamma$. The results of Khorashadizadeh *et al* are included in these figures which are presented by the red dotted line which does not consider the electron exchange-correlation effects [17].

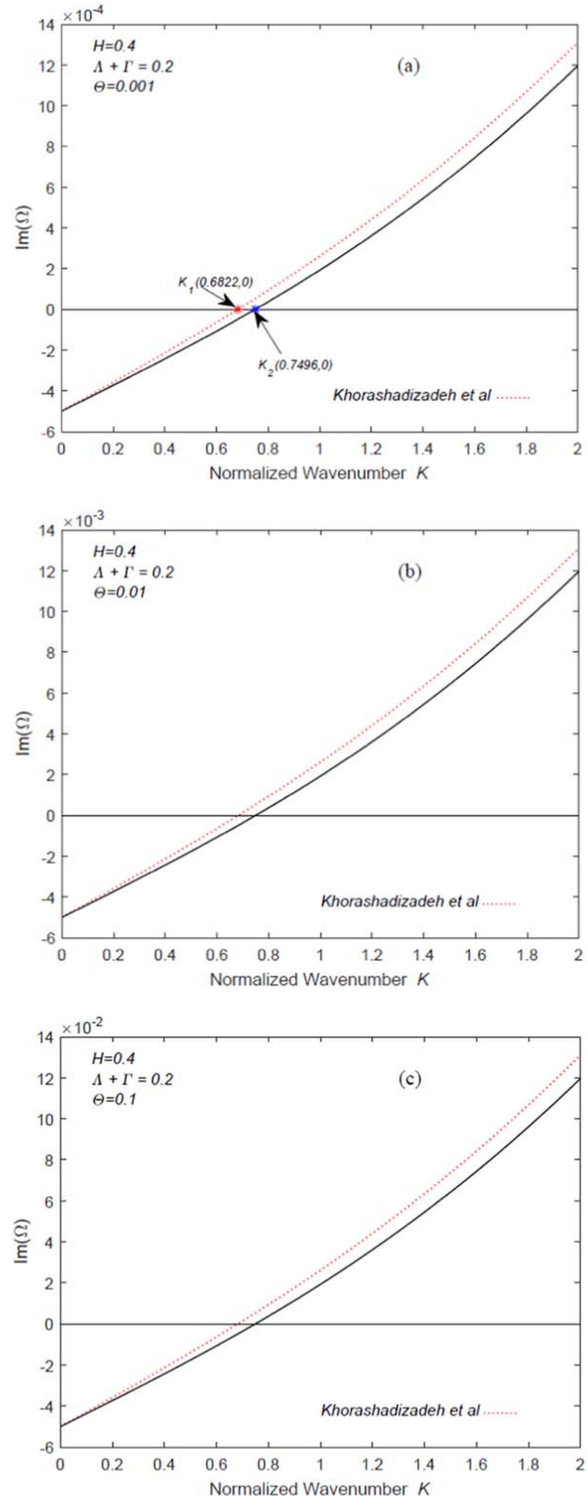

Figure 2. Plot of the imaginary frequency of the surface waves $\mathrm{Im}(\Omega)$ with respect to the normalized wavenumber $K = k_y v_{\mathrm{Fe}}/\omega_{pe}$ in collisional quantum surface plasmas with the electron exchange-correlation effects. $H = 0.4$, $\Lambda + \Gamma = 0.2$, for (a) $\Theta = 0.001$, (b) $\Theta = 0.01$, and (c) $\Theta = 0.1$. The red dotted line in (a)–(c) is the result of Khorashadizadeh *et al* which does not consider the electron exchange-correlation effects [17].

The numerical plots of the normalized real part of the frequency spectrum against the normalized wavenumber K for different values of the plasmonic parameter H are shown in figures 1(a)–(c). From these figures, one can find that in the presence of electron exchange-correlation, the value of the normalized real part of the frequency spectrum decreases and dispersion relation for the surface wave shifts to lower frequencies. The down-shift of the normalized real part of the frequency spectrum increases with the values of parameter $\Lambda + \Gamma$, especially in short wavelength region. On the other hand, the dynamic of the surface waves are modified evidently by the electron exchange-correlation effects in the short wavelength region. These figures indicate that the electron exchange-correlation effects tend to reduce the frequency of surface waves, but the quantum Bohm potential and Fermi statistical pressure effects display an opposite effects. From figures 1(a)–(c), we also notice that the frequency spectrum of the surface waves changes from a approximately straight line to a parabolic line when the value of the plasmonic parameter H increases gradually and its influence is more pronounced in short wavelength region. Thus, the propagation velocity of surface waves are enhanced due to the quantum effects. On the other hand, the plasmonic parameter H characterizes the quantum effects, and from figure 1, one can derive that the quantum effects can promote the increase of the real part of the frequency spectrum. Meanwhile, comparing our results (the black solid line, the green dashed line and the blue dashed–dotted line in figure 1) and the Khorashadizadeh's corresponding results (the red dotted line in figure 1), one can therefore find that the frequency spectrum of the surface waves is down-shifted due to the electron exchange-correlation effects in the short wavelength region.

Figure 2 shows the behavior of normalized imaginary parts against normalized wavenumber of the frequency spectrum (equation (29)), and is plotted in some typical parameters in metallic plasma for three different collisional frequencies. Figures 2(a)–(c) are depicted for $\Theta = 0.001$, $\Theta = 0.01$ and $\Theta = 0.1$, respectively. The horizontal axis represents the normalized wavenumber, K, and the longitudinal axis stands for the normalized growth rate of instability of the surface waves. From figures 2(a)–(c), it is found that the collisional effects are quite important when we study the propagation properties of the surface waves in such plasma system. Equations (28) and (29) indicate the collisional effects have no influence on the real part of the frequency spectrum, but the imaginary part of the frequency spectrum is apparently affected by the collisional effects. One can obviously see from these figures that the collisional effects can lead to damping or growth the surface waves, and the growth rates of surface waves increase by increasing the collision frequency. Equation (23) and figure 2 indicate that when

$$k_y > \frac{1}{\sqrt{2}\beta}\left[\left(\frac{\gamma}{3} + \frac{2\lambda}{3} - \alpha^2\right) + \sqrt{\left(\alpha^2 - \frac{\gamma}{3} - \frac{2\lambda}{3}\right)^2 + 2\beta^2\omega_{pe}^2}\right]^{\frac{1}{2}} \tag{30}$$

we need to consider the generation of instability. In addition, figures 2(a)–(c) indicate that the surface waves

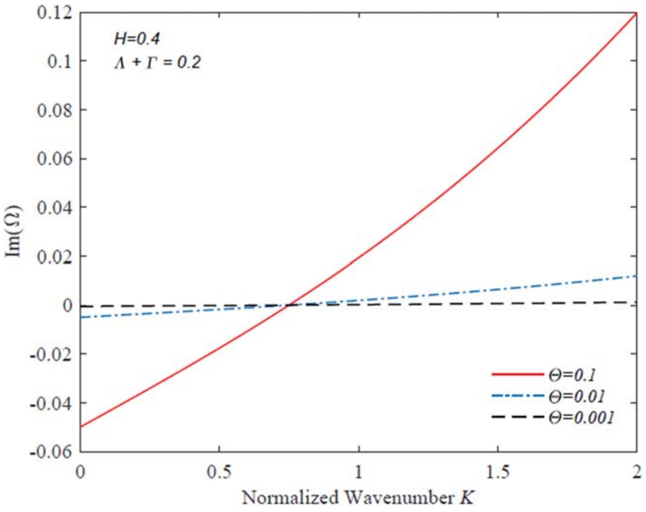

Figure 3. Plot of the normalized growth rate of the modulational instability in collisional quantum plasmas with the electron exchange-correlation effects. $H = 0.4$, $\Lambda + \Gamma = 0.2$, where $\Theta = 0.1$ (red solid line) , $\Theta = 0.01$ (blue dashed–dotted line), $\Theta = 0.001$ (black dashed line).

instability can arise in the presence of quantum effects, electron exchange-correlation effects as well as collisional effects, and the surface waves modulational instability growth rate increases by increasing the collisional effects, especially in the short wavelength region. By the way, we should point out that the numerical values of $\mathrm{Im}(\Omega)$ at $K = 0$ depends on the parameter $\Theta = \nu/\omega_{pe}$ and its value changes with different collision frequency at $K = 0$. Also from figure 2(a), one can see the value of K_2 is lager than K_1, which means that the critical point of damping and instability of surface waves can be changed by the electron exchange-correlation effects, and figures 2(b) and (c) also show the same physical situation.

In order to expound the influence of different collisional frequencies on the normalized imaginary part of the frequency spectrum, we plot figure 3 in the above. This figure shows that the growth rates of surface waves are significantly changed under the different collisional frequencies. The positive imaginary part of Ω shows that this system is modulational unstable and growing with the rate of $\mathrm{Im}(\Omega)$. The surface waves can be unstable in the presence of the collisional effects when $\mathrm{Im}(\Omega) > 0$, but in the case of $\mathrm{Im}(\Omega) < 0$, the surface waves will be damped. From the three different curves in figure 3, it is visible that the surface waves instability can increase by increasing the collisional frequency, and this situation is more obvious in the short wavelength region.

4. Summary and conclusion

In the present study, the propagation of surface waves in semi-bounded quantum collisional plasmas are studied. Combining the quantum Bohm potential, Fermi statistical pressure, electron exchange-correlation effects and collisional effects, a new general dispersion relation has been obtained, and discussed in some special cases. Analysis of the dispersion properties of surface waves shows that in the presence of electron exchange-correlation effects, the value of frequency of the system can be decreased, and the down-shifted frequency due to the electron exchange-correlation effects increases with increasing plasmonic parameter H. The numerical results indicate that the electron exchange-correlation effects tend to reduce the frequency of surface waves, but the quantum Bohm potential and Fermi statistical pressure effects display an opposite effects. The results also exhibit the collisional effects can lead to damping or growth of the surface waves, and the growth rates of surface waves increase by increasing the collision frequency, especially in the short wavelength region. Moreover, one can find that there is a threshold of k_y for the existence of surface wave instability in this system. The present results can be of interest in the study of the dispersion properties of surface waves in dense semi-bounded quantum collisional plasmas, such as on the interface of the metallic plasmas. Furthermore, this theoretical studies may be useful for design of nanotubes and metallic nanostructures.

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