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Generation of electromagnetic whistler mode instability for inhomogeneous ionospheric plasma

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ABSTRACT : Whistler mode instability having propagation parallel vector and oblique to ambient magnetic field has been studied for pitch angle loss-cone unperturbed distribution function for inhomogeneous ionospheric plasma. Dispersion relation and growth rate have been derived and calculated for ionospheric plasma having in homogeneity in perpendicular AC electric field, loss-cone and temperature anisotropy. The growth rate of electromagnetic circularly polarized whistler wave has been founded to be enhanced by free energy source like temperature anisotropy and loss- cone up to a limited angle of propagation. It is also inferred that perpendicular AC electric field modifies the resonance frequency condition of Doppler shift.

Keywords : Obliquely propagating whistler, Ionosphere.

I. INTRODUCTION

Plasma waves in earth's magnetosphere may have natural, artificial external origin. The energy of plasma waves generated internal to magnetosphere comes ultimately from solar wind flow past the earth and earth's rotation which is depressed throughout the magnetosphere in terms of magnetic field, electrified and particle kinetic energy which gets converted into wave energy through change into particle distribution function. Naturally occurring plasma waves of this type associated with earth ionosphere include whistlers lighting stokes are also one of the strong sources electro magnetic radiations, particularly in the very low frequency band. Part of it penetrates the ionosphere and is propagated towards. The remainder of the signal may travel large distance in the earth ionosphere wave guide, being reflected back and forth between the conducting ionosphere and the ground.

Electrons can be scattered into the Loss-cone by wave particle interaction between whistler mode radiation and energetic electrons in the magnetosphere. The whistler mode radiation responsible for this pitch angle diffusion may take the form of either incoherent or coherent emissions. Incoherent whistler mode radiation can result from instabilities driven by anisotropies in the velocity distribution of the hot electrons [1,2]. Coherent whistler emissions can result from phase bunching of energetic electrons triggered by external emissions or by incoherent whistler waves [3]. The scattering electron into the loss-cone by incoherent whistler radiation was considered by Kennel and Petschek [4], while the pitch angle scattering caused by coherent whistler emissions was treated by Inan et. al [5]. Whistler waves are believed to play an important role in the generation of the pulsating aurora. It is now firmly established that the glow of the pulsating aurora is caused by the quasi-periodic filling of the loss-cone and the subsequent precipitation of energetic electrons into the atmosphere [6]. Based on electron energy measurements obtained from sounding rockets experiments, the scattering mechanism is believed to occur in the equatorial plane. The ionosphere is believed to play some role in determining the spatial characteristics of the pulsating aurora because the drift rate of the auroral patches appears to be related to the movement of the neutral atmosphere [7]. Oguti [8] proposed that local enhancements in the ionospheric plasma density may explained to fill adjacent flux tubes with different plasma densities, there by creating the conditions needed at the equator to trigger auroral pulsations because the instability is directly driven by the precipitation process.

Huang et. al [9] calculated the characteristics of the incoherent whistler mode waves generated in the magnetosphere along the L = 5 geomagnetic field line which intersect the atmosphere in the region where the pulsating aurora is frequently observed and considered their implications for the pulsating aurora. They observed for the loss-cone driven Whistler instability, the growth rate along the L = 5 field line in largest just above the ionosphere where the loss-cone angle is also large.

Whistler mode instability produce by DC electric field have been study by Misra & Singh [10] in the magnetosphere of the earth, this study has been for the extended by Misra & Pandey [11] in which they have derived dispersion relation for the whistler mode instability, in an infinite magnetosphere in the presence of perpendicular AC electric field for a loss-cone type distribution function having an anisotropic temperature effect of cold plasma injection and temporal evaluation of whistler mode in stability have been studied in the presence of perpendicular AC electric field for generalize distribution function in the magnetosphere of Uranus [12,13].

Pandey et. al [14] have studied oblique whistler mode instability for a generalized drifted distribution function in the presence of perpendicular AC electric field by method of characteristic solution , the growth rate were evaluated for the plasma parameters suited to the magnetosphere of Uranus. It was found that only AC frequencies significantly affect the growth characteristic of the whistler waves, in addition to the external triggering AC electric filed. The complete processes of oblique whistler mode instabilities where studied due to anisotropic electron beam having linear results as well as two dimensional particle simulations [15]. This has a direct relevance for interpretation of wave activities observed in the earth magnetosphere by the GEOS1, GEOS2, and GEO TALL satellites or in Uranus bow shock by voggar2 were proposed.

Recently oblique whistler mode wave have been studied having k vector at an angle of magnetic field for a generalized distribution function with AC electric field at 1 AU by Pandey and Misra [16].

In this paper, Whistler mode instability having propagation vector to ambient magnetic field has been studied for pitch angle loss-cone unperturbed distribution function for inhomogeneous ionospheric plasma. Dispersion relation and growth rate have been derived and calculated for ionospheric plasma having in homogeneity in perpendicular AC electric field, loss-cone and temperature anisotropy. The growth rate of electromagnetic circularly polarized VLF wave has been found to be enhanced by free energy source like temperature anisotropy and loss-cone up to a limited angle of propagation. It is also in ferried that perpendicular AC electric field modifies the resonance frequency condition.

II. DISPERSION RELATION

An in-homogeneous, an-isotropic, collision-less ionospheric plasma subjected to an external magnetic field $B_0 = B_0\,\hat{e}_z$ and an electric field $E_0=(E_{0x}\sin\nu t\,\hat{e}_x)$ has been considered in order to obtain the relation. In case, the Vlasov-Maxwell equations are liberalized. The linear zed equations obtained after neglecting the higher order terms and separating the equilibrium and non-equilibrium parts, following the techniques of Pandey and Misra [16] are given as

$$v.\frac{\partial f_{s0}}{\partial r}.+\frac{e_s}{m_s}\left[E_{0x}\sin\nu t+(v\times B_0)\right]\left(\frac{\partial f_{s0}}{\partial v}\right)=0 \qquad ...(1)$$

$$\frac{\partial f_{s1}}{\partial t}+v.\frac{\partial f_{s1}}{\partial r}+\left(\frac{F}{m_s}\right)\left(\frac{\partial f_{s1}}{\partial v}\right)=S(r,v,t) \qquad ...(2)$$

where force is defined as F= mdv/dt

$$F=e_s\left[E_{0x}\sin\nu t+\left(v\times B_0\right)\right] \qquad ...(3)$$

The particle trajectories are obtained by solving the equation of motion defined in equ.(3) and S(r,v,t) is defined as.

$$S(r,v,t)=\left(-\frac{e_s}{m_s}\right)\left[E_1+v\times B_1\right]\left(\frac{\partial f_{s0}}{\partial v}\right) \qquad ...(4)$$

The method of characteristics solution is used to determine the perturbed distribution function f_{s1}. This is obtained from equation (2) by

$$f_{s1}(r,v,t)=\int_{\infty0}^{\infty}S\left\{r_0\left(r,v,t^{`}\right),v_0\left(r,v,t^{`}\right),t-t^{`}\right\}dt' \qquad ...(5)$$

where *s* denotes species and E_1, B_1 and f_{s1} are perturbed and are assumed to have harmonic dependence in f_{s1}, B_1 and $E_1 \cong \exp i\,(k.r-\omega t)$. We transformed the phase space co-ordinate system from (r,v,t) to $(r_0,v_0,t-t^{`})$ and $t^{`}=t-t^{`}$. The particle trajectories which have been obtained by solving eq.(3) for the given external field configuration and wave propagation

$$k=\left[k_\perp e_{x,}\,0,\;k_\parallel e_z\right].$$

$$x_0=x+\left(\frac{v_y}{\omega_{cs}}\right)+\left(\frac{1}{\omega_{cs}}\right)\left[v_x\sin\omega_{cs}t'-v_y\cos\omega_{cs}t'\right]+\left(\frac{\Gamma_x}{\omega_{cs}}\right)\left[\frac{\omega_{cs}\sin\nu t'-\nu\sin\omega_{cs}t'}{\omega_{cs}^2-\nu^2}\right]$$

$$y_0=y+\left(\frac{v_x}{\omega_{cs}}\right)-\left(\frac{1}{\omega_{cs}}\right)\left[v_x\cos\omega_{cs}t'-v_y\sin\omega_{cs}t'\right]-\left(\frac{\Gamma_x}{\nu\omega_{cs}}\right)\left[1+\frac{\nu^2\cos\omega_{cs}t'-\omega_{cs}^2\cos\nu t'}{\omega_{cs}^2-\nu^2}\right]$$

$$z_0=z-v_z t' \qquad ...(6)$$

and the velocities are

$$v_{x0}=v_x\cos\omega_{cs}t'-v_y\sin\omega_{cs}t'+\left\{\frac{\nu\Gamma_x(\cos\nu t'-\cos\omega_{cs}t')}{\omega_{cs}^2-\nu^2}\right\}$$

$$v_{y0}=v_x\sin\omega_{cs}t'+v_y\cos\omega_{cs}t'-\left\{\frac{\Gamma_x(\omega_{cs}\sin\nu t'-\nu\sin\omega_{cs}t')}{\omega_{cs}^2-\nu^2}\right\}$$

$$v_{z0}=v_z \qquad ...(7)$$

where $\omega_{cs}=\frac{e_sB_0}{m_s}$ is the cyclotron frequency of species *s*

and $\Gamma_x=\frac{e_sE_{0x}}{m_s}$ and AC electric field is varying as $E_0 = E_{0x}\sin \nu t$, ν being the angular AC frequency.

After doing some lengthy algebraic simplification and carrying out the time integration, the perturbed distribution function f_{s1} is written as

$$f_{s1}(r,v,t) = -\frac{e_s}{m_s\omega}\sum_{m,n,p,q}^{\infty}\frac{J_p(\lambda_2)J_m(\lambda_1)J_q(\lambda_3)e^{i(k.r-\omega t)}}{\{\omega - k_{\parallel}v_{\parallel} - (n+q)\omega_{cs} + p\nu\}}$$

$$\left[E_{1x}J_nJ_p\left\{(\frac{n}{\lambda_1})U^* + D_1(\frac{p}{\lambda_2})\right\}\right.$$

$$\left. -iE_{1y}\left\{J_n^{'}J_pC_1 + J_nJ_p^{'}D_2\right\} + E_{1z}J_nJ_pW^*\right] \quad ...(8)$$

Where the Bessel identity

$e^{i\lambda\sin\theta} = \sum_{k=-\infty}^{\infty} J_k(\lambda)\, e^{ik\theta}$ has been used, the arguments of the Bessel functions are

$$\lambda_1 = \frac{k_\perp v_\perp}{\omega_{cs}}, \lambda_2 = \frac{k_\perp\Gamma_x\nu}{\omega_{cs}^2 - \nu^2}, \lambda_3 = \frac{k_\perp\Gamma_x\omega_{cs}}{\omega_{cs}^2 - \nu^2}$$

where

$$C_1 = \frac{1}{v_\perp}\left(\frac{\partial f_{s0}}{\partial v_\perp}\right)(\omega - k_{\parallel}.v_{\parallel}) + \left(\frac{\partial f_{s0}}{\partial v_{\parallel}}\right)k_{\parallel}$$

$$U^* = C_1\left[v_\perp - \left\{\frac{\nu\Gamma_x}{\omega_{cs}^2 - \nu^2}\right\}\right]$$

$$W^* = \left[\left(\frac{n\omega_{cs}v_{\parallel}}{v_\perp}\right)\left(\frac{\partial f_{s0}}{\partial v_\perp}\right) - n\omega_{cs}\left(\frac{\partial f_{s0}}{\partial v_{\parallel}}\right)\right]$$

$$+\left[1 + \left\{\frac{k_\perp\nu\Gamma_x}{\omega_{cs}^2 - \nu^2}\right\}\{(p/\lambda_2) - (n/\lambda_1)\}\right]$$

$$D_1 = C_1\left\{\frac{\nu\Gamma_x}{\omega_{cs}^2 - \nu^2}\right\}, D_2 = C_2\left\{\frac{\omega_{cs}\Gamma_x}{\omega_{cs}^2 - \nu^2}\right\}$$

$$J_n^{'} = \frac{dJ_n(\lambda_1)}{d\lambda_1}, J_p^{'} = \frac{dJ_p(\lambda_2)}{d\lambda_2} \quad ...(9)$$

Following Pandey and Misra [16] the conductivity tensor $\|\sigma\|$ is written as

$$\|\sigma\| = -\sum\frac{e_s^2}{m_s\omega}\sum_{m,n,p,q}^{\infty}\int\frac{J_q(\lambda_3)S_{ij}d^3v}{\omega - kv - (n+q)\omega_{cs} + p\nu} \quad ...(10)$$

where

$$S_{ij} = \left\| \begin{matrix} v_\perp\frac{n}{\lambda_1}(J_n)^2 J_pA & iv_\perp J_nB & v_\perp W^*\frac{n}{\lambda_1}J_n^2J_p \\ v_\perp J_pAJ_nJ'_n & v_\perp J_n^{'}B & iv_\perp W^* J_pJ_nJ'_n \\ v_{\parallel}J_n^2J_pA & -iv_{\parallel}J_nB & v_{\parallel}W^*J_n^2J_p \end{matrix} \right\|$$

$$A = \left(\frac{n}{\lambda_1}\right)U^* + \left(\frac{p}{\lambda_2}\right)D_1, \qquad B = J_n^{'}J_pC_1 + J_n^{'}J_nD_2$$

From $J = \|\sigma\|.E_1$ and two Maxwell's curl equations for the perturbed quantities, we have

$$\left[k^2 - k.k - \frac{\omega^2}{c^2}\varepsilon(k,\omega)\right].E_1 = 0 \quad ...(11)$$

Where

$$\varepsilon(k,\omega) = 1 - \frac{4\pi}{i\omega}\|\sigma(k,\omega)\| \text{ is dielectric tensor} \quad ...(12)$$

The Maxwellian distribution function with loss-cone angle θ_c taken from Huang et al [9] is written as

$$f_{so} = \frac{n_0}{M\pi^{3/2}\alpha_\perp^2\alpha_{\parallel}}\exp\left[-\left(\frac{v_\perp}{\alpha_\perp}\right)^2 - \left(\frac{v_{\parallel}}{\alpha_{\parallel}}\right)^2\right] \quad \left|\frac{v_\perp}{v_{\parallel}}\right| > \tan\theta_c \quad ...(13)$$

Where normalization constant M is given as

$$M = \frac{1}{\sqrt{\frac{1+\tan^2\theta_c}{A_T + 1}}}$$

$$\|\varepsilon_{ij}(k,\omega)\| = 1 + \sum\frac{4\pi e_s^2}{m_s\omega^2}\int\frac{J_q(\lambda_3)\|S_{ij}\|d^3v}{\omega - kv - (n+q)\omega_{cs} + p\nu} \quad ...(14)$$

The generalized dielectric tensor may be written as

$$\left\| \begin{matrix} N^2\cos^2\theta_1 + \varepsilon_{11} & \varepsilon_{12} & N^2\cos\theta_1\sin\theta_1 + \varepsilon_{13} \\ \varepsilon_{21} & N^2\varepsilon_{22} & \varepsilon_{23} \\ N^2\cos\theta_1\sin\theta_1 + \varepsilon_{31} & \varepsilon_{33} & N^2\sin^2\theta_1 + \varepsilon_{33} \end{matrix} \right\|$$

If we remove the contribution of AC electric field and set normalization constant M = 1 above dielectric tensor is similar to Sazhin[17] and Pandey and Misra [16]. After using the for limits $k_\perp = k\sin ?_1 \to 0$ and $k_{\parallel} = k\cos ?_1$ the generalized dielectric tensor becomes simplified tensor and dispersion relation reduce as

$$\left\| \begin{matrix} -N^2 + \varepsilon_{11} & \varepsilon_{12} & 0 \\ -\varepsilon_{21} & -N^2 + \varepsilon_{22} & 0 \\ 0 & 0 & \varepsilon_{33} \end{matrix} \right\|$$

This is rewritten in more convenient form. Now for whistler wave

$$-N^4 - 2\varepsilon_{11}N^2 + \varepsilon_{11}^2 + \varepsilon_{12}^2 = 0$$

for electrostatic waves $\varepsilon_{33} = 0$

Neglecting the higher power of N the resulting relation becomes as

$$\varepsilon_{11} + \varepsilon_{12} = N^2 \quad ...(15)$$

Hence the dispersion relation of whistler wave is obtained from this for Bessel function order n = 1, p = 1, q = 0 and $j_p = 1$, $j_q = 1$

$$\frac{k^2c^2}{\omega^2} = 1 + \frac{\omega_p^2}{\omega^2}\left[\left(1+\frac{X_{ac}}{\alpha_\perp}\right)\left\{\frac{\omega}{Mk_\parallel \alpha_\parallel} Z(\xi) + A_T\left(1+\xi Z(\xi)\right)\right\} + \tan^2\theta_c \left\{\left(\frac{1}{2}\right) + \xi^2\left(1+\xi Z(\xi) + \frac{X_{ac}}{\alpha_\perp}\xi\left(1+\xi Z(\xi)\right)\right)\right\}\right] \quad ...(16)$$

where

$$X_{ac} = \frac{\nu\Gamma_x}{\omega_c^2 - \nu^2} \qquad X_3 = \frac{\omega_r}{\omega_c} \qquad X_4 = \frac{-\nu}{\omega_c}$$

$$k_3 = 1 - X_3 + X_4,\; k_4 = \frac{X_3}{k_3} \;\; k_1 = k$$

The required expression for growth rate and real frequency are obtained as

$$\frac{?}{?_c} = \frac{\frac{\sqrt{\lambda}}{Mk_1}\left[\left(1+\frac{X_{ac}}{\alpha_\perp}\right)(A_T - k_4) + \left(\frac{\tan\theta_c k_3}{Mk}\right)^2 - \frac{X_{ac}\tan\theta_c{}^2 k_3}{\alpha_\perp Mk_1}\right] k_3^3 \exp\left(-\left(\frac{k_3}{Mk_1}\right)\right)}{\left(1+\frac{X_{ac}}{\alpha_\perp}\right)\left\{1+X_4\frac{M^2A_T(1+X_4)}{2k_3^2} - \frac{M^2k_1^2}{k_3}(A_T-k_4)\right\} + \frac{X_{ac}\tan\theta_c{}^2}{2\alpha_\perp}} \quad ...(17)$$

$$X_3 = \frac{k_1^2}{2\beta}\left[1 + X_4\frac{M^2A_T\beta\left(1+\frac{X_{ac}}{\alpha_\perp}\right)}{(1+X_4)^2} + \frac{X_{ac}\tan\theta_c{}^2 M}{2\alpha_\perp k_1(1+X_4)}\right] \quad ...(18)$$

where $\beta = \frac{k_\beta T_\parallel n_0\mu_0}{B_0^2}$

III. RESULTS AND DISCUSSION

Following plasma parameters studied to the auroral ionosphere has been adopted for the calculation of the growth rate and the real frequency for the loss-cone Driven Whistler instability. Ambient magnetic field $B_0 = 1 \times 10^{-7}$T, electron density $n_0 = 1 \times 10^9$ m^3 electron energy $K_B T_{11}$=10ev. Temperature anisotropy A_T is supposed to vary from 0.25 to 0.75 and loss-cone angle $\theta°_c$ is to vary from 0 to 20°. AC electric field has been considered equal to 20 mV/m and its frequency to vary from 2 kHz to 6kHz.The angle of propagation has been taken to vary between zero to 60°. Fig. 1 shows the variation of the growth rate and the real frequency for various values of the temperature anisotropy in the presence of the AC field E_0 =20 mV/m with ac frequency of 2 kHz. It is observed that the growth rate increases by increasing the value of temperature anisotropy it means that it behaves like a free energy source. It is also observed that in the presence of AC field, the growth rate and also the bandwidth more increases in comparison to the case when the AC field is absent, this shows that the AC field has additive effect. Thus a minimum value of electric field magnitude is enough to trigger the Whistler emission and the existing growth of the wave to a higher value, increasing the power by a few deci Bels in comparison to that without the AC signal. These triggered emissions have been observed by instruments on board satellites [18,19] and if these emissions are ducting along the field lines they may be recorded by ground stations.

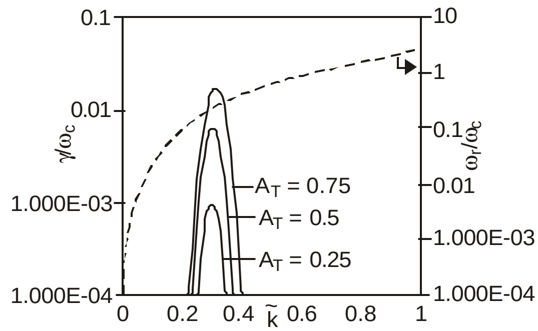

Fig. 1. Variation of Growth rate γ/ω_c (solid line) and real frequency ω_r/ω_c (dotted line) with respect to $\bar{k}$ for various values of temperature anisotropy at other fixed plasma parameters.

Fig. 2 shows the variation of growth rate and real frequency with respect to $\bar{k}$ for various values of AC field frequency in the case when temperature anisotropy is 0.5.In this case it is observed that the growth rate and also the bandwidth increase with the increase of the AC field frequency. It shows that AC field frequency introduces a small growth and provides some free energy to make the plasma unstable sustaining the growth of Whistler waves.

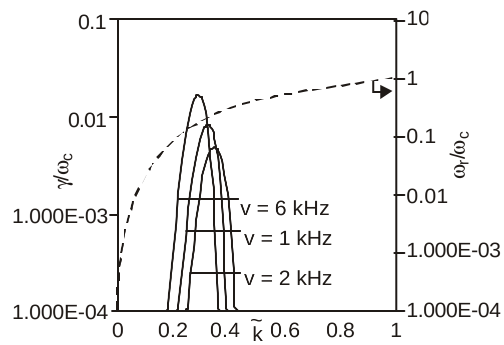

Fig. 2. Variation of Growth rate γ/ω_c (solid line) and real frequency ω_r/ω_c (dotted line) with respect to $\bar{k}$ for various values of AC field frequency at other fixed plasma parameters.

In Fig. 3 the growth rate and real frequency is plotted against $\bar{k}$ for various values of the loss-cone angle in the presence of temperature anisotropy for other fixed plasma

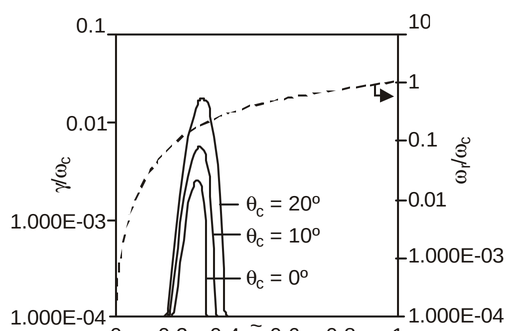

Fig. 3. Variation of Growth rate γ/ω_c (solid line) and real frequency ω_r/ω_c (dotted line) with respect to $\bar{k}$ for various values of loss-cone angle at other fixed plasma parameters.

parameters. It shows that with the increase of the loss-cone angle, the growth rate goes on increasing simultaneously increasing the bandwidth. This indicates that the loss cone angle is supposed to provide additional energy for generating Whistler wave of low frequencies.

Fig. 4 shows the variation of the growth rate and real frequency with $\bar{k}$ for various values of the magnitude of the electron energy $k_B T_{\|}$. It is observed that with the increase of the magnitude of the electron energy, the growth rate increases and broadens the range of $\bar{k}$. That emission is possible for extended values of $\bar{k}$. Fig. 5 shows the variation of growth rate and real frequency with $\bar{k}$ for various values of angle of propagation .With the increase of the angle of propagation the growth rate increases slightly and the change in obliqueness broadens the wave spectrum over wide range. This is in agreement with the observation due to the change in resonance condition.

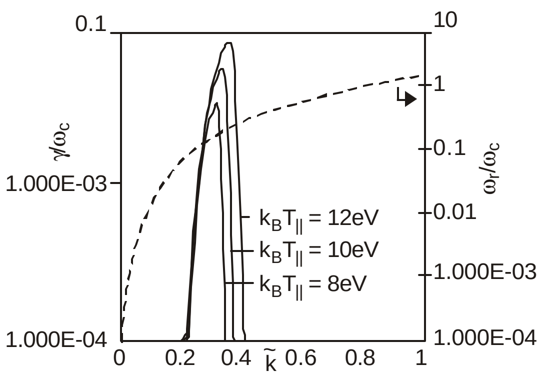

Fig. 4. Variation of Growth rate γ/ω_c (solid line) and real frequency ω_r/ω_c (dotted line) with respect to $\bar{k}$ for various values of electron thermal energy $K_B T$ at other fixed plasma parameters.

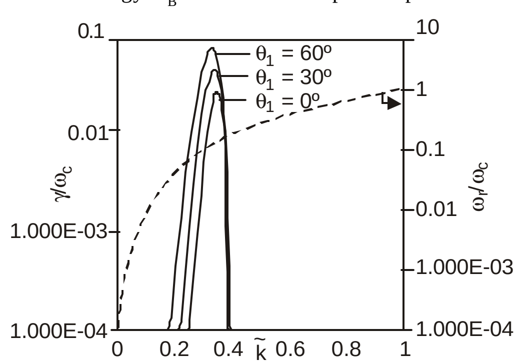

Fig. 5. Variation of Growth rate γ/ω_c (solid line) and real frequency ω_r/ω_c (dotted line) with respect to $\bar{k}$ for various values of angle of propagation at other fixed plasma parameters.

IV. CONCLUSION

The effect of pitch angle loss-cone distribution function for generation of oblique whistler mode wave has been more effective. The growth rate of oblique whistler waves are increases by increasing the temperature anisotropy also with the pitch angle anisotropy. Hence pitch angle anisotropy is also a free energy source for generating the whistler mode wave. The AC frequency also increases the growth rate and triggering effect. This result is better for ionospheric plasma due to the large number density of electron plasma.

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