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EFFECT OF THE IONOSPHERIC INDUCTION CURRENT ON MAGNETOHYDRODYNAMIC WAVES IN THE MAGNETOSPHERE

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Abstract: The eigenvalue problem for coupled magnetohydrodynamic (MHD) waves interacting with the anisotropically conducting ionosphere has been solved numerically by using a rectangular box model for the magnetosphere, and the effect of the ionospheric induction current on the MHD waves in the magnetosphere has been examined. The initial results obtained are as follows: (1) The eigenperiod of the localized toroidal (shear Alfvén mode) oscillation is effectively controlled by the height-integrated Hall conductivity. (2) A global monochromatic toroidal oscillation is excited by the fast magnetosonic wave via the ionospheric induction current.

1. Introduction

The interaction between magnetohydrodynamic (MHD) waves and the ionosphere has been studied from the view point of wave reflection by some researchers (*e.g.*, DUNGEY, 1963; NISHIDA, 1964: TAMAO, 1964; HUGHES, 1974; HUGHES and SOUTHWOOD, 1976). The concept of wave reflection is very useful to examine the direct ionospheric response to MHD wave incidence. However, to obtain a self-consistent picture of the ionospheric modification of MHD waves, one needs to directly solve the MHD equations under suitable boundary conditions (*e.g.* NEWTON *et al.*, 1978; ALLAN and KNOX, 1979a, b). NEWTON *et al.* (1978) examined the damping of guided mode oscillations along a field line by the ionospheric Pedersen conductivity. ALLAN and KNOX (1979a, b) found that the axisymmetric toroidal and poloidal modes in a dipole magnetic field interact via the ionospheric Hall current, and also discovered a new set of harmonics of a quarter-wave fundamental with longer periods than the classical half-wave one for a given magnetic shell under asymmetric northern and southern ionospheric Pedersen conductivities in the case of zero Hall conductivity.

Recently, eigenmode analyses of coupled MHD waves interacting with the anisotropically conducting ionosphere have been solved numerically by using a rectangular box model for the magnetosphere (FUJITA, 1993; YOSHIKAWA *et al.*, 1994). FUJITA (1993) has developed a computer simulation code based on the Galerkin method and has applied it to the coupled MHD oscillations in the magnetosphere-ionosphere system to study the mode coupling due to the Hall current. YOSHIKAWA *et al.* (1994) have also developed another computer simulation code for the eigenmode analysis of coupled MHD oscillations based on the finite difference scheme in consideration of the comprehensive ionospheric boundary conditions, and have found that the eigenfrequency of the localized toroidal (shear Alfvén mode) oscillation is effectively controlled by both the ionospheric Pedersen and Hall conductivities. They found that the ionospheric induction current plays an important role in the coupling between the MHD waves and the ionosphere.

It is well known that when the shear Alfvén wave is incident from the magnetosphere, the Hall current in the ionosphere generates the fast magnetosonic wave in the magnetosphere and the poloidal magnetic disturbance in the neutral atmosphere, while the Pedersen current is connected with the field-aligned current (FAC) (TAMAO, 1965). The emission of a fast magnetosonic wave from the ionosphere is related to the existence of the rotational electric field therein. In most past studies on the interaction between the shear Alfvén waves and the ionosphere, the rotational electric field in the ionosphere has been ignored (*e.g.*, GLASSMEIER, 1983, 1984; KIVELSON and SOUTHWOOD, 1988; HAMEIRI and KIVELSON, 1991). HAMEIRI and KIVELSON (1991) derived the irrotationality of the ionospheric electric field from an order estimation of the magnetic field in the atmosphere and ionosphere, then obtained a deriving equation of the 1st-order Alfvén mode variable by the 0th-order fast mode one and found that the amplitude of the 1st-order Alfvén mode variable was controlled by the ionospheric conductivities. However, they neglected the mode conversion between the shear Alfvén and fast magnetosonic waves in the ionosphere. Even if the inductive (rotational) electric field is relatively smaller in magnitude than the static (divergent) one, one should not ignore it, to obtain a self-consistent physical picture of the interaction between the MHD waves and the ionosphere. It will be shown in the present paper that the ionospheric induction current due to the inductive electric field, of which the divergent part is the Hall current and the eddy part the Pedersen current, is capable of bringing about effective mode conversion between the shear Alfvén and fast magnetosonic waves. Since we shall develop more detailed discussions on the eigenmode analysis of coupled MHD waves in a future full paper, we will give here only a brief outline of the effect of ionospheric induction current on the MHD waves in the magnetosphere.

2. Ionospheric Induction Current

The ionospheric sheet current $\mathbf{J}_{\perp}^{\mathrm{iono}}$ is given by

$$\mathbf{J}_{\perp}^{\mathrm{iono}} = \Sigma_{\mathrm{P}}\mathbf{E}_{\perp}^{\mathrm{iono}} + \Sigma_{\mathrm{H}}\mathbf{e}_{/\!/} \times \mathbf{E}_{\perp}^{\mathrm{iono}}, \tag{1}$$

with the ionospheric electric field $\mathbf{E}_{\perp}^{\mathrm{iono}}$ and the height-integrated Pedersen and Hall conductivities, Σ_{P} and Σ_{H}. Here, the subscripts // and $\perp$ denote the parts of a vector quantity parallel and perpendicular to the ambient magnetic field $\mathbf{B}_0$, respectively, which is assumed to be uniform and to penetrate the ionosphere vertically, and $\mathbf{e}_{/\!/}$ is the unit vector parallel to $\mathbf{B}_0$. We can always separate the ionospheric electric field into the static (divergent) and inductive (rotational) parts:

$$\mathbf{E}_{\perp}^{\mathrm{iono}} = -\nabla_{\perp}\varphi - \frac{\partial}{\partial t}\mathbf{A}_{\perp}, \tag{2}$$

where φ is a scalar potential and $\mathbf{A}$ a vector one (*e.g.*, TAMAO, 1986; FUJITA and TAMAO, 1988). Then, the ionospheric current is expressed in terms of the divergent current which is connected with the FAC and the eddy current which generates the fast magnetosonic wave in the magnetosphere and the poloidal magnetic disturbance in the neutral atmosphere:

$$\mathbf{J}_{\perp}^{\mathrm{iono}} = -\left(\Sigma_{\mathrm{P}}\nabla_{\perp}\varphi + \Sigma_{\mathrm{H}}\mathbf{e}_{//}\times\frac{\partial}{\partial t}\mathbf{A}_{\perp}\right) - \left(\Sigma_{\mathrm{H}}\mathbf{e}_{//}\times\nabla_{\perp}\varphi + \Sigma_{\mathrm{P}}\frac{\partial}{\partial t}\mathbf{A}_{\perp}\right). \tag{3}$$

When both Σ_{P} and Σ_{H} are horizontally uniform, the first and second terms on the right hand side of eq. (3) are the divergent and eddy parts of the ionospheric current, respectively.

Figure 1 is a flow chart of the mode conversion between the shear Alfvén and fast magnetosonic waves which occur in the ionosphere. The induction current associated with the vector potential is inevitably required for the mode conversion to occur. The Hall part $(-\Sigma_{\mathrm{H}}\mathbf{e}_{//}\times\partial\mathbf{A}_{\perp}/\partial t)$ of the induction current flows as a divergent current, which plays an essential role in the interconnection of MHD waves in the ionosphere and contributes to the closing current to the FAC partly in the case of localized toroidal oscillation and mainly in the magnetospheric cavity oscillation. On the other hand, its Pedersen part $(-\Sigma_{\mathrm{P}}\partial\mathbf{A}_{\perp}/\partial t)$ flows an eddy current, which makes minor and major contributions to the magnetic flux originat-

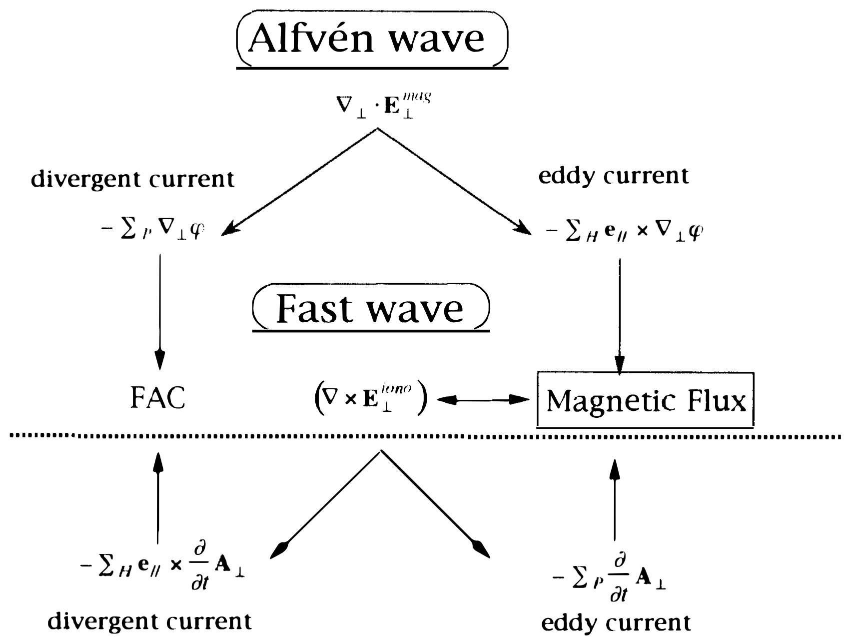

Fig. 1. Flow chart of mode conversion between the shear Alfvén and fast magnetosonic waves which occur in the anisotropically conducting ionosphere. See the text.

ing in the ionosphere in the former and latter cases, respectively.

Figure 3 of TAMAO (1984) shows the similar concept for such an ionospheric response to the incidence of ducted shear Alfvén and fast magnetosonic waves propagating along a vertical magnetic field line. However, since only the direct response to the incident wave is treated in his paper, the Hall current due to the inductive electric field is neglected in case of the incidence of shear Alfvén wave.

3. Model and Results

3.1. Model

We employ a rectangular box model for the magnetosphere in the eigenmode analysis (Fig. 2). The ambient magnetic field $\mathbf{B}_0$ is assumed to be uniform and to penetrate the northern and southern ionospheres vertically (the z axis is taken to be parallel to $\mathbf{B}_0$), and the background cold magnetized plasma to be homogeneous along the magnetic field lines as well as in the azimuthal (y) direction but to be inhomogeneous in the radial (x) direction. The northern and southern ionosphere are regarded as anisotoropically conducting thin sheets with height-integrated Hall and Pedersen conductivities, Σ_P, Σ_H, and the equatorial ionosphere as an conducting thin sheet with the height-integrated Cowling conductivity $\Sigma_C(=1.83\times10^{12}\,\mathrm{esu})$. In the following the height-integrated conductivities in the northern and southern ionospheres are assumed to be horizontally uniform and symmetric. Further, the neutral atmosphere is regarded as an insulating region, the solid earth as a perfect conductor and the magnetopause also as a perfect reflector. The radial size of the magnetospheric box is $9\,r_E$ and the length of a magnetic field line also $9\,r_E$, where r_E ($=6378$ km) is the earth's radius. The height of the ionosphere, d, is 100 km. The radial profile of the Alfvén velocity V_A is given by

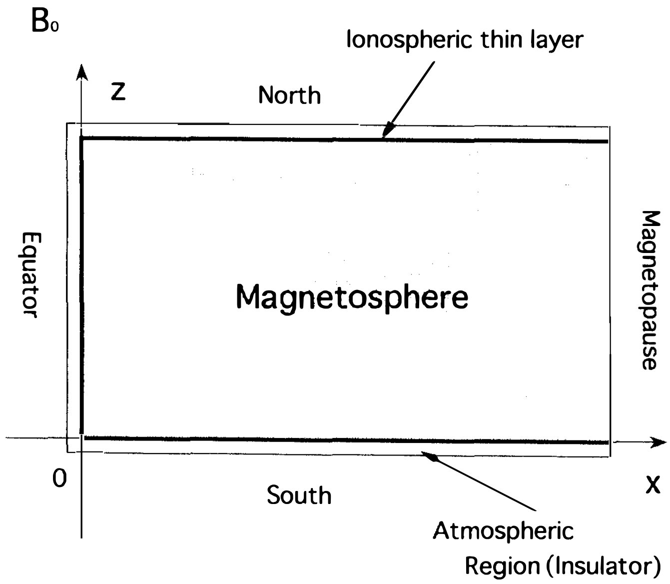

Fig. 2. Schematic illustration of a rectangular box model for the magnetosphere-ionosphere system.

$$V_A(x) = V_{A0}(10/(x/r_E + 1))^2,$$

where V_{A0} is 303.3 km/s. Therefore, the Alfvén wave conductance $\Sigma_A = 1/(\mu_0 V_A)$, where μ_0 is the magnetic permeability of vacuum, varies with the radial coordinate x.

To solve the eigenvalue problem, we assume an electromagnetic perturbation having a spatial and time variation of the form $\exp[i(my - \omega t)]$ with an azimuthal wave number of m and a complex frequency of ω. Our simulation code is incapable of treating the case of $m = 0$ that there exist no coupling between the shear Alfvén and fast magnetosonic waves in the magnetosphere. This incapability is not due to insufficiency of the code but rather comes from an intrinsic property of the model for the magnetosphere-ionosphere system. Further, when the value of m is sufficiently large ($mr_E > \sim 1$), the localized toroidal oscillation cannot be separated from the magnetospheric cavity oscillation owing to their strong coupling. Those oscillations will be demonstrated below. We consider quasi-axisymmetric cases ($mr_E = 10^{-3}$) in which there exists very weak coupling between the MHD waves in the magnetosphere.

The equation that the perturbation electric field $\mathbf{E}_\perp^{\mathrm{mag}}$ in the magnetosphere should satisfy becomes

$$\frac{\omega^2}{V_A^2} \mathbf{E}_\perp^{\mathrm{mag}} - [\nabla \times (\nabla \times \mathbf{E}_\perp^{\mathrm{mag}})]_\perp = 0. \tag{4}$$

As for the derivation of eq. (4), for example, see RADOSKI and CAROVILLANO (1966). A jump between the horizontal perturbation magnetic fields in the magnetosphere ($\mathbf{b}_\perp^{\mathrm{mag}}$) and in the neutral atmosphere ($\mathbf{b}_\perp^{\mathrm{atm}}$) across the ionosphere, which is due to the sheet current $\mathbf{J}_\perp^{\mathrm{iono}}$ flowing therein, is given by

$$\mu_0 \mathbf{J}_\perp^{\mathrm{iono}} = \pm \mathbf{e}_{/\!/} \times (\mathbf{b}_\perp^{\mathrm{mag}} - \mathbf{b}_\perp^{\mathrm{atm}}), \tag{5}$$

where the upper and lower signs correspond to the southern and northern ionospheres, respectively. From the divergence of eq. (5) with its left hand side expressed in terms of eq. (1), we have

$$\Sigma_P \nabla_\perp \cdot \mathbf{E}_\perp^{\mathrm{iono}} - \Sigma_H (\nabla \times \mathbf{E}_\perp^{\mathrm{iono}})_{/\!/} = \pm \frac{i}{\mu_0 \omega} \lim_{\mathrm{mag} \to \mathrm{iono}} \nabla_{/\!/} (\nabla_\perp \cdot \mathbf{E}_\perp^{\mathrm{mag}}), \tag{6}$$

where the first and second terms on the left hand side are the divergent components of the ionospheric currents driven by the static and inductive electric fields, respectively, and the right hand side gives the FAC associated with the shear Alfvén wave. On the other hand, from the parallel component of the rotation of eq. (5), we take

$$\begin{aligned} &\Sigma_P (\nabla \times \mathbf{E}_\perp^{\mathrm{iono}})_{/\!/} + \Sigma_H \nabla_\perp \cdot \mathbf{E}_\perp^{\mathrm{iono}} \\ &\quad = \pm \frac{i}{\mu_0 \omega} \left\{ \lim_{\mathrm{mag} \to \mathrm{iono}} \nabla_{/\!/} (\nabla \times \mathbf{E}_\perp^{\mathrm{iono}}) \mp \frac{1}{d} (\nabla \times \mathbf{E}_\perp^{\mathrm{iono}})_{/\!/} \right\}, \end{aligned} \tag{7}$$

where the first and second terms on the left hand side are the rotational components of the ionospheric currents driven by the static and inductive electric fields, respectively, and the right hand side gives the relation between the fast magnetosonic wave in the magnetosphere and the poloidal magnetic disturbance in the neutral atmosphere. Here, the upper and lower signs in eqs. (6) and (7) also correspond to the southern and northern ionospheres, respectively. Note that we use an approximate relation

$$\lim_{\mathrm{atm}\to\mathrm{iono}} \nabla_{/\!/}(\nabla\times\mathbf{E}_\perp)_{/\!/} \cong \pm\frac{1}{d}(\nabla\times\mathbf{E}_\perp^{\mathrm{iono}})_{/\!/}, \tag{8}$$

in eq. (7). In the neutral atmosphere, the governing equation for $(\nabla\times\mathbf{E}_\perp^{\mathrm{iono}})_{/\!/}$ is

$$\left(\nabla^2+\frac{\omega^2}{c^2}\right)(\nabla\times\mathbf{E}_\perp^{\mathrm{atm}})_{/\!/}=0, \tag{9}$$

where c is the light velocity. To be exact, we have to solve eq. (9) in the neutral atmosphere. However, eq. (8) will be valid for the MHD waves with a scale $l_\perp$ of the horizontal spatial variation such that $k_\perp=2\pi/l_\perp$ is sufficiently small compared with $1/d$. The Courant condition in the neutral atmosphere requires much finer mesh grids than that in the magnetosphere. Since we cannot but utilize a fairly rough mesh grid in numerically solving the eigenvalue problem in the finite difference scheme owing to the limitation of CPU power and memory, the use of eq. (8) is very advantageous. Then, we solve eqs. (4), (6) and (7) as an eigenvalue problem using the finite difference scheme.

3.2. *Localized toroidal oscillation*

It is well known that if the ionosphere can be regarded as a perfect conductor, it behaves like a Joule-loss-free boundary and the energy incident from the magnetosphere is perfectly reflected. Under such a situation, no eddy current flows in the ionosphere and the eigenperiod of field line oscillation is determined only by the Alfvén transit time. In case of the real ionosphere, on the other hand, the divergent electric field which is carried from the magnetosphere to the ionosphere by the shear Alfvén wave drives the Hall current as an eddy current ($-\Sigma_\mathrm{H}\mathbf{e}_{/\!/}\times\nabla_\perp\varphi$). The eddy current produces the magnetic flux and its temporal variation induces a rotational electric field, owing to which the divergent Hall current ($-\Sigma_\mathrm{H}\mathbf{e}_{/\!/}\times\partial\mathbf{A}_\perp/\partial t$) flows. Thus, the FAC is to be closed via not only the Pedersen but also the Hall current (cf. Fig. 1). Taking into account the closing Hall current corresponds to adding an extra loading coil to an LCR circuit equivalent to the magnetosphere-ionosphere current system which is formed by the standing shear Alfvén wave, and so the Hall conductivity controls the time constant of current system.

Figure 3 shows the control of the eigenperiod at given magnetic shells by the Hall conductivity Σ_H. The following three patterns are found according to the ratio of the Pedersen conductivity Σ_P ($=1.83\times10^{12}$ esu) to the Alfvén wave conductance Σ_A:

1) In the case of an insulator-like ionosphere ($\Sigma_\mathrm{P}<(\Sigma_\mathrm{A})_{x/r_\mathrm{E}=8.4}=2.09\times10^{12}$ esu), the eigenperiod of the fundamental increases monotonously with Σ_H (Fig. 3a).

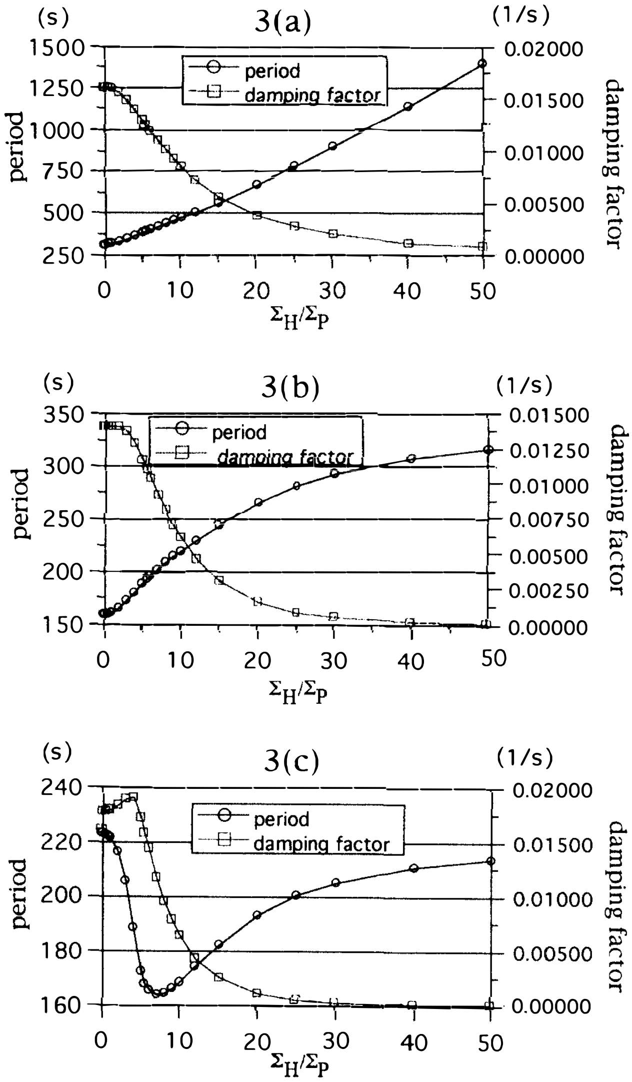

Fig. 3. *Control of the eigenperiod and damping factor by the normalized Hall conductivity Σ_H/Σ_P ($\Sigma_P=1.83\times10^{12}$ esu) for (a) the fundamental in the case of an insulator-like ionosphere ($\Sigma_P<\Sigma_A=2.09\times10^{12}$ esu) at the magnetic shell of $x/r_E=8.4$, (b) for the second higher harmonics in the case of an insulator-like ionosphere ($\Sigma_P<\Sigma_A=2.09\times10^{12}$ esu) at the magnetic shell of $x/r_E=8.4$ and (c) for the fundamental in the case of a conductor-like ionosphere ($\Sigma_P>\Sigma_A=1.36\times10^{12}$ esu) at the magnetic shell of $x/r_E=6.6$.*

2) For all nth harmonics except the fundamental for the insulator-like ionosphere ($\Sigma_P<(\Sigma_A)_{x/r_E=8.4}=2.09\times10^{12}$ esu), the eigenperiod also grows large with Σ_H but converges to the eigenperiod of the $(n-1)$th harmonics for the conductor-like ionosphere (Fig. 3b).

3) For all harmonics including the fundamental for the conductor-like ionosphere ($\Sigma_P>(\Sigma_A)_{x/r_E=6.6}=1.36\times10^{12}$ esu), the eigenperiod first becomes smaller with an increase of Σ_H, then turns to increasing when Σ_H exceeds a critical value, and eventually converges to the value for the perfectly conducting ionosphere (Fig. 3c).

3.3. Magnetospheric cavity oscillation

The rotational electric field that is carried by the fast magnetosonic wave directly drives the Pedersen current as an eddy current ($-\Sigma_P \partial \mathbf{A}_\perp / \partial t$) and the Hall current as a divergent current ($-\Sigma_H \mathbf{e}_{//} \times \partial \mathbf{A}_\perp / \partial t$). In this case the FAC is mainly closed via the Hall current (cf. Fig. 1).

Since the magnetospheric cavity mode principally consists of the poloidal electric field, its eigenstate is discretized according to the size of the magnetospheric cavity, and the rotational electric field prevails in the overall ionosphere. Then, there can exist a global monochromatic toroidal oscillation which is induced via the divergent Hall current and is quite different from the usual localized toroidal oscillation that can occur only in the vicinity of a specific magnetic shell.

Figure 4 illustrates the amplitude of poloidal and toroidal electric fields in the fundamental magnetospheric cavity mode whose eigenperiod is closely related to that of the fundamental decoupled poloidal mode. If the shear Alfvén wave is weakly coupled with the fast magnetosonic wave in the magnetosphere and there exists no coupling between those waves in the ionosphere, the toroidal electric field is strongly enhanced only in the vicinity of a specific magnetic shell whose eigenfrequency matches that of the poloidal cavity mode. Because of the coupling via the divergent Hall current, however, the toroidal oscillation occurs globally and its parallel wavelength varies according to a distribution in the Alfvén velocity, as found in the right panel of Fig. 4.

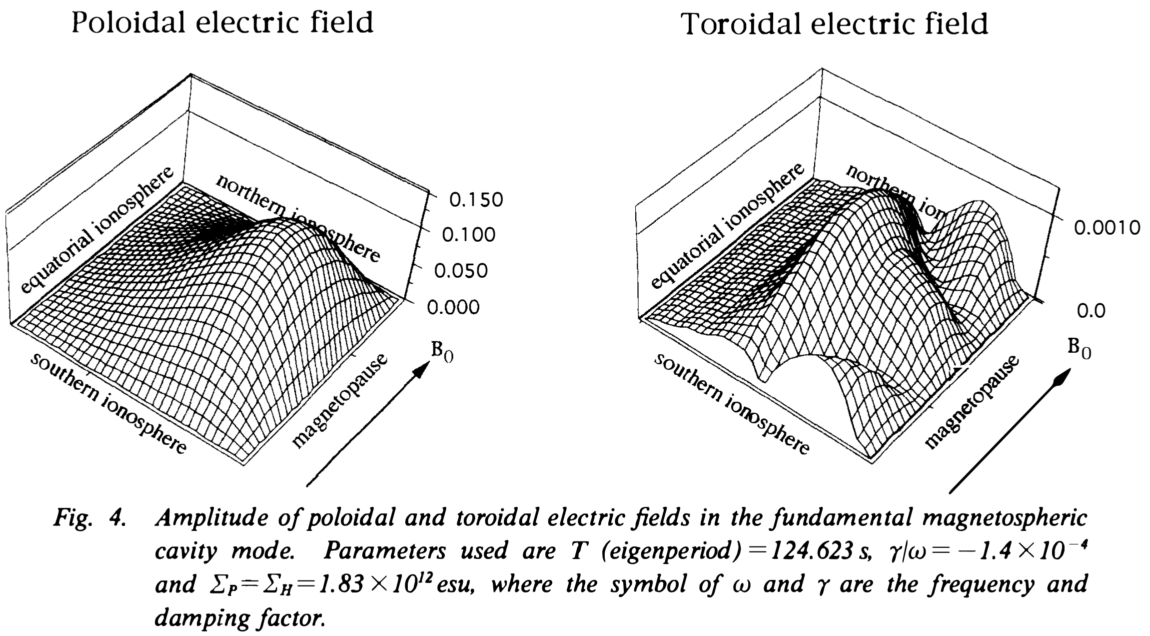

Fig. 4. Amplitude of poloidal and toroidal electric fields in the fundamental magnetospheric cavity mode. Parameters used are T (eigenperiod) = 124.623 s, $\gamma/\omega = -1.4 \times 10^{-4}$ and $\Sigma_P = \Sigma_H = 1.83 \times 10^{12}$ esu, where the symbol of ω and γ are the frequency and damping factor.

4. Summary and Discussion

The eigenvalue problem for coupled MHD waves interacting with the anisotropically conducting ionosphere has been solved numerically by using a rectangular box model for the magnetosphere, and the effect of the ionospheric induction current on the MHD waves in the magnetosphere has been examined. The initial results obtained are as follows:

1) The eigenperiod of the localized toroidal (shear Alfvén mode) oscillation is effectively controlled by the height-integrated Hall conductivity.

2) A global monochromatic toroidal oscillation is excited by the fast magnetosonic wave via the ionospheric induction current.

When the shear Alfvén wave is incident from the magnetosphere, the ionospheric eddy current ($-\Sigma_{\mathrm{H}}\mathbf{e}_{/\!/}\times\nabla_{\perp}\varphi$) driven by the divergent electric field produces the magnetic flux, its temporal variation induces the rotational electric field, and the Hall part of the resulting ionospheric induction current ($-\Sigma_{\mathrm{H}}\mathbf{e}_{/\!/}\times\partial\mathbf{A}_{\perp}/\partial t$) is fed back into the FAC.

TAMAO (1975, 1984) discussed the time response of the magnetosphere-ionosphere current system in terms of an equivalent circuit model. ROSTOKER and LAM (1978) studied a generation mechanism of Pc5 geomagnetic pulsations by regarding the magnetosphere-ionosphere system as an LCR circuit. Taking into account the divergent Hall current ($-\Sigma_{\mathrm{H}}\mathbf{e}_{/\!/}\times\partial\mathbf{A}_{\perp}/\partial t$) corresponds to adding an extra loading coil to their LCR circuit. Such a coil represents an alternating storage and release of energy in the ionosphere. Thus, the Hall conductivity controls the time constant of the current system effectively.

When the fast magnetosonic wave is incident from the magnetosphere, the rotational electric field directly drives the Pedersen current as an eddy current ($-\Sigma_{\mathrm{P}}\partial\mathbf{A}_{\perp}/\partial t$) and the Hall current as a divergent current ($-\Sigma_{\mathrm{H}}\mathbf{e}_{/\!/}\times\partial\mathbf{A}_{\perp}/\partial t$), and the FAC is produced as a divergence of the Hall current. Our result (Fig. 4) suggests that there may exist an overall monochromatic toroidal oscillation in the region where the fast magnetosonic wave is incident.

Finally, we mention two problems concerning our model. One is the validity of eq. (8). In the case of localized toroidal (shear Alfvén mode) oscillation, its horizontal width may violate this approximation, although we cannot give any definite answer to this problem owing to the rough mesh grid in our model. However, we believe that the control of eigenfrequency of the localized toroidal oscillation by the ionospheric Hall conductivity would hold independently of the validity of eq. (8), because it can be physically interpreted. The other is whether the localized toroidal oscillation exist for $m=0$ or not. When $m=0$, the shear Alfvén wave is not driven directly by the fast magnetosonic wave in the magnetosphere but is generated indirectly via the ionospheric Hall current. Hence, the shear Alfvén wave is only a subsidiary existence in the magnetosphere-ionosphere system. Thus, we maintain that the localized toroidal oscillation, where the shear Alfvén wave plays a primary role and the fast magnetosonic wave is only a subsidiary existence, cannot occur for $m=0$. More detailed research into these problems should be done as future work.

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