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MHD RESPONSES OF A MODEL MAGNETOSPHERE TO MAGNETOPAUSE PERTURBATIONS

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We have developed a simple MHD computer code that simulates transient responses of a "box" magnetosphere, having inhomogeneties of Alfvén speed distribution in the radial direction, with respect to poloidal magnetopause perturbations of a variable initial wave form. An impulsive magnetopause perturbation with a small azimuthal wave number and a broad-band frequency under quiet geomagnetic condition, is confirmed to stimulate the magnetospheric cavity resonance composed of different harmonics which further ouple into the toroidal Alfvén resonances, where the eigen periods match those of the cavity harmonic waves. Another impulsive magnetopause perturbation, having a larger azimuthal wave number and a lower band frequency under disturbed geomagnetic condition, can excite a transient Alfvén resonance oscillation in the outer magnetosphere, of which amplitude and period decrease with increasing the distance from the magnetopause. The frequency range and azimuthal wave number of the initial magnetopause perturbations and the plasmapause position associated with the geomagnetic activity are found to be key parameters, controlling which of the localized toroidal Alfvén, the transient Alfvén, and the magnetospheric cavity resonances is predominantly stimulated in the model magnetosphere. The change in the Alfvén speed distribution plays more important role and dominates the magnetospheric cavity resonance process.

1. Introduction

Inhomogeneities in the magnetosphere are regarded as important in the mode coupling of low-frequency hydromagnetic (HM) wave and allow the excitation of field-line resonance by a fast mode of magnetosonic source wave in the outer magnetosphere. In order to explain a continuous Pc-type pulsation, many researchers [e.g., Tamao, 1965; Radoski, 1971; Chen and Hasegawa, 1974; Southwood, 1974; Junginger, 1985; Yumoto, 1985] have been theoretically examined characteristics of resonant HM waves excited by steady state source with a monochromatic frequency, e.g., surface waves in the magnetospheric boundary and upstream waves in the earth's foreshock [see review of Yumoto, 1988]. However, most of the field-line resonance theories are a stationary model that assumes continuous source wave with a monochromatic (or discrete) frequency at the magnetopause, in the earth's foreshock, and in the magnetospheric cavity. Kivelson and Southwood [1985, 1986] and Allan et al., [1985, 1986] recently demonstrated a possibility that impulsively-stimulated compressional cavity wave can drive local field-line resonance where the cavity period matches that of the uncoupled torsional field-line oscillation, in order to explain why an observed resonance response of the magnetosphere was dominated by a discrete frequency.

There is a few theoretical model available for the transient stage, i.e., when impulsive and continuous source wave activities are switched on the magnetopause. Using the Laplace transform methods, Allan *et al.* [1985, 1986] could give general time-dependent solutions at the finite-difference grid points in x in the magnetosphere with respect to transient perturbation. They demonstrated that even harmonics of the cavity mode, having a node on the plasmapause were all enhanced compared with the odd harmonics without a node on the plasmapause. Employing somewhat different techniques, Inhester [1987] also investigated the dependence of the magnetospheric response from the plasmapause to the magnetopause on the azimuthal wave number of the magnetopause perturbation.

In the present study, using the simple rectangular box-like magnetosphere model from the earth's surface to the magnetopause, in which the Alfvén speed distribution with a rapid change at the plasmapause depends on the geomagnetic activity, we have developed a computer code that simulates the electromagnetic response of the simplified magnetosphere with respect to the magnetopause perturbations of variable initial wave forms.

2. Theoretical Model

In the present simulation we employed the following linearlized MHD equations for one-fluid model with isotropic pressure and compressible plasmas:

$$\rho_{om}\partial\vec{v}/\partial t = -\nabla P_1 + \mu_o^{-1}[(\nabla\times\vec{b})\times\vec{B}_o + (\nabla\times\vec{B}_o)\times\vec{b}], \quad (1)$$

$$\partial P_1/\partial t = -\gamma P_o(\nabla\cdot\vec{v}) - (\vec{v}\cdot\nabla)P_o, \quad (2)$$

$$\partial\rho_{1m}/\partial t = -\rho_{om}(\nabla\cdot\vec{v}) - (\vec{v}\cdot\nabla)\rho_{om}, \quad (3)$$

and

$$\partial\vec{b}/\partial t = \nabla\times(\vec{v}\times\vec{B}_o), \quad (4)$$

where ρ_{om}, $\vec{B}_o$, and P_o are unperturbed terms of the ambient mass density, magnetic field, and kinetic pressure, respectively, and are assumed to satisfy the condition of $\nabla(P_o + B_o^2/2\mu_o) = 0$ in the model magnetosphere. $\rho_{1m}, \vec{b}, P_1$ and $\vec{v}$ are perturbations of the mass density, magnetic field, kinetic pressure, and plasma drift velocity, respectively.

Mean wave Poynting vectors and field-aligned current of HM waves in the model magnetosphere can be derived from the plasma drift velocity by Ohm's and Faraday's laws as follows:

$$\vec{S} = (\vec{E}\times\vec{b}^*)/\mu_o = B_o/\mu_o(v_x b_z^*, v_y b_z^*, -v_x b_x^* - v_y b_y^*), \quad (5)$$

and

$$J_{||} = (\nabla\times\vec{b})_z/\mu_o, \quad (6)$$

where the superscript * indicates the conjugate complex.

Geometry and boundary conditions of a simplified "box" magnetosphere model are illustrated in Fig. 1. The homogeneous ambient magnetic field $\vec{B}_o$ is directed along the z-axis. At $z = 0$ and $z = 1$, boundary surfaces of finite conductivity have been introduced, which correspond to the southern and northern "ionospheres", respectively. At the magnetopause corresponding to $x = 0$, a source wave with perturbation of plasma drift velocity in the radial, x direction is assumed to be propagating into the azimuthal, y direction;

$$v_x = v_{xo}(t)[c_1 e^{ik_{||}(z-0.5)} + c_2 e^{-ik_{||}(z-0.5)}]e^{imy}, \quad (7)$$

where $k_{||}$ and m are parallel and azimuthal wave numbers, respectively. c_1 and c_2 are arbitrary constants determined by the ionospheric boundary condition. Eq. (7) holds only for the situation when the oscillation has reached its steady state and transients that propagate the information along the field-line have died out. In this paper our considerations are stressed mainly on the magnetospheric plasma response in the radial, x direction with respect to the magnetopause perturbation. The boundary at $x = 1$ corresponds to the "dayside ionosphere" at lower latitude of $|\Phi|\lesssim 22^\circ$, where the magnetic lines of force are almost entirely in the ionosphere, and act like a solid wall with the boundary condition of $v_x = 0$.

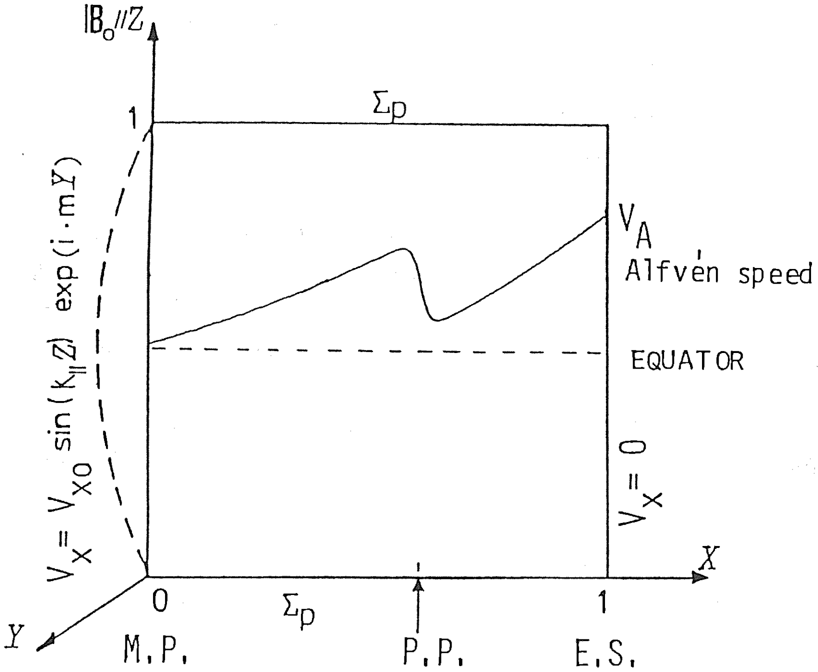

Fig. 1. Geometry and boundary conditions of a "box" magnetosphere. The magnetic field is in the z direction. Boundaries at $z = 0$ and 1 correspond to the southern and northern "ionosphere", respectively, with a finite conductivity Σ_p. The Alfvén velocity varies in the radial, x direction. Radial positions of $x = 1.0, 0.6$, and 0.0 correspond to the earth's surface (ES), the plasmapause (PP), and the magnetopause (MP), respectively, in a model magnetosphere. The y axis is in the azimuthal direction.

Neglecting small transformations into magnetosonic modes at the reflection levels and the Hall currents in the higher-latitude ionospheres, we obtain the following boundary conditions at $z = 0$ and $z = 1$ for Alfvén mode [see Southwood and Hughes, 1983; Pilipenko *et al.*, 1986],

$$[\Sigma_p \partial E_A/\partial t \pm (\partial E_A/\partial z)/\mu_o]_{z=0,1} = 0, \tag{8}$$

where $E_A = \nabla_\perp \cdot \vec{E}_\perp$ and Σp is the integrated Pedersen conductivity in the ionosphere. Substituting eq. (7) into eq. (8), we can express the boundary conditions (8) as

$$k_{||} = n - iIn|R|, \tag{9}$$

with $c_2 = -Rc_1 e^{-ik_{||}}$ and n is an integer. Here R is a coefficient of wave reflection from the "ionospheres", and

$$R = (\Sigma_p - \Sigma_A)/(\Sigma_p + \Sigma_A), \tag{10}$$

where $$\Sigma_A = -ik_{||}/[\mu_o(InE_A)/\partial t]. \tag{11}$$

The order of magnitude of the Pedersen conductivity Σp in the model is determined by the condition that the ionospheric resistivity is less than the wave impedance of the shear Alfvén wave in the dayside magnetosphere, *i.e.*, $\Sigma p > \Sigma_A$.

A radial variation of the Alfvén speed $V_A = B_o/(\mu_o \rho_{om})^{1/2}$ in the model magnetosphere is approximately given by a solid curve in Fig. 1, and expressed by

$$V_A^2 = V_{Ao}^2(c+x)^d/[(c+x)^4 + a(1+\tan h(x-x_{pp})/b)], \tag{12}$$

where $(c+x)$ with a constant c is the radial coordinate in the equatorial plane. The ambient magnetic field is assumed to be homogeneous, while the mass density in the model magnetosphere is expressed as a function of the radial coordinate. A rapid change of the plasma density at the plasmapause of $x = x_{pp}$ is described using characteristic parameters a (amplitude) and b (width). Empirical models of the average magnetospheric Alfvén speed were also given by Moore *et al.* [1987]. The square of the sound velocity $V_s^2 = \gamma P_o/\rho_{om}$ is given by $\beta_1 V_A^2$, where the plasma β-ratio is $2\beta_1$.

The model is thus completely specified by eqs. (1)–(4), (7), (9), and (12). Solutions for the inhomogeneous problem have been obtained numerically as one dimensional simulation in the radial x direction, in which the total number of grid is one hundred, by means of an explicit and centered finite difference scheme.

3. Simulation Results

In order to examine the response of the model magnetosphere to external stimulus, a radial motion of the magnetopause boundary was assumed to be time-depending as follows:

$$v_{xo}(t) = v_{xo}\ exp(-|t-t_o|^2/T^2)\ e^{-i\omega t}, \tag{13}$$

where t_o, T, and ω are a characteristic onset time, a time duration, and a dominant frequency, respectively, of the magnetopause stimulation. In the present study boundary conditions of HM oscillations excited by the magnetopause perturbation were further assumed to be $dv_y/dx = db_z/dx = d\rho_{1m}/dx = 0$ at the magnetopause of $x = 0.0$, indicating that the excited oscillations have maximum amplitudes at the magnetopause. Ionospheric Pedersen conductivity Σ_p was chosen to ensure that electric wave field $(\vec{E}_\perp)$ has a "near-node" in the "ionospheres", from which the coefficient

(R) of wave reflection is 0.98 for $\Sigma_A/\Sigma_p = 10^{-2}$. The larger ionospheric conductivity yields only a small damping of the field-line resonance oscillation. Newton *et al.* [1978] have shown for standing field-line oscillations in the earth's magnetosphere the approximate relation of the damping (γ) due to the ionospheric Joule dissipation ($\gamma \sim 10^{-1}\Sigma_P^{-1}L^{-1}$), where L is the McIlwain shell parameter, and γ and Σ_P are given in s^{-1} and mho. In our model magnetosphere, the damping caused by the incomplete ionospheric reflection is about $\gamma \sim 10^{-2}s^{-1}$ for $\Sigma_P = 10^2\Sigma_A$, $\Sigma_A \sim 0.02mho$, $L = 5$ and $\omega = \pi s^{-1}$.

3.1 Localized Alfvén resonance excited by a monochromatic source.

We first investigate the magnetospheric response to the magnetopause perturbation with a narrow-band frequency. Recently, Sibeck *et al.* [1989] and Potemra *et al.* [1989] found that the periodic solar wind density variations produce the electromagnetic field oscillations at the magnetopause, which are correlated with magnetic pulsations in the dayside magnetosphere.

Figure 2 shows an example of simulation results, illustrating histories of the plasma drift velocity v_x and v_y, the magnetic perturbation field b_z, and the plasma density fluctuation ρ_{1m} in the equatorial plane at $z = 0.5$, and the field-aligned current $J_{||}$ associated with HM resonance waves in the northern ionosphere at $z = 1.0$. Simulation parameters in the model magnetosphere with cold plasma were given by $|v_{xo}|/V_{Ao} = 0.01/0.6$, $\beta_1 = 0.0$, $a = 15.0$, $b = 0.02$, $c = 0.8$, $d = 10$, and $x_{pp} = 0.6$. The ordinate is the radial, x axis, and then positions of $x = 0.0$, 0.6, and 1.0 correspond to the magnetopause, the plasmapause, and the earth's surface, respectively, in the model magnetosphere. The abscissa indicates the time axis (t) normalized by the half period of the source wave ($T_o/2 = \pi/\omega$). The amplitudes of v_x, v_y, b_z, ρ_{1m}, and $J_{||}$, respectively, are normalized by v_{xo}, v_{xo}, $B_o v_{xo}/V_{Ao}$, $\rho_{om} v_{xo}/V_{Ao}$, and $\mu_o^{-1} B_o k_{||} v_{xo}/V_{Ao}$. The compressional source wave at the magnetopause (MP) has a narrow-band frequency ($\omega = \pi$) as shown in the power spectrum in the left-side top panel and a packet-like structure with $t_o = 18$ and $T = 12$ in eq. (13) as illustrated in the v_x panel. Wave numbers of the source wave are $m/k_{||} = -0.3$ and $k_{||} = \pi$. Candidates for the external source wave with a narrow-band frequency are upstream waves driven by reflected ion beams in the earth's foreshock, surface waves excited by the Kelvin-Helmholtz type instability in the finite magnetospheric boundary layer [see review of Yumoto, 1988], and the periodic solar wind density variations [Sibeck *et al.*, 1989; Potemra *et al.*, 1989]. The right-side top panel shows radial variation of the Alfvén frequency, which is consistent with the local frequency of toroidal standing field-line oscillations in the model magnetosphere. A rapid change of the Alfvén frequency corresponds to the plasmapause at $x = 0.6$.

It is noteworthy how the poloidal compressional source wave (v_x) with $m/k_{||} = -0.3$ at the magnetopause propagates into the magnetosphere, and excites toroidal

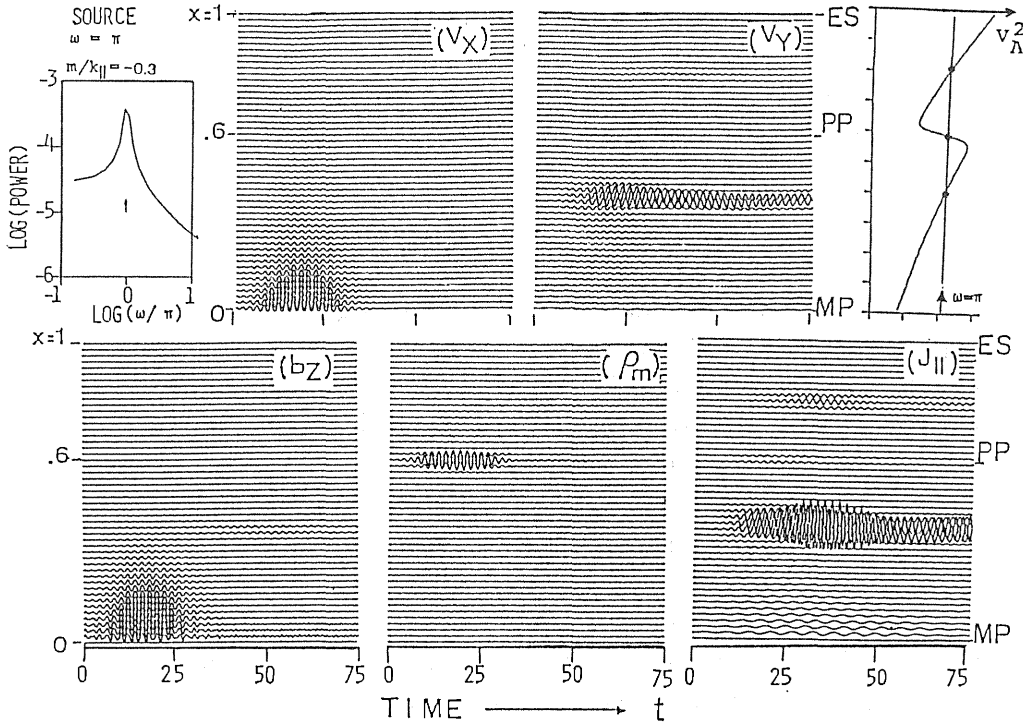

Fig. 2. HM resonance oscillations (v_y, $J_{||}$) excited by a monochromatic source wave (v_x) at the magnetopause (MP). Left-side top panel shows a power spectrum of the driving source wave (v_x). Right-side top panel shows a relation between the dominant source frequency (ω) and the radial variation of Alfvén frequency (ω_A) in the model magnetosphere. v_x, v_y, b_z, ρ_m and $J_{||}$ -panels illustrate histories of the plasma drift velocities in the radial and azimuthal directions, the magnetic field perturbation, and the plasma density fluctuation in the equatorial plane ($z = 0.5$), and the field-aligned current of excited waves in the northern ionosphere ($z = 1.0$), respectively. The abscissa indicates the time axis normalized by the half period of the source wave (π/ω).

Alfvén resonance oscillations (v_y) at $x = 0.39$ and 0.8 in the magnetosphere and a surface wave on the plasmapause ($x = 0.6$), wherever the nearly monochromatic frequency (ω) of compressional source wave matches the local Alfvén frequency (ω_A). The compressional damped oscillation at the magnetopause is recently called a fast mode of MHD surface wave, which is one of the most important subject of recent theoretical investigations associated with Alfvén-wave heating in the fusion plasma [e.g., Appert *et al.*, 1984; Amagishi, 1986]. A surface wave excited on the plasmapause shows an enhancement of density fluctuation (ρ_{1m}). Even if the resonance is due to the shear Alfvén wave, the density fluctuation in the inhomogeneous plasma, expressed by $-(\partial\rho_{1m}/\partial t) = \rho_{om}[\partial v_x/\partial x(\omega^2 - \omega_A^2)\{\omega^2 - V_A^2(m^2 + k_{||}^2)\}^{-1} + v_x \partial(In\rho_{om})/\partial x]$ for $\beta =$ 0.0, can be perturbed near the plasmapause, because of $-(\partial\rho_{1m}/\partial t) = v_x \partial\rho_{om}/\partial x$ for $\omega^2 = \omega_A^2$ and the larger, rapid change of the ambient plasma density across the plasmapause, and the driving source component (v_x). Enhancements of field-aligned currents ($J_{\|}$) can be seen around the resonance points near $x = 0.39, 0.6$, and 0.8.

The toroidal plasma velocity (v_y) variation with time dependence of $e^{-i\omega t}$ in an inhomogeneous cold plasma is given by Yumoto *et al.* [1987] as follows:

$$v_y \simeq imV_A^2[\omega^2 - V_A^2(m^2 + k_{\|}^2)]^{-1}\partial v_x/\partial x. \tag{14}$$

The toroidal v_y variation is stimulated by the radial gradient of poloidal velocity of propagating compressional wave from the magnetopause, and then should be composed of the compressional and the excited Alfvén waves. The small inward directed difference at the early time ($t < 25$) in the v_x, v_y, and b_z panels in Fig. 2 indicates an inward propagation of the compressional magnetopause wave. On the other hand, the field-aligned current, expressed by $J_{\|} \simeq (k_{\|}B_o/\omega\mu_o)v_y(\omega^2/V_A^2 - k_{\|}^2)^{-1}\partial(\omega^2/V_A^2)/\partial x$, is logarithmically enhanced in the Alfvén resonance regions of $\omega^2 \simeq V_A^2k_{\|}^2$. The small amplitude v_y variation, different from the $J_{\|}$ at the early time ($t < 25$) in Fig. 2, indicates the component of propagating compressional (b_z) wave from the magnetopause.

The width of excited field-line resonance in the radial, x direction is controlled both by the scale of inhomogeneity gradient and by the amount of dissipation [cf. Southwood and Hughes, 1983]. In the present case of our model magnetosphere with a higher coefficient of wave reflection from the ionosphere ($R = 0.98$), the width of the field-line resonance varies inversely as the inhomogeneity gradient. The ratio (~ 6) of the scale of Alfvén speed gradient around the plasmapause of $x_{pp} = 0.6$ to that at the resonance point of $x = 0.39$ is consistent with the ratio of the width of field line resonance at $x = 0.39$ to that at the plasmapause. It is also noteworthy that directions of phase propagations in the resonant part of v_y and $J_{\|}$ oscillations are all outward. Since the eigen frequency $\omega_A = V_Ak_{\|}$ decreases towards the magnetopause, field-lines further out lag behind the oscillation at field-lines further inward. The resonance oscillations in the $J_{\|}$ panel can be detected on the ground, and should be categorized as the continuous Pc magnetic pulsations. It is confirmed that a poloidal magnetopause perturbation with a wave-packet structure and a narrow-band frequency can propagate into the magnetosphere, and drive HM resonance oscillations, *i.e.*, Alfvén modes in the outer and inner magnetosphere and surface wave on the plasmapause, wherever the nearly monochromatic frequency of the compressional source wave matches the individual eigen frequency of torsional field-line oscillations.

A dependence of magnetospheric responses on azimuthal wave number of the magnetopause perturbation with a narrow-band frequency is demonstrated in Fig. 3. From left-side top to right-side bottom, normalized azimuthal wave numbers $|m/k_{\|}|$ of the source wave are increasing. The other simulation parameters are the same as in Fig. 2. Histories of the plasma drift velocities v_x and v_y in the equatorial plane at $z = 0.5$ are illustrated for each azimuthal wave number. For smaller azimuthal wave number of $|m/k_{\|}| < 1$, the poloidal source wave can penetrate into the inner

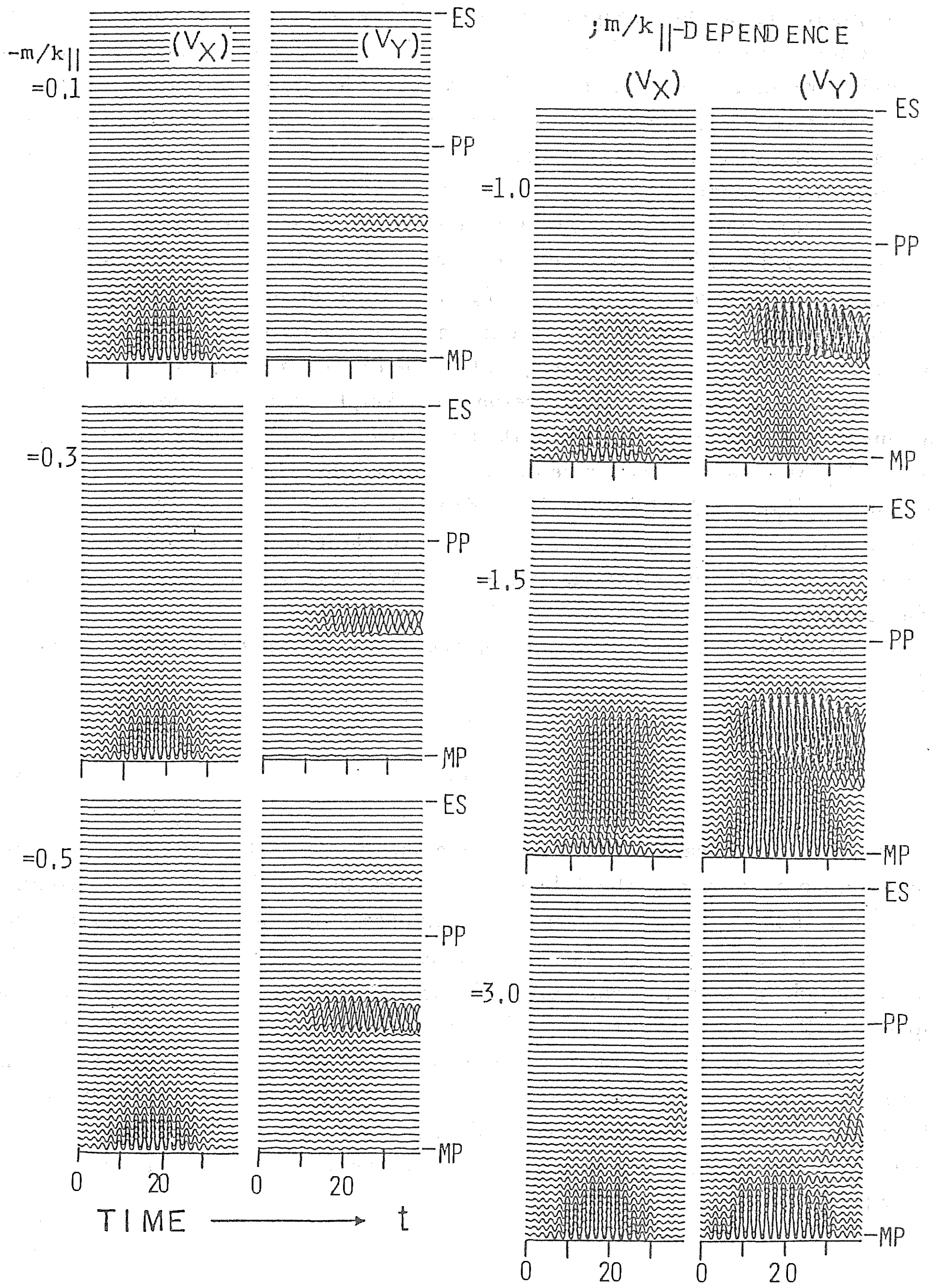

Fig. 3. Azimuthal wave number ($-m/k_{||}$ for $k_{||} = \pi$) dependence of HM resonance oscillations (v_y) excited by the monochromatic magnetopause perturbation (v_x at MP) in the equatorial plane. The other simulation parameters are the same as in Fig. 2.

magnetosphere. Then, the strength of coupling of the compressional source wave (v_x) to the resonant toroidal Alfvénic oscillation (v_y) increases linearly with increasing the azimuthal wave number (see eq. (14)). On the other hand, for azimuthal wave number of $|m/k_{||}| = 1.0, 1.5$, and 3.0 the magnetospheric cavity modes are also stimulated around $x = 0.35, 0.25$ and 0.1, respectively. For the larger azimuthal wavenumber amplitudes of the magnetopause source wave, except for the cavity resonance components, are more rapidly damped with radial distance from the magnetopause. The v_y variations consist of the Alfvén resonance wave at $x = 0.39$ and the compressional cavity resonance wave around $x = 0.32$ (b_z; not shown in the figure). The apparent "outward reflection" near the Alfvén resonance region is not due to the reflection of the compressional wave at the resonance layer, but due to the superimposed v_y component of the compressional magnetospheric resonance. Amplitudes of the compressional v_y variations at $x \lesssim 0.3$ are proportional to the normalized azimuthal wave number $|m/k_{||}|$ (cf. eq. (14)), whereas the Alfvén resonance v_y components at $x = 0.39$ are dropped rapidly for $|m/k_{||}| > 2.0$. It can be concluded that the source waves having a larger azimuthal wave number, propagating almost into the azimuthal direction, can not penetrate deeply into the inner magnetosphere, and then amplitudes of the excited Alfvén resonance oscillations decrease with increasing the azimuthal wave number.

A dimensionless coupling parameter [see Speziale and Catto, 1977; Kivelson and Southwood, 1986]

$$q \simeq m^2/(k_{||}^2 V_A^2 \partial V_A^{-2}/\partial x)^{2/3} \tag{15}$$

can be formed which was found to determine the strength of coupling between the fast magnetosonic wave and the Alfvén wave. It has been found for monochromatic source waves that the coupling efficiency maximizes at $q \simeq 0.5$, which in our model corresponds to $|m/k_{||}| \sim 1.5$. The amplitudes of excited field line resonances did not vary significantly in the comparatively broad range $|m/k_{||}| = 0.5$ to 1.8, and dropped rapidly outside this range. The broader azimuthal wave number range is in agreement with the results in the similar model geometry of Inhester [1987]. The Alfvén resonance oscillations in our model magnetosphere are most effectively excited by the magnetopause perturbation with azimuthal wave number comparable to field-aligned component, which is consistent with the works of Allan *et al.* [1986] and Inhester [1987].

3.2. Impulsively-stimulated magnetospheric cavity and transient Alfvén resonances.

The response of the simplified magnetosphere to impulsively-stimulated compressional waves is also investigated in order to clarify how selected field-line resonances are excited by broad-band sources. The sudden impulsive external sources are, for example, a tailward traveling, large-scale magnetopause surface wave with a single rarefaction/compression pulse caused by the passage either of an interplanetary shock or discontinuity [Fig. 14 of Nishida, 1978] and a sporadic multiple x-line reconnection process at the dayside magnetopause [Lee *et al.*, 1988].

We first analyzed weakly coupled cases ($m/k_{||} = -0.01$) to determine the structure of magnetospheric cavity resonances in our model magnetosphere. The bottom panels of Fig. 4a detail the three Alfvén speed distribution within the magnetosphere used in the present paper. The V_A outside the plasmapause varies proportional to $(c+x)^3$, where $c = 0.8$ and $d = 10$ of eq. (12). The characteristic parameters of the plasmapause at $x_{pp} = 0.4, 0.6$, and 0.7 are chosen as a (density change) $=$ 15.0 and $b(width) = 0.02$. The plasmapause at $x_{pp} = 0.4$ (equivalent position of $L = 6$) and at $x_{pp} = 0.7 (L = 3)$ represent situations likely to occur under quiet and disturbed geomagnetic conditions, respectively. The impulsive source wave with amplitude of $v_{xo}/V_{Ao} = 0.02/1.0$ and broad band frequency of $\omega = 5.0 * \pi, T = 0.1$ and $t_o = 10$ was stimulated at the magnetopause (see ω_{source} in the left panel of Fig. 4b). Power spectra of the excited cavity resonance oscillations (v_x) at $x = 0.2$ in the three model magnetospheres were calculated in Figure 4b. There are various, decomposed eigen frequencies of compressional harmonics of the cavity with the odd modes ($\omega_1, \omega_3, \omega_5, ...\omega_{2n+1}$) and the even modes ($\omega_2, \omega_4, \omega_6, ...\omega_{2n}$) for each model magnetosphere. The harmonic frequencies of ω_1 are constant over the whole cavity. The odd modes of ω_{01} and ω_{02} have smaller amplitudes and turning points [e.g. Kivelson *et al.*, 1984] in the outer magnetosphere ($x < 0.4$) as shown in the bottom panel of Fig. 4a. In the bottom panels also shown are the lower part of the corresponding harmonic resonance eigen-frequencies normalized by the field-aligned wave number ($\omega_n/k_{||} < 5.0, k_{||} = \pi$). It is noteworthy that the eigen frequencies ($\omega_n, n \gtrsim 1$) of the magnetospheric cavity modes increase with increasing the distance of the plasmapause from the magnetopause, *i.e.*, approximately proportional to the geomagnetic activity.

The top panels of Fig. 4a show relative absolute amplitudes of the poloidal plasma velocity v_x of compressional cavity harmonics in the three radial Alfvén speed distributions within the magnetosphere. The fundamentals (ω_1) of magnetospheric cavity waves are no longer the dominant harmonic, that is in agreement with the result of Allan *et al.* [1986]. Allan et al. demonstrated that the harmonics with node on or near the plasmapause were enhanced, while those with near-antinode on the plasmapause were attenuated. However, such a clearer plasmapause dependence of the cavity resonance amplitudes can not be confirmed in the present model magnetosphere (see the top panels of Fig. 4a). The averaged Alfvén speed in the magnetosphere is a function of the position of the plasmapause, related to the geomagnetic activity, and determines the structures of eigen-frequencies and amplitudes of the cavity modes. Especially, the eigen frequency of magnetospheric cavity modes is proportional to the averaged Alfvén speed, and becomes higher in the higher magnetic activity condition.

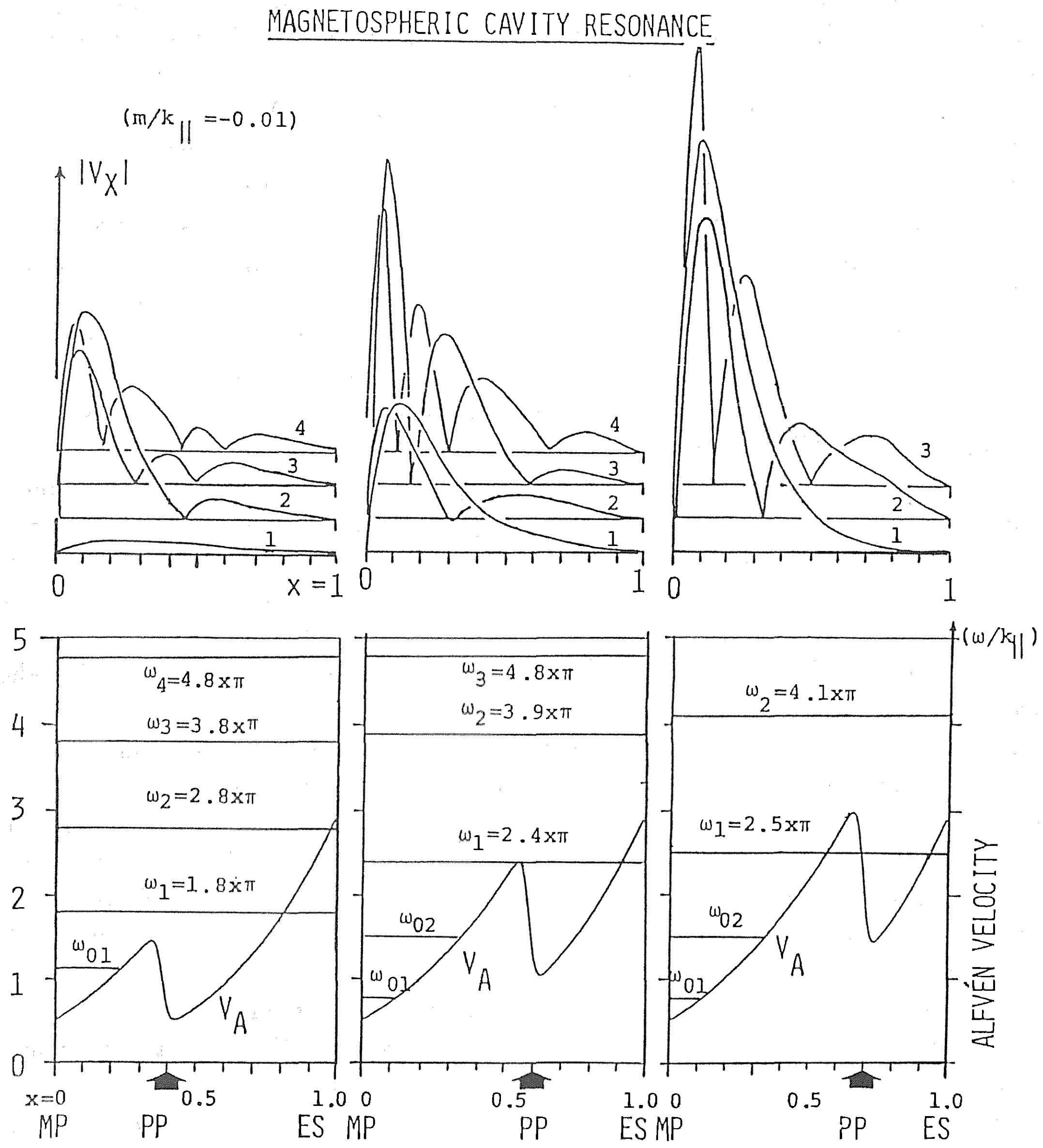

Fig. 4a. (Top) Relative amplitudes of harmonic modes ($n = 1,..,4$) of the magnetospheric cavity resonances with $m/k_{||} = -0.01$ under quiet (the plasmapause position of $L_{pp} = 6$), moderate ($L_{pp} = 4$), and disturbed ($L_{pp} = 3$) geomagnetic activity conditions. (Bottom) Relations between normalized eigen frequencies of the harmonic cavity modes (ω_n) and the radial Alfvén speed distributions in three model magnetospheres. ω_{01} and ω_{02} have small amplitudes and turning points in the outer magnetosphere.

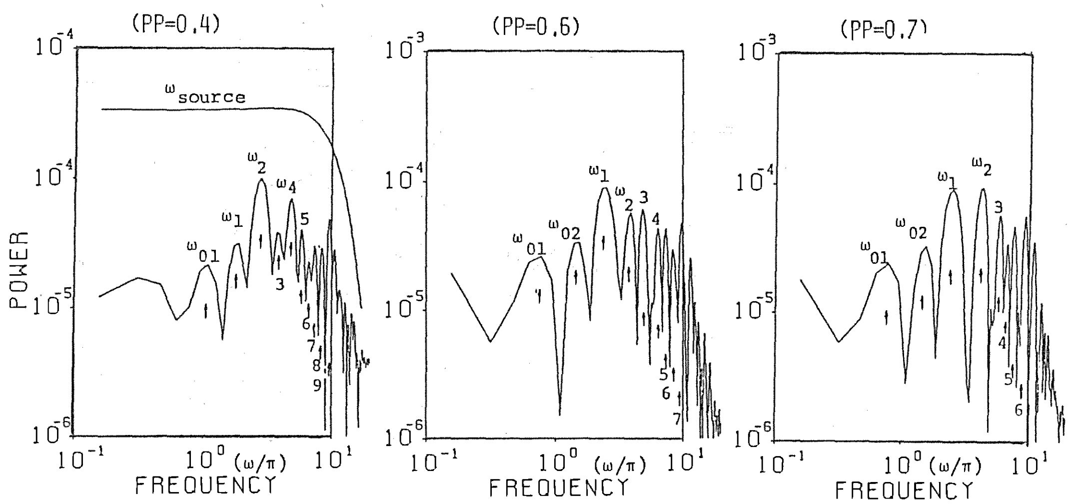

Fig. 4b. Power spectra of the excited magnetospheric cavity resonances at $x = 0.2$ in the three model magnetosphere (in the bottom panel of Fig. 4a). ($\omega_1, \omega_3, \ldots \omega_{2n+1}$) and $(\omega_2, \omega_4, \ldots \omega_{2n})$ are odd and even modes, respectively, of the cavity for each model magnetosphere.

In the case of impulsive source wave with a smaller azimuthal wave number $(m/k_{||} = -0.2, k_{||} = \pi)$ and a broad-band frequency, the magnetospheric cavity resonance modes tend to be stimulated, and further couple into Alfvén resonance oscillations in the model magnetosphere as shown in Fig. 5 [e.g. Kivelson and Southwood, 1985; Allan *et al.*, 1986]. The smaller azimuthal wave number corresponds to the longer azimuthal wave length of the magnetopause perturbation. The right-side top panel shows a relation between harmonic frequencies of the global cavity resonance and the radial Alfvén speed distribution under quiet geomagnetic condition ($L_{pp} = 6$; L-value of the plasmapause). We used the impulsive, initial perturbation of a special form of $|v_{xo}|/V_{Ao} = 0.02/1.0, T = 0.25, t_o = 10$, and $\omega = 2.6 * \pi$ by eq. (13), however, the calculated power spectrum (ω_{source} in the left-side top panel) of the impulsive source wave of poloidal plasma velocity at the magnetopause ($x = 0.0$) is never special, but reasonable one presenting a typical shock-like variation in the solar wind. The left-side top panel also shows a power spectrum of the excited cavity harmonic oscillations (v_x) at $x = 0.2$ in the outer magnetosphere. As well known the noisy wave-form of the global cavity resonance in the v_x-panel consists of different harmonics ($\omega_{01}, \omega_1, \omega_2, \omega_3$, and ω_4). The spectral power of excited cavity modes depends both on the power spectrum of the initial perturbation (ω_{source}) and on the radial Alfvén speed distribution in the model magnetosphere. The panel indicates that the second mode (ω_2) of the cavity wave predominates at $x = 0.2$ in the model magnetosphere.

Histories of the cavity oscillations (v_x, v_y, b_z, ρ_m, and $J_{||}$) are also illustrated in the top-side middle and the bottom panels of Fig. 5. The scales of v_y and $J_{||}$ amplitudes in the figure are 0.2 times those in Fig. 2. The compressional cavity oscillations (v_x, b_z) are excited mainly in the outer magnetosphere ($x \lesssim 0.35$, *i.e.*, $L \gtrsim 6.5$),

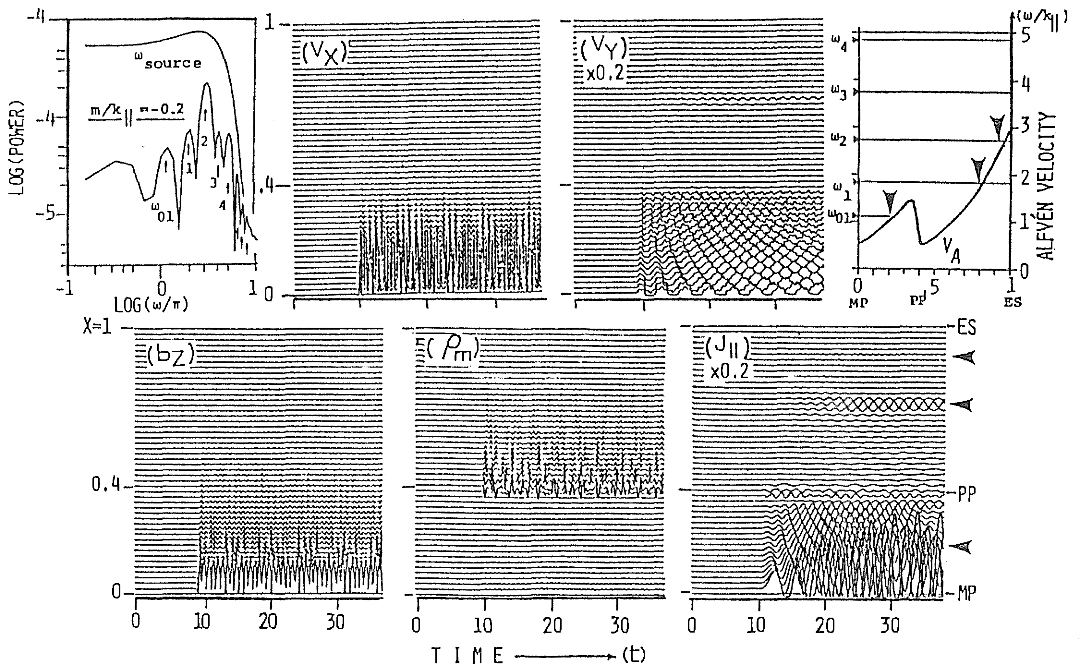

Fig. 5. The magnetospheric cavity resonance composed of different harmonics which further couple into the Alfvén resonances, excited by the magnetopause perturbation having a smaller azimuthal wave number ($m/k_{||} = -0.2$) and a broad-band frequency under quiet geomagnetic condition ($L_{pp} = 6$). (Left-side top) The power spectra of the magnetopause perturbation (ω_{source}) and the excited magnetospheric cavity resonance mode (v_x) at $x = 0.2$. (Right-side top) Relation between the harmonic frequency and the Alfvén speed distribution. v_x, v_y, b_z, ρ_{1m}, and $J_{||}$-panels are the same as in Fig. 2, except for the time axis, the plasmapause position ($L_{pp} = 6$) under quiet geomagnetic condition, and the scales of v_y and $J_{||}$ amplitudes of 0.2 times those in Figs. 2 and 6.

whereas the plasma density variations appear inside the plasmapause ($L \lesssim 6$). Around the turning points of the fundamental $\omega_{01}(x = 0.2), \omega_1(x = 0.7)$ and the second $\omega_2(x = 0.9)$ poloidal cavity waves, indicated by the arrows in the right-side panels, we can see weakly excited, multiple toroidal oscillations (v_y) and associated field-aligned currents ($J_{||}$), of which frequencies are consistent with those (ω_{01}, ω_1, and ω_2) of the cavity resonance modes, respectively. The width of the standing field-line oscillations in Fig. 5 is about one second of those in Fig. 2, because of two times of the Alfvén speed gradient. The damping of the magnetospheric cavity resonance as shown in Fig. 5 is small, because the energy conversion (mode coupling) from the cavity waves into the torsional standing field-line oscillations in the inner magnetosphere is small in the case of the small azimuthal wave number (cf. eq. (14)). The growth rate (γ/ω_r) of the small-amplitude Alfvén resonance oscillations stimulated by the cavity modes is about 0.1 as shown in the v_y panel of Fig. 5. Although we had not detailed

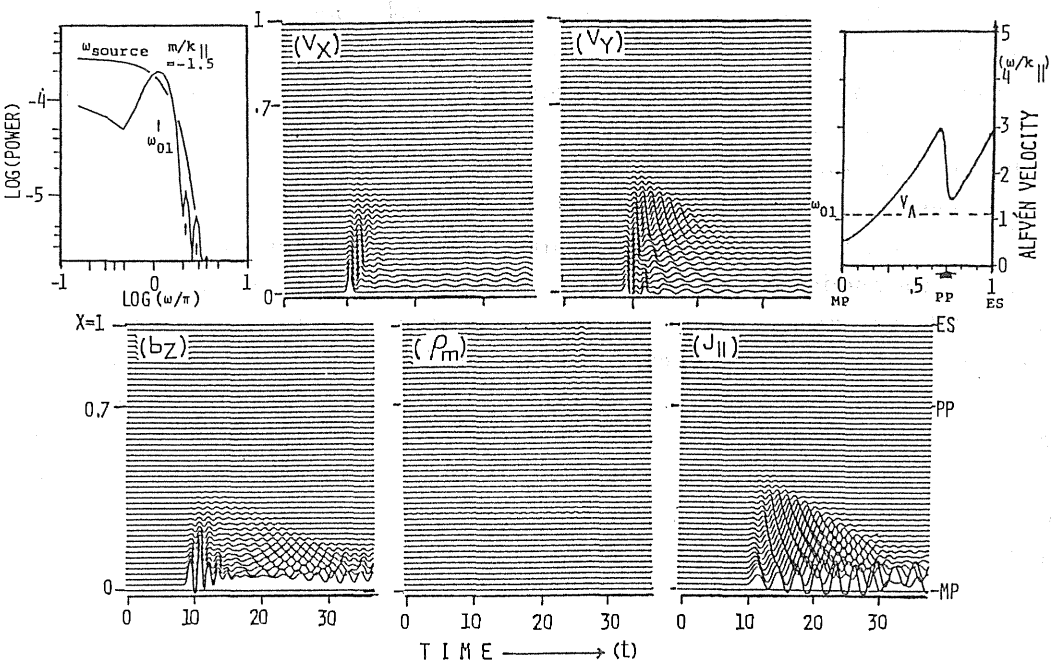

Fig. 6. A transient Alfvén resonance ($v_y, J_{||}$) with latitudinally varying periods, excited by the magnetopause perturbation with a larger azimuthal wave number ($m/k_{||} = -1.5$) and a lower band frequency. The same as in Fig. 2, except for the time scale, the power spectrum of the magnetopause perturbation, and the plasmapause position ($L_{pp} = 3$) under disturbed geomagnetic condition.

considerations on the wave energy flow in the azimuthal, y direction, most of the cavity wave energy will be convected away across the ambient magnetic field into the magnetotail. Therefore, the magnetospheric cavity resonance must appear in a less cycle in the real magnetosphere. The impulsive magnetopause perturbation also drives a weak transient Alfvén resonance, of which period and amplitude increase with increasing the geocentric distance, in the outer magnetosphere ($x < 0.2; L > 8$), which will be discussed in the following figure.

Another magnetospheric response to a sudden impulse of the magnetopause perturbation is found to appear as shown in Fig. 6. In this case the compressional source wave with amplitude of $|v_{xo}|/V_{Ao} = 0.02/1.0$ at the magnetopause has a larger azimuthal wave number ($m/k_{||} = -1.5$) and a lower band frequency of $T = 0.5, t_o = 10$ and $\omega = 0.5 * \pi$ in eq. (13) (see the spectrum of ω_{source} in left-side top panel). The right-side top panel shows the relation between the broad-band frequencies around $\omega_{01}/k_{||} = 1.1$ of the magnetospheric cavity mode and the radial Alfvén speed distribution under disturbed geomagnetic condition ($L_{pp} = 3$). The amplitude scales of v_x, v_y, b_z, ρ_m, and $J_{||}$ panels are the same as in Fig. 2. The impulsive magnetopause perturbation (v_x) with the larger azimuthal wave number and the lower band frequency can drive individual torsional standing field-line oscillation (v_y) and the associated field-aligned current ($J_{||}$) in the outer magnetosphere, of which amplitude and period decrease with increasing the distance from the magnetopause. In the v_x panel we can also see a stimulated fundamental cavity mode of ω_{01} in wave packets of only a few cycle in length.

Because of the larger field-aligned current variations ($J_{||}$), and toroidal oscillations (v_y) with the individual Alfvén frequency in the outer magnetosphere, this response to the sudden impulse should be categorized as a transient Alfvén resonance with latitudinally varying periods. This type response of the magnetosphere is really observed and called sc-associated pulsations, Psc [e.g., Glassmeier *et al.*, 1984]. Pouter and Nielsen [1982] reported numerous STARE radar observations of the transient ULF waves with latitudinally varying periods. Singer *et al.* [1979] and Lin *et al.* [1986] also preported observations of a decrease of the eigenperiod of resonance field lines with decreasing L, using magnetometer data from the ISEE 1 and 2 satellite pair and the DE 1 spacecraft, respectively.

4. Summary and Discussion

In the present paper, we have developed a simple MHD computer code that simulates the transient response of the "box" magnetosphere with inhomogeneous magnetized plasmas with respect to the poloidal compressional perturbation at the magnetopause. Using radial Alfvén speed distributions chosen to represent possible situations in a quiet and a disturbed magnetosphere, we have showed how impulsive and wave-packet-like stimulations of the compressional magnetopause perturbations can couple into HM oscillations in the "box" magnetosphere. We could confirm the Alfvén resonance (Fig. 2), analytically predicted by Chen and Hasegawa [1974] and Southwood [1974], and the azimuthal wave number dependence of the resonance (Fig. 3) with similar results of Allan *et al.* [1986] and Inhester [1987]. Our computer simulations have also indicated supporting results for the previous idea that an impulsive magnetopause perturbation with a smaller azimuthal wave number can stimulate the magnetospheric cavity resonance, and further excite standing field-line oscillations, of which periods are consistent with those of the cavity resonance [Kivelson and Southwood, 1985; Allan *et al.*, 1986; see Fig.5].

The present computer simulation results that effectively indicated the support to the previous outcome have further predicted new evidences for the propagation characteristics of MHD waves for the global feature through the magnetosphere-ionosphere regions; these are summarized as follows;

(1) The structure of eigen frequencies and amplitudes of impulsively-stimulated magnetospheric cavity resonance modes are controlled by the position of the plasmapause,

which is related to the geomagnetic activity and determines the averaged Alfvén speed in the model magnetosphere. The eigen frequency of magnetospheric cavity modes tends to be higher in the higher geomagnetic activity (Fig.4).

(2) In the case of impulsive magnetopause perturbation with a smaller azimuthal wave number $|m/k_{\parallel}|\lesssim 0.2$, the magnetospheric cavity and Alfvén resonances tend to occur in the model magnetosphere under quiet geomagnetic condition ($L_{pp} = 6$) (Fig. 5). On the other hand, for another impulsive magnetopause perturbations, having a larger azimuthal wave number $|m/k_{\parallel}|\gtrsim 1.5$ and a lower band frequency ($\omega_{source}/\pi\lesssim 1$), a transient Alfvén resonance with latitudinally varying periods can be excited in the outer magnetosphere under disturbed geomagnetic condition ($L_{pp} = 3$), (Fig. 6).

The increase of the cavity frequency with the geomagnetic activity is due to the increase of averaged Alfvén velocity in the model magnetosphere. For more active period, the plasmapause put further inward, which will create a larger outer magnetospheric cavity between the magnetopause and the plasmapause and a lower resonant frequency of the cavity [see Allan *et al.*, 1986]. In the present simulation, the change of the Alfvén speed distribution was found to play more important role than that of the distance from the magnetopause to the plasmapause. The Alfvén velocity $B_o/(\mu_o \rho_{om})^{1/2}$is influenced mainly by the rapid change of plasma density around the plasmapause, of which location is a function of magnetic activity [see Fig. 7 of Chappell *et al.*, 1970]. Mean states for three levels of activity; quiet ($K_p < 1_+$), average ($K_p \sim 3$), and disturbed ($Kp \gtrsim 5$) correspond to the plasmapause positions at $L = 6$ ($x_{pp} = 0.4$ in the model magnetosphere), 4 (0.6), and 3 (0.7), respectively, in Fig. 4a. It is concluded that the change of the Alfvén speed distribution in the model magnetosphere, depending on the location of the plasmapause, *i.e.*, a function of geomagnetic activity, plays more important role on the determination of structures of eigen frequencies and amplitudes of the magnetospheric cavity resonances.

The azimuthal wave number and the frequency range of the poloidal compressional perturbation at the magnetopause are also found to control transient responses of the model magnetosphere as shown in Figs. 5 and 6. The magnetopause impulse with a smaller azimuthal wave number, *i.e.*, a longitudinally longer wave length, has a smaller coupling between poloidal (v_x) and toroidal (v_y) variations (see eq.(14) or eq.(15)), and then tends to stimulate the magnetospheric cavity resonance. While the magnetopause impulse with a larger azimuthal wave number, *i.e.*, having a larger coupling of v_x and v_y, can excite the transient Alfvén resonance with latitudinally varying periods in the outer magnetosphere.

From the simulation results, we can conclude that the initial magnetopause perturbations, being a function of the frequency range and azimuthal wave number, and the plasmapause position associated with the geomagnetic activity are key parameters, controlling which of the localized Alfvén, the impulsively-stimulated magnetospheric cavity and the transient Alfvén resonances is predominantly excited in the magnetosphere.

Possible attenuation mechanisms for the resonance oscillations are collisionless damping [e.g., Southwood, 1973], the ionospheric Joule dissipation [e.g., Newton *et al.*, 1978], or the mode conversion [e.g., Hasegawa, 1976]. In the night-side magnetosphere the Joule dissipation is clearly dominant source of dampings, and can become very significant. However, in the present "box" magnetosphere the Joule dissipation in the ionosphere was assumed to be less significant, which is true for typical dayside ionosphere ($\Sigma_p > 10^{12} e.s.u.$) [cf. Newton *et al.*, 1978]. In our model of the dayside magnetosphere the excited Alfvén waves occur in wave packets of perhaps 60 cycles in length. This corresponds to the ionospheric damping rate of $\gamma/\omega_r \sim 0.003$.

The damping rate of toroidal field-line oscillations coupled with the magnetospheric cavity waves should be controlled by the damping of the cavity modes rather than energy dissipation from the field-line resonances. In the near future we can estimate the damping rate of HM coupling resonance oscillations due to a combination of at least three processes; mode coupling, direct Joule dissipation and transmission losses in the realistic model magnetosphere, including the gradients of the Alfvén velocity along the ambient dipolar-like magnetic field, non-uniform ionospheric conductivity distribution, the effective collision frequency, and transmission losses into the magnetotail. Then, we can make a quantitative comparison with the observation [e.g., Crowley *et al.*, 1987].

The present numerical discussions have been focused on inhomogeneities in the radial direction, ignoring gradients of the Alfvén velocity along the unperturbed field direction. Southwood and Kivelson [1986] theoretically demonstrated that the natures of coupling and effectiveness of excitation are significantly modified by the presence of such gradients. Therefore, the present result would be modified by the effect. A numerical study of two dimensional simulation including the effect will be also the subject of a future paper.

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