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On the possibility of Alfvén wave resonance in collisionless magnetic reconnection

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Abstract

Alfvén wave resonance and magnetic reconnection are among the potential candidates for efficient dissipation of magnetic energy in space and astrophysical plasmas. In this paper, the correspondence between Alfvén resonance and the electron-inertia driven reconnection in a sheared force-free magnetic field is discussed. By analytical scaling the linear regimes of compressible tearing instability in the two-fluid magnetohydrodynamic (MHD) model, we present parametric conditions for the possibility of Alfvén resonance existence. Meanwhile, it is argued that the slow MHD Alfvénic resonance can take place only in the "intermediate" – called Hall-MHD regime when $\beta > \mu$. β is the ratio of plasma thermal pressure to the pressure in equilibrium magnetic field and μ is the electron to ion mass ratio. There is no room for such a resonant dissipation phenomenon either in the single-fluid MHD or the electron-MHD regimes.

Keywords: Magnetohydrodynamics; Tearing instability; Magnetic reconnection; Alfvén wave resonance

1. Introduction

Among various schools of thoughts concerning the efficient dissipation of magnetic energy in the highly conductive environments of space plasmas there are two main ones: Alfvén mode resonance which can explain the enhanced dissipation in dynamical processes such as magnetohydrodynamic (MHD) waves (Hasegawa and Chen, 1974; Wang et al., 1998; Erdélyi and Goossens, 1995; Ruderman et al., 1997), and magnetic reconnection which is usually associated with longer time scales compared with the Alfvén time (Birn and Priest, 2007; Priest and Forbes, 2000; Yamada et al., 2010; Zweibel and Yamada, 2009). In a collisionless plasma with negligible plasma resistivity, the electron-inertia is a potential means of breaking the frozen-in condition to convert magnetic energy into the kinetic and thermal energy of plasma. The inclusion of electron inertia, inevitably, requires that the two-fluid MHD description of reconnection is to be considered, in which Hall effect plays an important role by facilitating the pace of magnetic reconnection (Drake et al., 2008; Fitzpatrick and Porcelli, 2004; Mirnov et al., 2004; Hosseinpour et al., 2009; Shay et al., 2001; Terasawa, 1983).

In the Hall-MHD reconnection via tearing instability the current sheet acquires a double-layer structure: The inertial region surrounded by a much wider layer, where the electron-inertia plays no role, but the poloidal magnetic field is still advected towards the reconnection region by the Hall effect rather than by the bulk plasma motion. Relative importance of Hall effect and the electron inertia is characterized by the following non-dimensional parameters: $d_e \equiv c/(\omega_{pe} l)$, the scaled electron inertial skin-depth (l is the magnetic shear length scale), for the electron inertia; $d_i \equiv c/(\omega_{pi} l) = \mu^{-1/2} d_e \gg d_e$, $\mu \equiv m_e/m_i \ll 1$, the scaled ion skin depth, for the Hall effect. c and $\omega_{pi/e}$ are the speed of light and the ion/electron plasma frequency, respectively.

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At sufficiently small values of d_i (see below), the Hall effect turns out to be less important, so that, the single-fluid MHD can adequately describe the dynamics of reconnection ("standard"- MHD regime). In contrast, at much larger values of d_i (see below), ion component of plasma does not play any role in reconnection dynamics and therefore, the electron-MHD (EMHD) regime dominates. In the intermediate values of d_i both electron and ion components determine the dynamics of reconnection, we call it an "intermediate" Hall-MHD regime. Each of these linear regimes of tearing instability are characterized by their respective current sheet width and the instability growth rate.

In such a tearing instability, most of the magnetic energy is stored in the low-frequency MHD waves such as Alfvén waves that can be generated by magnetic reconnection and propagated along the reconnected field lines (Kigure, 2010; Wang, 2002; Ma et al., 1995). One of the proposed mechanisms for dissipation of Alfvén waves is resonant absorption (Poedts et al., 1989; Ionson, 1978; Hasegawa and Chen, 1974). Wang et al. (2011) has reported that the MHD perturbations due to tearing mode reconnection on the outer rational surface mediate in generating two Alfvén resonance layers on the both sides of the inner rational surface and then prevent the formation of island growth (tearing mode suppression). However, in the Hall-MHD reconnection with the large guide field different types of waves can be excited such as kinetic or inertial Alfvén waves. Kinetic Alfvén waves can propagate at $\beta > \mu$, while inertial Alfvén waves are excited at $\beta < \mu$ (Huang, 2010; Rogers, 2001; Lyask and Lotko, 1996; Hasegawa and Chen, 1975; Hasegawa, 1976; Goertz and Boswell, 1979). These waves determine the electron dynamics in the ion diffusion region. Even, Whistler waves can propagate inside the electron inertial length scale (Wei, 2013; Wang and Luan, 2013). In order to concentrate our discussions on the Alfvén resonance, we assume that the wave vector of fluctuations has no component along the guide field, thus it leaves no room for the kinetic/inertial Alfvén waves and only the slow Alfvénic waves are permitted to propagate regardless of the excitation mechanism for Alfvén waves.

In magnetic reconnection with nonuniform equilibrium magnetic field, the location of resonance layer varies with the Alfvén frequency (see below). If the location of resonance layer lies within the current sheet formed by magnetic reconnection, then Alfvén resonance, in fact, cannot occur and therefore, the dynamics of tearing mode is not influenced by the resonance phenomenon. It is of interest to investigate the possibility of occurring the Alfvén resonance in each of the two-fluid MHD regimes of collisionless reconnection.

It is worthy of note that, previously, the relation between Alfvén resonance and magnetic reconnection has been argued by Uberoi (1994) and Vekstein (2000), but in the case of forced magnetic reconnection. In this type of reconnection the externally sinusoidal perturbation of plasma boundaries with a certain frequency leads to the magnetic reconnection at the surface where poloidal field changes its sign. Furthermore, the sinusoidal boundary perturbation can excite Alfvénic waves. Uberoi (1994) in the absence of Hall effect has interpreted forced magnetic reconnection as the Alfvén resonance with zero frequency, from which it was deduced in Uberoi and Zweibel (1999) that the theory of forced magnetic reconnection is actually embedded in the Alfvén resonance theory. On the other hand, Vekstein (2000) discussed that these phenomena are operating separately, and transition from resonant absorption to forced reconnection occurs when the frequency of the external driver becomes sufficiently small. However, in the tearing instability, Alfvén waves can be generated following the onset of magnetic reconnection and then propagated along the magnetic fields (Kigure, 2010; Wang, 2002; Ma et al., 1995; Sakai et al., 2000; Lazarian and Vishniak, 1998). Here, unlike the forced reconnection, there is no externally driven mechanism.

In this study, we first analytically scale both the width of current sheet and the growth rate of collisionless tearing instability at different linear regimes within the two-fluid MHD framework and then investigate the possibility of occurring Alfvén resonance at each of these regimes. To do so, we compare the location of Alfvén resonance layer with the width of current sheet. If the resonance layer is located inside the current sheet, then the appearance of Alfvén resonance is not expected. It should be note that, in this study, the mechanisms which can generate Alfvén resonance will not be discussed, but only the possibility of Alfvén resonance existence in the presence of linear tearing instability will be investigated. The structure of paper is as follows: Section 2 gives the description of the model and basic equations. Analytical analysis of collisionless reconnection regimes are included in Section 3 and discussions regarding the possibility of Alfvén resonance occurrence are presented in Section 4, which is followed by a brief summary and conclusion in Section 5.

2. The model and basic equations

A planar slab of a highly conductive uniform plasma [density n_0] embedded in a sheared force-free magnetic field

$$\mathbf{B}^{(0)}(x) = \mathbf{z}B_z^{(0)}(x) + \mathbf{y}B_y^{(0)}(x), \tag{1}$$

with

$$B_y^{(0)} = B_0 f(x), \quad B_z^{(0)} = B_0[1 - f^2(x)]^{1/2} \tag{2}$$

is surrounded by two perfectly conducting walls at $x = \pm l$.

For the tearing perturbation of the form $exp(iky)$ reconnection occurs at the $x = 0$, where the poloidal field component $B_y^{(0)}$ changes its sign: $f(x) \approx \alpha x$ for $|x| \ll l$. Therefore, the wave number has only one component which is along the 'y' direction. The governing equations defining temporal evolution of perturbations about the initial equilibrium are as follows: