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Research Paper

Magnetohydrodynamic Simulation of Forced Magnetic Reconnection

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Abstract. Magnetic reconnection is a fundamental process in laboratory, astrophysical, and space plasmas, which is a mechanism for converting magnetic energy into the thermal and kinetic energy of plasma and the efficient acceleration of charged particles. Using two-dimensional magnetohydrodynamic simulations, we investigate the onset and the growth of instability associated with the forced magnetic reconnection phenomenon in the well-known equilibrium structure of the Harris current sheet in the presence of a resistive plasma. To derive externally the magnetic reconnection process, we perturb the velocity of plasma close to the up and down boundaries in the form of two localized pulses. The results show that these pulses propagate towards the current sheet, where the magnetic field changes direction, generates a perturbed magnetic field consequently, and triggers the magnetic reconnection phenomenon in an X-point in the center of the current sheet. We realized that increasing the amplitude of pulses results in a faster reconnection, and symmetric pulses are more efficient in conducting the reconnection. Furthermore, by imposing a transient (time-dependent) MHD wave normal to the current sheet, we found that an MHD wave with a more significant period (lower frequency) considerably affects the current sheet's topology and excites a faster reconnection. A similar conclusion was also obtained for an MHD wave with a larger wavelength (lower wavenumber). The obtained results are of interest for understanding the interaction of an MHD wave with an equilibrium current sheet in confined fusion plasmas and solar corona plasmas.

Keywords: Solar plasma, Forced magnetic reconnection, Magnetohydrodynamic simulation, Current sheet

1 Introduction

Magnetic reconnection is one of the most fundamental and significant processes that occurs in highly conductive magnetized plasmas. By altering the configuration of magnetic field lines, this process converts the stored magnetic energy into the kinetic and thermal energies, and can also accelerate charged particles to relativistic kinetic energies. During this physical

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phenomenon, the electric current layer, which is created at the location of disconnection and reconnection of magnetic field lines, undergoes a nonlinear evolution. This instability arises in regions where the magnetic field changes its direction within a narrow region where the plasma resistivity as a non-ideal MHD effect exists, and so dissipates the magnetic energy [1-2].

Well-known classical theories predict that magnetic reconnection triggers and develops within the current sheet in a single point where the structure of magnetic field lines has an X-like shape [3-4]. Therefore, the reconnection site is named as an X-point. Following the sufficient development of magnetic reconnection, which is triggered at an X-point within the current sheet, both the plasma velocity and magnetic field on the boundaries become eventually affected. In other words, an instability excited at small scales, consequently affect the global topology of magnetic field lines. This type of magnetic reconnection has been studied extensively [5-10]. This first kind of magnetic reconnection or the current-sheet formation is associated with the MHD instabilities (e.g., resistive tearing mode and ideal kink mode) known as spontaneous magnetic reconnection [11-13]. Recent theories suggest a vice-versa mechanism. The second kind of current sheet can be formed in the MHD stable configuration, where some external perturbations trigger the forced magnetic reconnection [14]. The forced magnetic reconnection may be activated by nonlinear MHD waves, which may be caused by explosive solar activities [15-17]. Therefore, the forced magnetic reconnection may be developed due to boundary perturbation [18-19]. In fact, the disturbances of either plasma velocity or magnetic field on the boundaries can also propagate towards the center (current layer), and then trigger the magnetic reconnection process there [5-10]. This type of magnetic reconnection is also named as externally driven or forced magnetic reconnection. It has been believed that this type of reconnection is taking place both in fusion plasmas in tokamaks and in space plasmas especially in the solar corona. Note that, both types of reconnection require the presence of non-ideal MHD effects within the current sheet such as the plasma resistivity, the electron inertia or the pressure tensor gradient.

Birn et al (2005) have used a multi-code approach to study the GEM reconnection challenge in which the dynamical evolution of the current sheet is induced by forced magnetic reconnection [20]. Now, it is strongly believed that the random motion of the footpoints of coronal loops anchored in the photosphere region can result in the forced magnetic reconnection within the current sheets of solar flares [21-23]. In another important study, Jess et al. (2010) have reported the observation of a micro-flare which is triggered by forced magnetic reconnection [24]. The large fraction of released magnetic energy during the process of forced magnetic reconnection is consumed to heat the relatively cooler plasma in the photospheric or chromospheric regions of the Sun [25-28]. The main motivation for our numerical study is a recent observational study by Srivastava et al (2019) [23]. In this work, they have observed the process of forced reconnection in the solar corona. In more detail, they have used a combination of multi-wavelength imaging observations from the AIA/SDO on 2012 May 3 to observe such a process. They claim that a novel scheme for the formation of an X-point in the solar corona is observed, where the main agent to derive the forced reconnection is the eruptive expansion of a prominence in the vicinity of a bunch of open field lines with a direction opposite to the direction of magnetic field lines of prominence. They conjecture that therefore the oppositely directed field lines are pushed toward each other to form temporarily a diffusion region and an X-point. The reconnection and related plasma outflows may occur thereafter at considerably larger rates. Considering, this observational results, it was of interest, to numerically investigate, the physics of forced magnetic reconnection.

Fitzpatrick (2004) [19] has conducted MHD numerical simulations of forced magnetic reconnection with assuming an incompressible plasmas. This study perturbs the magnetic field on the boundaries. However, our study, considers the general case of a compressible one and perturbs the velocity on the boundaries rather than the magnetic field which is more realistic. Potter et al (2019) [6] have investigated the effect of the form of the external perturbation and initial current sheet on the evolution of the reconnection region and the energy release process. The main difference of their study with our one which is very important is concerned with the equilibrium structure of magnetic field. They have assumed a simple force-free magnetic field topology, which results in a contestant plasma pressure throughout a region. However, in our model, a realistic form of initial magnetic field is used with a spatial dependent profile of initial plasma pressure. Hahm and Kulsrud (1985) [14] in a seminal paper in the field of forced magnetic reconnection have discussed analytically the problem of forced reconnection in a very simple model of force-free magnetic field and identified some different linear and nonlinear regimes of instability. They have assumed an external perturbation of magnetic fields. Our study investigates the numerical simulation of this problem with perturbing the velocity on the boundaries. Sakai et al (1983) [15] have also investigated the problem of forced magnetic reconnection which is triggered by the plasma vortex and MHD waves. Their study showed that there is a threshold amplitude for the external MHD waves. Birn et al (2005) [20] by using a multi-code approach, investigated current sheet thinning and the onset and progress of fast magnetic reconnection, initiated by temporally limited, spatially varying, inflow of magnetic flux. We note that our study considers the perturbation of plasma velocity rather than the magnetic flux on the boundaries. Vekstein (2017) [13] in a tutorial-style selective review explains the basic concepts of forced magnetic reconnection. It is based on a celebrated model of forced reconnection suggested by J. B. Taylor. He discussed analytically different regimes of forced magnetic reconnection. However, our study uses the approach of MHD simulation. Furthermore, Jain et al (2005) [22] investigated the rate of energy release during forced magnetic reconnection. They perturbed the boundaries with pulses of magnetic field. Remind that, our study considers the perturbation of boundaries with plasma flow pulses.

Although, the forced magnetic reconnection by applying the perturbed magnetic field to the boundaries has already been investigated, but the other more possible case has not been studied which is the imposing of perturbed plasma velocity on the boundaries. In fact, imposing any kind of velocity disturbances to the boundaries, will immediately results in the generation of perturbed magnetic fields on the boundaries according to the Faraday's and the Ohm's laws. In other words, this mutual relation between the plasma velocity and the magnetic field on the boundaries is defined by the “frozen-in flow” constraint, since the ideal MHD assumption is essentially satisfied close to the boundaries. Boundary perturbations can take place only on one boundary or on both ones either symmetric or asymmetric. Moreover, they can be single pulses which are generated only initially, or their generation can be continuous up to a specific time of simulation. The amplitude of pulse, the width of pulse and the pulse generation time duration are some of main parameters that define the reconnection rate and the magnetic field topology.

On the other hand, the pulses on the up and down boundaries can be replaced by a transient or stationary MHD wave which is present throughout the system normal to the current sheet (y-axis) and affect the current sheet structure from the beginning of simulation. In this case, the period (or frequency), wavelength (or wavenumber), and the amplitude of MHD wave are the main parameters.

In this study it is of interest to investigate the triggering, the growth of magnetic reconnection and the change of magnetic field topology by applying perturbed plasma velocity to the boundaries. We will also discuss the case of a transient/stationary MHD wave interaction with a current sheet and the associated excitation of magnetic reconnection. To do so, we will carry out two-dimensional (2D) MHD simulations. Three types of interaction will be considered:

1: imposing two pulses on the up and down boundaries localized around the center of current sheet;

2: imposing a transient MHD wave normal to the current sheet;

3: imposing a stationary MHD wave normal to the current sheet.

Therefore, in the next section the model, numerical method and the code is explained. Results and discussion are presented in Section 3 and a brief conclusion is followed in Section 4.

2 Model and Numerical Method

To run MHD simulations, we use a finite-volume 2D resistive MHD code, OpenMHD, which was developed by Zenitani [29]. Numerical fluxes are estimated by an HLLD approximate Riemann solver [30], and the second-order TVD Runge-Kutta time marching method is used. Also, the hyperbolic divergence cleaning method ($\nabla.\mathbf{B} = 0.$) is employed for the solenoidal condition [31], which is a critical issue in MHD simulations. The basic one-fluid compressible resistive MHD equations that are solved by using OpenMHD code in a Cartesian geometry system are as follows: The continuity equation

$$\partial_t \rho = -\nabla.(\rho \mathbf{V}), \tag{1}$$

where ρ is plasma mass density, and $\mathbf{V}$ is plasma flow velocity; the Euler equation

$$\partial_t(\rho \mathbf{V}) = -\nabla.[\rho \mathbf{V}\mathbf{V} + p_{tot}\mathbf{I} - \mathbf{B}\mathbf{B}], \tag{2}$$

where $p_{tot} = p + B^2/2$ is the total pressure, $\mathbf{B}$ is the magnetic field, and $\mathbf{I}$ is the unitary tensor; the energy equation

$$\partial_t \epsilon = -\nabla.[(\epsilon + p_{tot})\mathbf{V} - (\mathbf{V}.\mathbf{B})\mathbf{B} + \eta \mathbf{j} \times \mathbf{B}], \tag{3}$$

with $\epsilon = p/(\Gamma - 1) + \rho v^2/2 + B^2/2$ is total energy density, η is electrical resistivity, and $\mathbf{j}$ is the current density; the induction equation

$$\partial_t \mathbf{B} = -\nabla.(\mathbf{V}\mathbf{B} - \mathbf{B}\mathbf{V}) - \nabla \times (\eta \mathbf{j}), \tag{4}$$

$$\mathbf{E} + \mathbf{V} \times \mathbf{B} = \eta \mathbf{j}. \tag{5}$$

We set the specific heat ratio $\Gamma = 5/3$. All variables are functions of space (x, y) and time (t). Also, the variation of variables in the z-direction is ignored $(\partial/\partial z = 0)$. For the convenience of numerical computations, all variables are dimensionless. For example, $\mathbf{B}/\mathbf{B}_0 \to \mathbf{B}, \rho/\rho_0 \to \rho, \mathbf{V}/\mathbf{V}_A \to \mathbf{V}, t/\tau_A \to t$, where τ_A is the Alfvénic time, L is the length scale of the system to normalize spatial scales and $\mathbf{V}_A$ is the Alfvén velocity. The simulations are performed in a rectangular box of size $x = [0, Lx = 22.5]$ and $y = [0, Ly = 7.41]$. Here, x is the longitudinal direction, and y is the normal direction to the current sheet, with 772×254 cells. The numerical grid sizes are $\Delta x = \Delta y = 0.029$, which is assumed uniform in space and constant in time. Time-step is calculated at each step of integration according to the CFL condition and the velocity of generated MHD waves at that time, and therefore, time-step is not a constant during the numerical simulation. The dimensionless electrical resistivity ($\eta = \eta_m/LV_A$) is assumed to be uniform everywhere equal to 0.01 with η_m being the physical value of the electrical resistivity. The initial magnetic field profile is the Harris sheet in the form

$$B_x(y) = B_0 \tanh\Big(\frac{y - Ly/2}{a_B}\Big), \quad B_y = 0, \quad B_z = B_g = 0.0, \tag{6}$$

where $B_0 = 1.0$ is initial asymptotic magnetic field strength and a_B, the half width of the initial current sheet. B_g is the guide field that is perpendicular to the reconnection plane. The equilibrium magnetic field structure and its profile is shown in Figure 1. By solving the condition of initial force-balanced equilibrium, the thermal pressure is given by $P = \frac{B_0^2}{2}(1.0 + \beta/2 - B_x^2)$ and assuming the initial thermal equilibrium condition, the plasma mass density is obtained by $\rho = P/(1.0 + \beta)$, where β is the plasma-beta parameter, and its value is fixed to be 0.2 in this study. There is no initial plasma velocity, and we will only consider perturbations of plasma velocity close to the boundaries either in the form of a pulse or a transient/stationary wave. The details of such perturbations are described in the next section.

3 Results and discussion

Our MHD simulations are categorized in two subsections:

1. reconnection driven by two symmetric/asymmetric pulses;
2. reconnection driven by a transient/stationary MHD wave.

3.1 Driven by two symmetric/asymmetric pulses

Up ($y = Ly$) and down ($y = 0.$) boundaries are perturbed by two velocity pulses, localized around $x = Lx/2$ in the form

$$V_{\pm Ly} = \left[exp(-(\frac{y - Ly/16}{Ly/70})^2) - A_v exp(-(\frac{y - Ly + Ly/16}{Ly/70})^2)\right] exp\left(-(\frac{x - Lx/2}{0.8})^2\right). \tag{7}$$

Choosing the parameter $A_v = 1.0$, results in the symmetric pulses from up and down boundaries. The denominators $Ly/70$ and 0.8 determine the width of pulse in the y and x directions. Additionally, $Ly/16$ and $-Ly + Ly/70$ terms on the numerators of the first and second terms determine the location of pulse peak along the y-axis close to the boundaries. The pulses are localized in the x-axis around $x = Lx/2$. Figure 2 shows the contour plots of magnetic field lines and the y-component of plasma velocity (V_y) at time $t = 1$ in the $x - y$ plane. As seen, the pulses imposed initially close to the boundary, propagate towards the current sheet ($y = Ly/2$). They excite MHD-like waves (disturbances), which propagate in both x and y directions. In other words, the wavenumber vector (k) of generated waves make an angle with the equilibrium magnetic field (oblique wave). Since, the V_y component is mainly responsible for the modification of the current sheet, the V_x plots have not been presented here. As the disturbances reach the current sheet, the topology of magnetic field lines changes slowly from straight lines along x-axis (equilibrium topology) into an X-point shape, where the magnetic field lines cut and reconnect each other continuously.

In fact, in the absence of initial pulses, we did not observe any signature of magnetic reconnection even at very late times. Therefore, the pulses which disturbed the system as the external agents, are responsible for this kind of instability which is associated with magnetic reconnection. Thus, disturbing the plasma velocity on the boundaries can result in the triggering of magnetic reconnection within the current sheet.

The most appropriate diagnostic to monitor the process of magnetic reconnection is the parameter of “reconnection rate”, E_R. It is calculated by averaging the absolute value of electric field component perpendicular to the reconnection plane (Ez) on the line $y = Ly/2$. The electric field is calculated by the combination of Faraday's and generalized Ohm's Laws. Actually, the strong spatial gradients of magnetic field around the X-point, and its temporal variation, generates a significant component of electric field perpendicular to the reconnection plane according to the Ampere's law. Therefore, measuring Ez magnitude, can be a valuable diagnostic for monitoring the growth rate of magnetic reconnection in the X-point. Figure 3 shows the logarithmic temporal variation of the reconnection rate for different values of A_v, which determines the extent of symmetry for up and down pulses. As seen, the reconnection mainly starts at $t \sim 0.65$ and increases sharply in the linear-like regime, and finally saturates around $t \sim 1.0$. This behavior takes place for all four different values of $A_v = -1.0; 0.5; 1.0; 1.5$. It should be noted that, the saturated reconnection rate for the case of $A_v = -1.0$ (initially symmetric pulses are moving towards the current sheet) is slightly higher than others and reaches the maximum $R \sim 0.01$. This is in fact a fast reconnection process. It is very promising that such a large value of reconnection rate is achievable based on our model of forced magnetic reconnection.

3.2 Driven by a transient/stationary MHD wave

Now, instead of perturbing the boundaries with two pulses, we apply throughout the y-direction (normal to the current sheet) a transient MHD wave by defining its new velocity profile. Similar to the previous case, in terms of x-direction, this wave is localized around $x = Lx/2$. This localization results in a sharp X-point reconnection in the current sheet at the center ($x = Lx/2$, $y = Ly/2$). The profile of initial plasma wave is

$$V(x, y, t) = A_v \cos\Big(\frac{2\pi}{\lambda} y - \frac{2\pi}{T} t\Big) exp\Big(-(\frac{x - Lx/2}{0.8})^2\Big). \tag{8}$$

Here, A_v, λ, T are the amplitude, wavelength and the period of transient wave. The cosine function dictates a wave-like variation in y-direction and the exponential term enforces the localization of wave around $x = Lx/2$. Therefore, the wave is propagating in the y-axis while it is localized in the x-axis around $x = Lx/2$. Although a broad range of values can be considered but we set $A_v = 0.12; \lambda = 2.0; T = 0.5, 2.0, 6.0$.

Figure 4 plots the magnetic field contours on top of the y-component of plasma velocity at $t = 2.0$ for three values of $T = 0.5, 2.0, 6.0$. As seen, perturbing the whole system with an MHD wave, results again in the reconnection process, and very interestingly, by increasing (decreasing) the wave period (frequency) a more drastic topological change in the structure of the initial X-point appears. Figure 4C shows a nonlinear regime of reconnection, named plasmoid instability, in which two X-points are generated with a large plasmoid between them. One can conclude that, slower transient MHD waves (larger periods T), affect more strongly on the structure of the X-point compared with faster ones. This point can also be deduced from Figure 5, which plots the reconnection rate versus time for three values of wave period. According to this figure, larger reconnection rate belongs to a system with a larger T.

It is of interest to discuss the case for which the wave is not a transient. To do so, we remove the time-dependency of wave by assuming

$$V(x, y, t) = A_v \cos\Big(\frac{2\pi}{\lambda} y\Big) exp\Big(-(\frac{x - Lx/2}{0.8})^2\Big), \tag{9}$$

with $A_v = 0.12, \lambda = 0.5, 2.0, 6.0$. Figure 6 shows the contour plot of field lines over the V_y for all three values of wavelength, λ. According to that, increasing (decreasing) the wavelength, λ (wavenumber, $k = 2\pi/\lambda$) of the wave, modifies more significantly the topology of an initial X-point, and even tilts the current sheet around the initial X-point. Furtehrmore, the rate of reconnection is slightly faster when the wavelength is larger (see Figure 7).

4 Conclusion

Two-dimensional MHD simulations have been carried out to investigate the onset and growth of an instability associated with forced magnetic reconnection phenomenon in the well-known equilibrium structure of Harris current sheet. It is already known that by perturbing the magnetic field on the boundaries of plasma, the equilibrium topology of magnetic field lines in the current sheet will be affected, and subsequently, in the presence of electrical resistivity of plasma, the process of magnetic reconnection is triggered in an X-point. In this study, however, we disturbed the boundaries by imposing velocity perturbations in the form of two up and down pulses which may have different amplitudes of velocity. The pulses are localized around the center of x-direction in order to observe explicitly the reconnection X-point. The results showed that, as a result of such perturbation, the process of magnetic reconnection turns on in an X-point and proceeds continuously. The rate of reconnection varies in a sinusoidal-like manner with time, since the constructive or destructive superposition of pulses changes the topology of the X-point. Therefore, the rate of reconnection, even in the saturation regime varies slightly with time. Moreover, increasing the amplitude of pulses, leads to a faster reconnection.

As the initial pulses are propagating towards the current sheet, their kinetic energy are distributed over a larger space, and also a fraction of this energy is converted to the magnetic energy by generating perturbed magnetic fields. Therefore, the amplitude of secondary pulses decreases. Even, the amplitude of pulses in the vicinity of current sheet decreases two or three orders of magnitude compared to the amplitude of initial pulses on the boundary. This means that, the generated reconnection becomes slower. To overcome this physical problem and understand what will happen for the magnetic reconnection with a larger amplitude of perturbation, we decided to assume a transient wave-like perturbation of plasma velocity throughout the y-direction (normal to the current sheet), which is again localized around the center of x-direction. In this case, the amplitude, period, T (or frequency) and wavelength (or wavenumber) of plasma wave are the main parameters that may affect the reconnection process and define its rate.

We concluded that MHD waves with a larger period (or lower frequency) affect more considerably both on the reconnection rate and on the topology of current sheet. As the period increases, the rate of reconnection increases too and the secondary nonlinear X-points are generated. In other words, the interaction of a transient MHD wave with an equilibrium current sheet results in a significant dynamical evolution associated with the instability of magnetic reconnection process, and even, the well-known tearing instability appears in the current sheet. We also found that an MHD wave with a larger wavelength (or lower wavenumber) can also result in a faster reconnection and even makes current sheet tilted.

These results are of interest in the contexts of both fusion plasma devices of Tokamaks and solar corona plasmas. In both environments, the existence and propagation of various kinds of MHD waves alongside of the current sheets, where magnetic field changes its direction, are clearly understood. Therefore, their interaction with each other is a non-negligible phenomenon, and eventually results in a complicated nonlinear dynamics of system. Meanwhile, any unbalanced magnetohydrodynamic perturbation of plasma velocity on the outside boundary of confined plasma in tokamaks, can propagate inwards and affect the current sheet existed at a layer with a safety factor $q = 1$. Regarding the solar corona plasmas, we note that according to the standard flare model, the plasma velocity on the boundaries of current sheet of a flare can be disturbed by the motion of other neighboring loops or plasma jets. As a result, the magnetic reconnection phenomenon may be triggered inside the current sheet. This is the mechanism that the excess magnetic energy of a flare is released and converted to the thermal and kinetic energy of plasmas and also the acceleration of charged particles.

Our study can be extended to the cases where the perpendicular component of the equilibrium magnetic field, namely, guide field, is not zero. Observational studies of relevant magnetic structures have reported the presence of a weak perpendicular component, which results in a modified rate of reconnection. Furthermore, extending this study from a single-fluid to the two-fluid MHD will be interesting. In the two-fluid model, the dynamics of an ion and electron components become separated. The ions close to the X-point become motionless, while the electron component of plasma flow still continues and convects the magnetic field lines to the reconnection site faster. Advanced reconnection models have indicated that including the Hall effect will facilitate the rate of reconnection. The last but not the least assumption is that, the pulses can intersect the current sheet oblique rather than perpendicular which was the case in our work.

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Authors' Contributions

All authors have the same contribution.

Data Availability

No data available.

Conflicts of Interest

The authors declare that there is no conflict of interest.

Ethical Considerations

The authors have diligently addressed ethical concerns, such as informed consent, plagiarism, data fabrication, misconduct, falsification, double publication, redundancy, submission, and other related matters.

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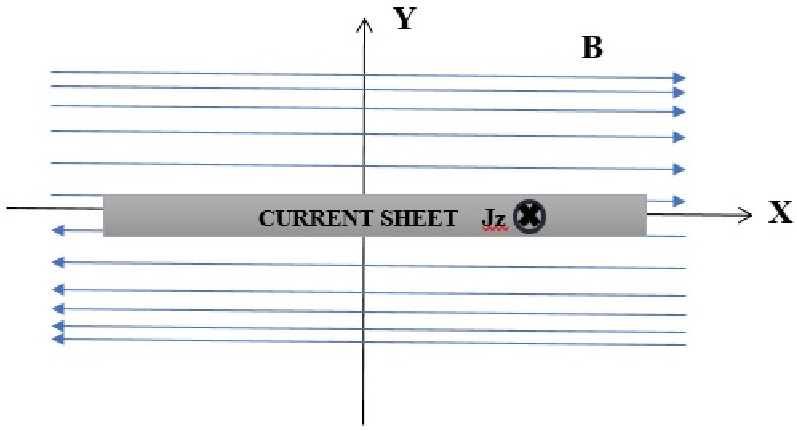

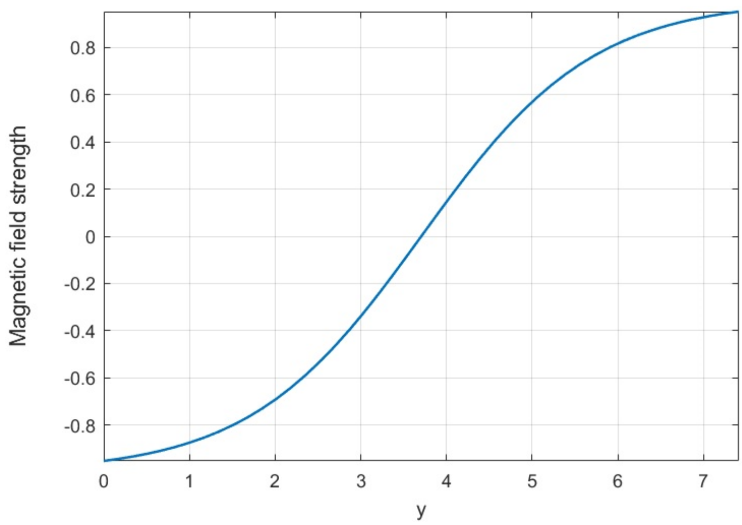

Figure 1: The equilibrium magnetic field structure and profile.

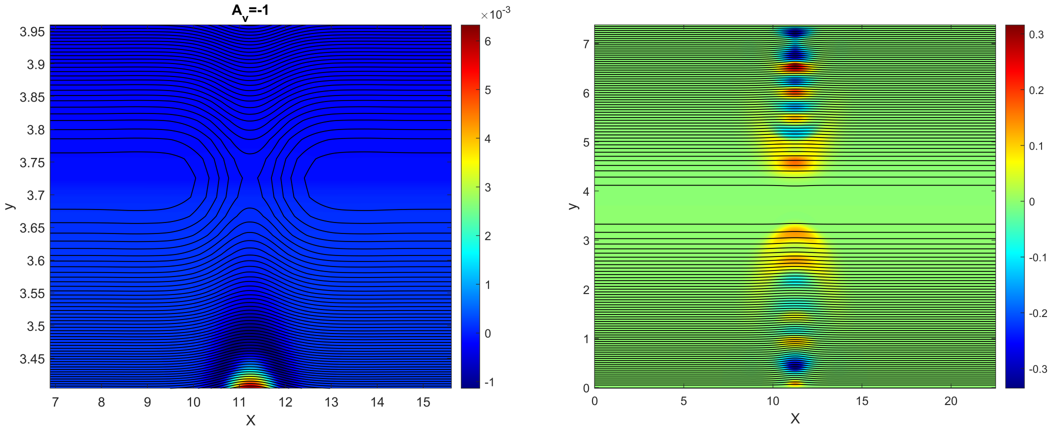

Figure 2: The contours of magnetic field lines and the image of plasma velocity (Vy) at $t = 1$. Right: for all simulation box; Left: for a zoomed-in region close to the current sheet.

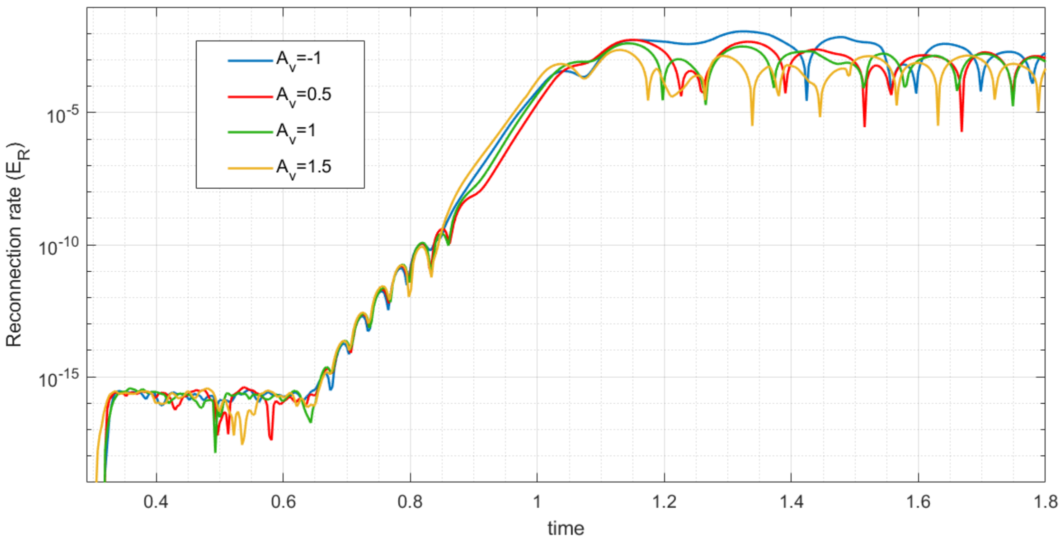

Figure 3: Temporal variation of reconnection rate for different values of velocity amplitude, A_v.

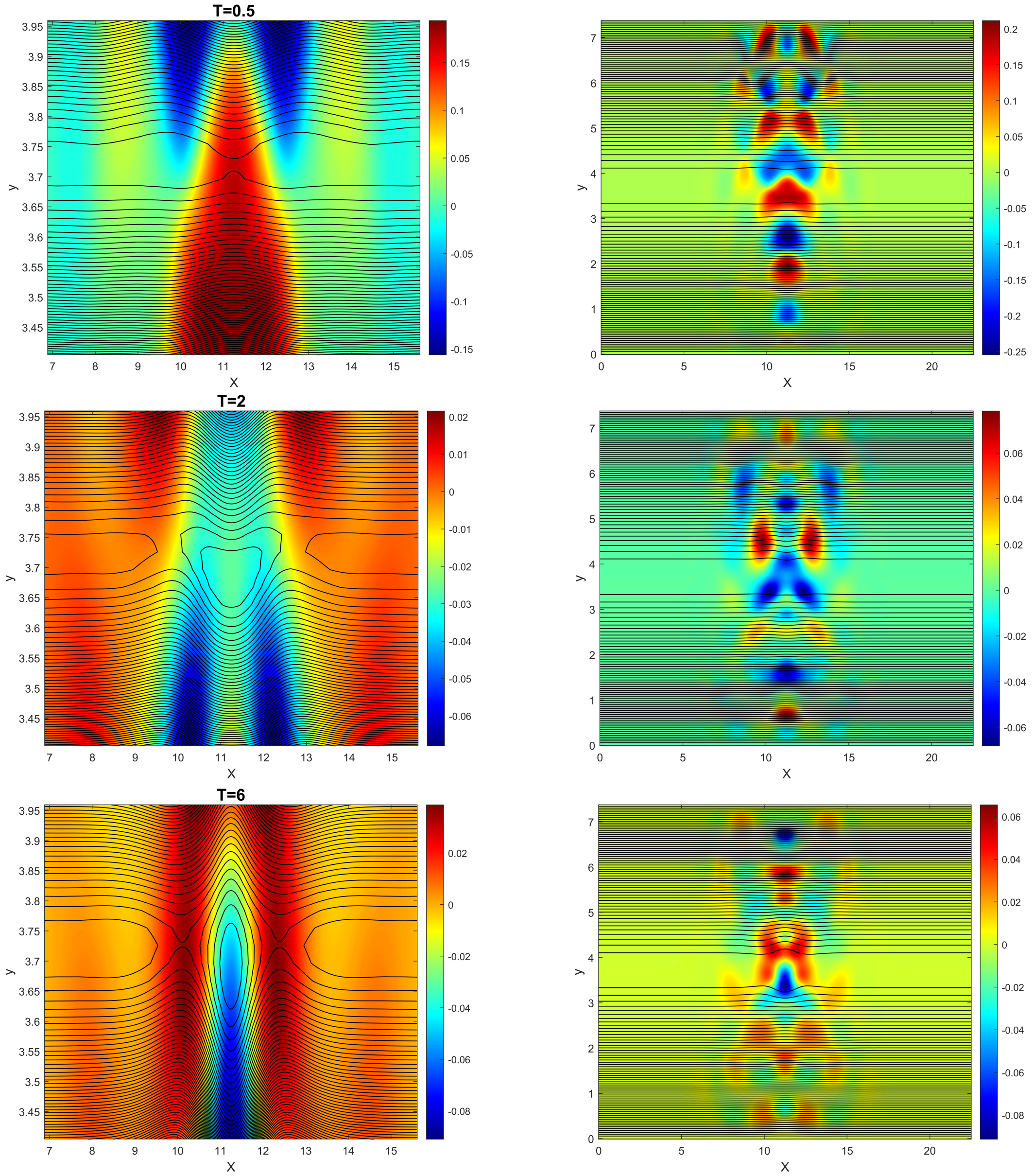

Figure 4: The plot of magnetic field lines and the plasma velocity (Vy) at $t = 2.0$ for three values of $T = 0.5, 2.0, 6.0$. Right: for all simulation box; Left: for a zoomed-in region.

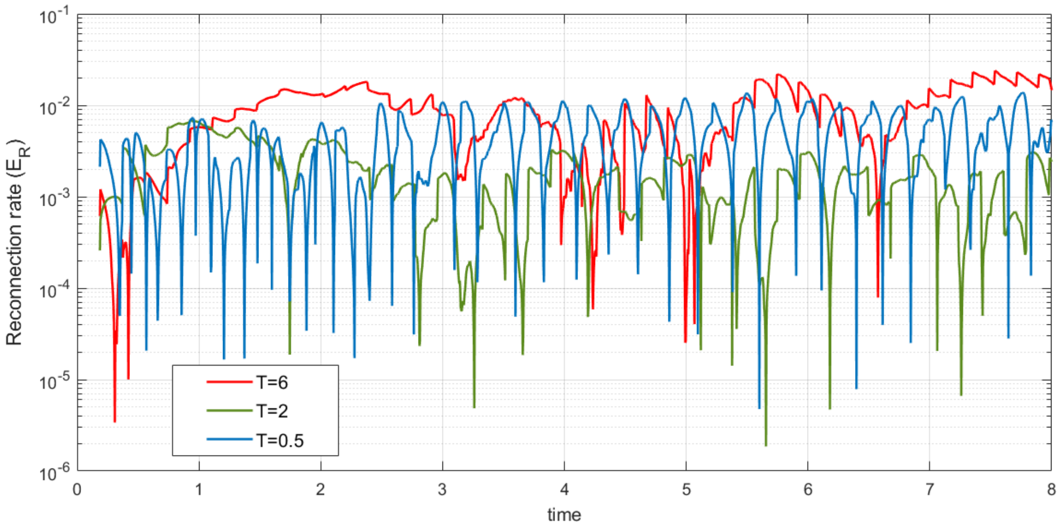

Figure 5: Temporal variation of reconnection rate for different values of wave period, T.

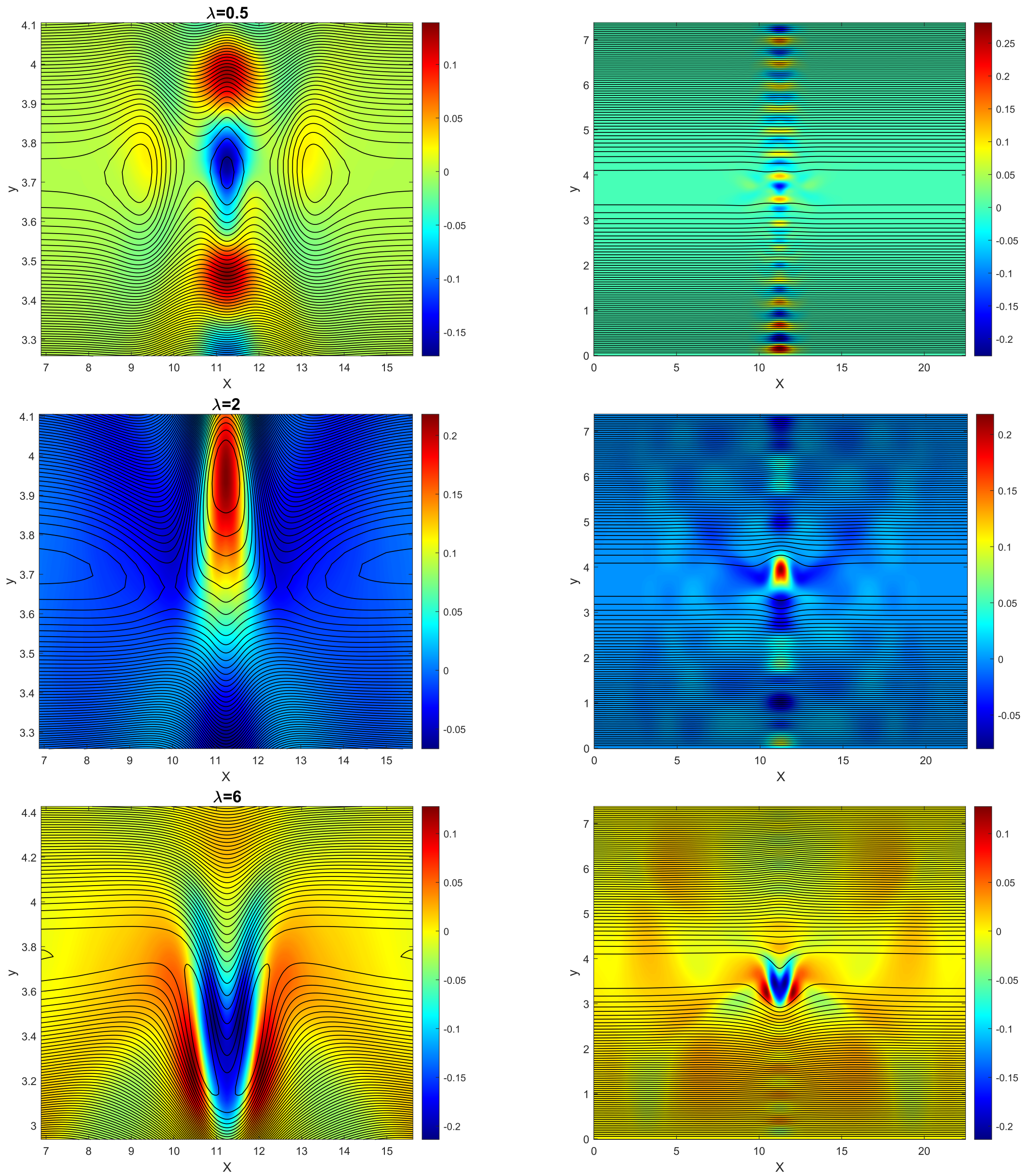

Figure 6: The plot of magnetic field lines and the plasma velocity (Vy) at $t = 11.6$ for three values of wavelength. Right: for all simulation box; Left: for a zoomed-in region.

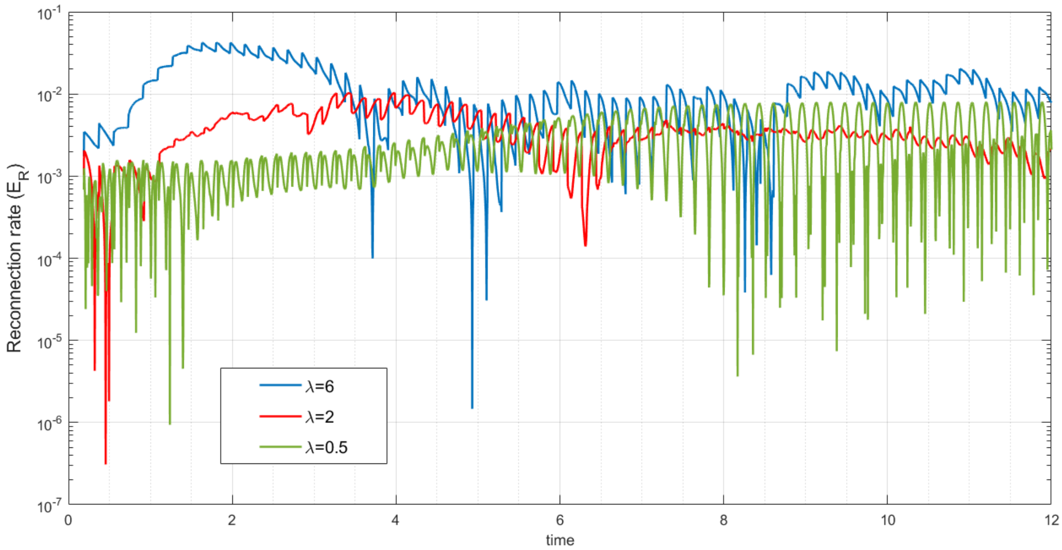

Figure 7: Temporal variation of reconnection rate for different values of wavelength.