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Effects of resonant magnetic perturbation on the instability of single tearing mode with non-shear flow*

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Non-shear flow can change the O-point position of a magnetic island, and thus it may play an important role in the effects of resonant magnetic perturbation (RMP) on the single tearing mode. We employ the nonlinear magnetohydrodynamics model in a slab geometry to investigate how RMP affects the single tearing mode instability with non-shear flow. It is found that the driving and suppressing effects of RMP on single tearing mode instability will appear alternately. When the flow velocity is small, the suppressing effect plays a major role through the development of the mode, and the tearing mode instability will be suppressed. With the flow velocity increasing, the driving effect will increase, while the suppressing effect will decrease. When the two effects reach equilibrium, the tearing mode will become stable.

Keywords: resonant magnetic perturbation, tearing mode, instability, flow

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1. Introduction

The tearing mode is an important unstable mode in tokamak plasmas, which is driven by current density gradient and finite plasma resistivity. How to suppress tearing mode instability has become a hot topic. The analytic linear theory of the tearing mode with shear flow has been studied by many researchers.[1–13] They found that the equilibrium shear flows approaching the Alfvén velocity can greatly modify the stability criteria of the tearing mode instability. Moreover, Ofman *et al*. studied the effect of shear flow on the nonlinear evolution of tearing mode instability.[14] They found that the shear flow can decrease the saturation magnetic island width, implying that the shear flow can suppress the tearing mode instability. In recent decades, researchers found from experiments that the resonant magnetic perturbation (RMP) can also suppress the tearing mode instability.[15–18]However, the physical mechanism of the suppressing effect of RMP on the tearing mode instability is not very clear.[15–18]

In this paper, we investigate the effects of RMP on the single tearing mode with flow in a two-dimensional (2D) geometry based on the magnetohydrodynamics (MHD) model. In order to better study the suppressing effect of RMP, we use a non-shear flow to eliminate the suppressing effect of the shear flow on the tearing mode instability. This paper is organized as follows. In Section 2, the nonlinear MHD equations in slab geometry are presented, together with the initial magnetic fields and the boundary conditions that excite the single tearing mode. The numerical results are presented in Section 3, and the summary is given in Section 4.

2. Model and basic equations

We consider a problem in which an equilibrium current is embedded in the z-direction in the standard sheared magnetic field. The magnetic field is set as $\boldsymbol{B} = B_T\hat{z} + \nabla \times (\psi\hat{z})$, with $\psi(x,y)$ being the magnetic flux, and B_T being the magnetic field strength at the $x = 0$ surface. We apply the following dimensionless resistive MHD equations to solve this problem:[19]

$$\frac{\partial \rho}{\partial t} = -\boldsymbol{u}\cdot\nabla\rho - \rho\nabla\cdot\boldsymbol{u}, \tag{1}$$

$$\frac{\partial P}{\partial t} = -\boldsymbol{u}\cdot\nabla P - \Gamma P\nabla\cdot\boldsymbol{u}, \tag{2}$$

$$\frac{\partial \boldsymbol{u}}{\partial t} = -\boldsymbol{u}\cdot\nabla\boldsymbol{u} - \frac{1}{2\rho}\nabla(\beta P + B^2) + \frac{1}{\rho}(\boldsymbol{B}\cdot\nabla\boldsymbol{B} + \nu\nabla^2\boldsymbol{u}), \tag{3}$$

$$\frac{\partial \psi}{\partial t} = -\boldsymbol{u}\cdot\nabla\psi + \eta\nabla^2\psi, \tag{4}$$

where the plasma density ρ, plasma pressure P, lengths x and y, magnetic field $\boldsymbol{B}$, magnetic flux ψ, plasma velocity $\boldsymbol{u}$, and time t are scaled by ρ_0, P_0, L_0, B_0, $\psi_0 = B_0L_0$, $u_{\rm A} = B_0/\sqrt{4\pi\rho_0}$, and $\tau_{\rm A} = L_0/u_{\rm A}$, respectively. Γ represents the adiabatic index. The dimensionless viscosity ν and resistivity η are normalized as $\nu = \nu_{\rm m}/(u_{\rm A}L_0\rho_0)$ and $\eta = \eta_{\rm m}/(u_{\rm A}L_0)$, where $\nu_{\rm m}$ and $\eta_{\rm m}$ are the plasma viscosity and resistivity, respectively. $\beta = 8\pi P_0/B_0^2$ is the poloidal plasma beta.[19]

Initially, the equilibrium magnetic field and flow profiles are chosen as follows:[20]

$$\boldsymbol{B}(x) = B_0\tanh(x/a)\boldsymbol{e}_y, \tag{5}$$

$$\boldsymbol{u}(x) = u_0\boldsymbol{e}_y, \tag{6}$$

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where the parameter a is the half-thickness of the current sheet. B_0 and u_0 are the magnetic field strength and flow velocity.

The externally applied magnetic perturbation has the form of

$$B_x|_{x=1} = B_{x0}\left[\frac{\pi}{L_y}\sin\left(\frac{\pi y}{L_y}\right)\right], \tag{7}$$

where $B_{x0} = 0.001$ is the RMP amplitude, and L_y is the simulation width in the y-direction with $0 \le y \le L_y$.[21]

The simulation domain is set as $-1 \le x \le 1$ and $0 \le y \le 2$. The periodic and free boundary conditions are imposed at $y = 0, 2$ and $x = \pm 1$, respectively. A Runge–Kutta finite difference method is employed to solve Eqs. (1)–(4), with fourth-order accuracy in time and second-order accuracy in space. In this simulation, the parameters $\nu = 5 \times 10^{-5}$ and $\eta = 5 \times 10^{-4}$ are used to satisfy $\sqrt{\eta} \gg \triangle x$ and the temporal step length also decreases to satisfy the Courant–Friedrichs–Lewy numerical stability condition.[22–24]

3. Numerical results

Figure 1 shows the dependence of the maximum value of magnetic island width $W_{\max}$ on the flow velocity u_0 for two different cases: one with RMP and the other without RMP. For case 1, it can be seen that $W_{\max}$ does not change with u_0. This indicates that the non-shear flow has no effect on the tearing mode instability. For case 2, when u_0 increases, $W_{\max}$ decreases with u_0 first, and then reaches a minimum value that approximately equals that of the case without RMP at $u_0 = 0.05$. When $u_0 > 0.05$, $W_{\max}$ will increase slightly and finally become almost unchanged. It suggests that the tearing mode is suppressed, but the degree of the suppression does not increase with the increase of u_0.

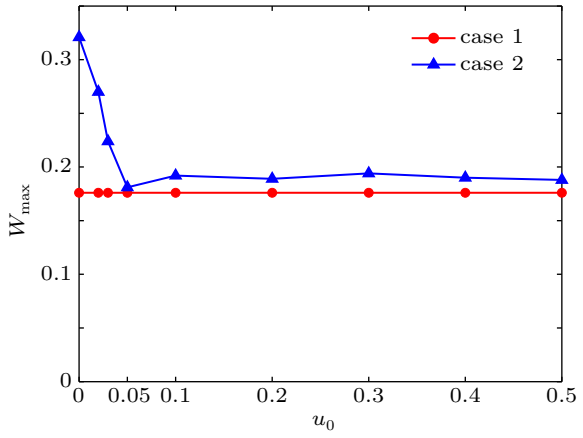


Fig. 1. Dependence of the maximum value of magnetic island width on the flow velocity. Case 1: without RMP (red dots); case 2: with RMP (blue triangles).

In order to illustrate the reasons for the above results, we present the time evolution of the magnetic island width and the O-point position for different u_0 as shown in Figs. 2 and 3, respectively. It can be seen from Fig. 2 that the growth curve of the magnetic island width is a smooth line when $u_0 = 0$. However, when $u_0 \neq 0$, the growth curves are no longer smooth but have a periodic fluctuation, and the period of fluctuation decreases with u_0. From Fig. 3, we find that the above results are related to the O-point position of the magnetic island. When $u_0 = 0$, the O-point position is at $y = 0$ as shown in Fig. 3(a), and the growth curve of the magnetic island width is a smooth line. When $u_0 \neq 0$, the O-point position will fluctuate in the y-direction, and the frequency of the fluctuation increases with u_0.

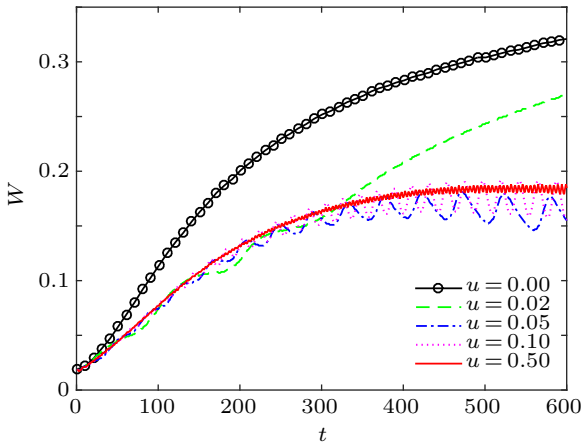


Fig. 2. Time evolution of the magnetic island width with RMP for different u_0.

The effects of RMPs on the instabilities of tearing modes have been discussed, and it is thought that the case for non-shear flow can be treated as that without flow but the boundary perturbation rotated.[25,26] Here, we find that the above results are similar those for the double tearing mode with flow.[19,27,28] Therefore, for the driving and suppressing effects of RMP on single tearing mode instability, we give another interpretation as follows. As we know, for the double tearing mode, when the O-point positions of two magnetic islands are 'antisymmetric' (O–X), the double tearing mode is unstabilized by the mutual driving of the magnetic islands.[19] On the other hand, when the O-point positions of two magnetic islands are 'symmetric' (O–O), the double tearing mode is stabilized by the mutual suppressing of magnetic islands.[28] For the single tearing mode with RMP, the RMP is like a magnetic island (M1) with an invariable position, whose O and X-point positions are at $y = 1$ and $y = 0$ as shown in Fig. 4, respectively. When the magnetic island (M2) appears on the rational surface, M2 and M1 will form a mode which is similar to the double tearing mode. When $u_0 = 0$, the O-point position of M2 is at $y = 0$ (see Fig. 3(a)). The O-point positions of M1 and M2 are antisymmetric, so M1 will drive the M2 to growth. In other words, the RMP plays a role of driving. When $u_0 \neq 0$, the O-point position of M2 will show a periodic change from $y = 0$ to $y = 2$, and this period will decrease with u_0 (see Fig. 3). In one period, while the O-point position of M2 changes from $y = 0$ to $y = 1$, the O-point positions of M1

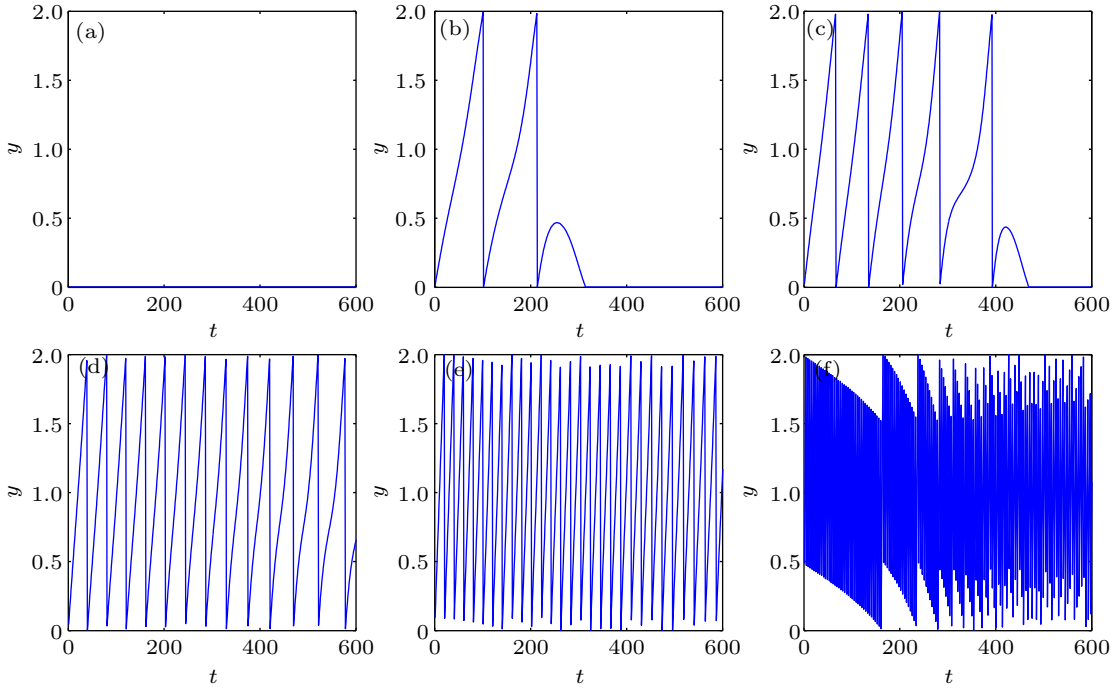


Fig. 3. Time evolution of the O-point position of magnetic island with RMP for different u_0. (a) $u_0 = 0$; (b) $u_0 = 0.02$; (c) $u_0 = 0.03$; (d) $u_0 = 0.05$; (e) $u_0 = 0.1$; (f) $u_0 = 0.5$.

and M2 gradually change from antisymmetric to symmetric, and the effect of RMP gradually changes from driving to suppressing. However, when the O-point position of M2 changes from $y = 1$ to $y = 2$, the O-point positions of M1 and M2 gradually change from symmetric to antisymmetric, and the effect of RMP gradually changes from suppressing to driving. Therefore, in one period, the driving and suppressing effects of RMP will appear alternately. These facts explain the reason why, when $u_0 \neq 0$, the growth curves of the magnetic island width have periodic fluctuation as shown in Fig. 2. Moreover, the longer the period time, the stronger the suppressing effect of RMP and the smaller the maximum value of the magnetic island width. For example, before $t \approx 200$, for the case of $u_0 = 0.02$, the period of the O-point position changing from $y = 0$ to $y = 2$ is longer than that in the other cases, implying $W_{\max}$ in this case is the smallest. However, since the flow velocity is too small, it cannot continuously affect the tearing mode through the development of the whole mode. The O-point positions gradually become $y = 0$ after $t \approx 200$. At this point, the O-point positions of M2 and M1 gradually become antisymmetric, causing the width of M2 to increase. As a result, the $W_{\max}$ of M2 does not decrease, but increases. These results coincide with the green dashed line in Fig. 2. With u_0 increasing, when the flow exactly and continuously affects the tearing mode through the whole development of the mode ($u_0 = 0.05$), $W_{\max}$ will reach the minimum value. If u_0 increases further, the period will become shorter, and the suppressing effect of RMP becomes weaker. As a result $W_{\max}$ will increase (e.g. $u_0 = 0.1$). When u_0 reaches a value that can balance the driving and suppressing effects of RMP, $W_{\max}$ will hardly change (e.g. $u_0 = 0.5$).

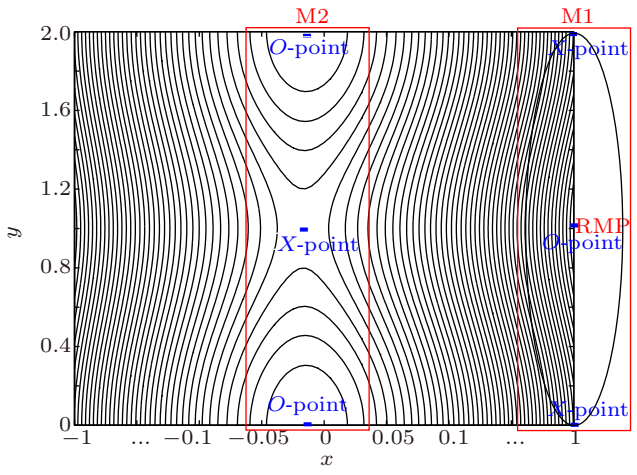


Fig. 4. A double tearing mode consisting of RMP and magnetic island.

The simulations also show that there exists a threshold u_{0c}, over which the RMP has little influence on the tearing mode instability. This threshold value can be determined when the magnetic island width does not fluctuate up and down. This phenomenon can be understood as follows: when the flow velocity reaches the threshold u_{0c}, the effects of the drive and the suppression of RMP will reach a balance, the magnetic island width will not change and the tearing mode will become stable. In fact, the physical mechanism for this phenomenon may also be explained by the structure and dynamics of the Alfvén resonance layer,[26] which are beyond the scope of this work, thus we do not give further discussions here.

4. Conclusion

In this paper we have studied the effects of RMP on single tearing mode instability with non-shear flow in a 2D geometry based on the MHD model. From the simulations, we found that RMP behaves like a magnetic island with a fixed position, while the flow can change the *O*-point position of the magnetic island on the rational surface. Therefore, the driving and suppressing effects of RMP on single tearing mode instability appear alternately, leading to a periodic fluctuation for the growth curve of magnetic island width. When the flow velocity is small, the suppressing effect of RMP plays a major role in the development of the mode, and this will cause the maximum of the magnetic island width to decrease. When the flow velocity increases, the driving effect of RMP will increase, while the suppressing effect will decrease. When these two effects reach an equilibrium, the maximum of the magnetic island width will become almost unchanged, and the tearing mode will be stable.

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