Stabilization of resistive tearing modes by applied resonant magnetic perturbations

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1. Introduction and theoretical model

Tearing modes and neoclassical tearing modes (NTMs) can often be unstable in tokamak plasmas, leading to magnetic islands inside the plasmas, which have been found experimentally to degrade the energy confinement and to limit the β value of tokamak plasmas well below the ideal MHD limit [1-4]. The intrinsic error field of tokamaks or externally applied resonant magnetic perturbations (RMPs) can significantly affect the tearing modes [5-13]. For the plasma being originally stable to tearing modes, an applied RMP can penetrate through to the rational surface and generate a magnetic island there [5-7, 13]. Once an island is sufficiently large, it will be locked to the machine error field or applied RMPs [5, 8-10, 12]. In addition, RMPs of moderate amplitude were found to reduce the island size in tokamak experiments [5, 11-12]. These different findings have attracted great interest in fusion research, and further investigation is required in order to understand the plasma response to RMPs.

Here nonlinear numerical modeling based on reduced MHD equations has been carried out. Both the mode locking and mode stabilization by RMPs are obtained from numerical modeling. It is found that the suppression of the m/n=2/1 tearing mode by RMPs of moderate amplitude is possible for a sufficiently high plasma rotation velocity and lower Alfvén velocity. A larger plasma viscosity enhances the mode stabilization.

The large aspect-ratio tokamak approximation is utilized. The magnetic field is expressed as $\mathbf{B}=B_{0t}\mathbf{e}_t-(kr/m)B_{0t}\mathbf{e}_\theta+\nabla\psi\times\mathbf{e}_t$, where B_{0t} is equilibrium toroidal field, m/r and k=n/R are the wave vectors in $\mathbf{e}_\theta$ (poloidal) and $\mathbf{e}_t$ (toroidal) direction, respectively. The stream function ϕ is defined by $\mathbf{v}=\nabla\phi\times\mathbf{e}_t$.

The Ohm's law, the equation of motion and the energy conservation equation are utilized. Normalizing the length to the minor radius a, time t to the resistive time $\tau_R=a^2\mu_0/\eta$, the helical flux ψ to aB_{0t}, velocity $\mathbf{v}$ to a/τ_R, and electron temperature T_e to $T_e(r=0)$, one has

$$\frac{d\psi}{dt}=E-\eta(j-j_b), \tag{1}$$

$$\frac{dU}{dt}=-S^2\nabla_{\parallel}j+\mu\nabla_{\perp}^2U+S_m, \tag{2}$$

$$\frac{3}{2} n_e \frac{dT_e}{dt} = n_e \nabla_{\parallel}(\chi_{\parallel} \nabla T_e) + n_e \nabla_{\perp}(\chi_{\perp} \nabla T_e) + S_P, \tag{3}$$

where $d/dt=\partial/\partial t + v_\perp \times \nabla$, $j=\nabla_\perp^2\psi-2nB_t/(mR)$ and $j_b=-c_b(r/R)^{1/2}n_eT_e'/B_\theta$ are the toroidal plasma current density and the bootstrap current density respectively. η is the normalized plasma resistivity, E the equilibrium electric field, and $U=-\nabla_\perp^2\phi$ the plasma vorticity. $S=\tau_R/\tau_A$, $\tau_A=a/V_A$ is the toroidal Alfvén time, μ the plasma viscosity, $\chi_\parallel$ and $\chi_\perp$ the parallel and perpendicular heat conductivities, S_p the heating power, S_m the poloidal momentum source, and n_e the electron density. The effect of a single helicity RMP with m/n=2/1 is taken into account by the boundary condition $\psi_{m/n}(r=a)=\psi_a aB_t\cos(m\theta+n\varphi)$.

2. Numerical results and summary

Equations (1)-(3) are solved simultaneously using the initial value code TM1, which has been used for modeling the nonlinear growth and saturation of NTMs and their stabilization by RF current earlier[10]. In figure 1 the normalized mode angular frequency, ω_p/ω_0, and the island width at nonlinear saturation are shown as a function of the applied RMP amplitude ψ_a for $\omega_0=1.6\times10^4/\tau_R$, $S=10^7$, $\mu=3a^2/\tau_R$, $\chi_\perp=3a^2/\tau_R$, $\chi_\parallel=3.0\cdot10^8a^2/\tau_R$, and the bootstrap current density fraction at the resonant surface $f_b=j_b/j_0=0$ [12]. ω_0 is the original mode frequency without RMPs. A monotonic profile for the safety factor q is assumed with the q=2 surface located at $r_s=0.7a$. Three different regimes are seen from figure 1:

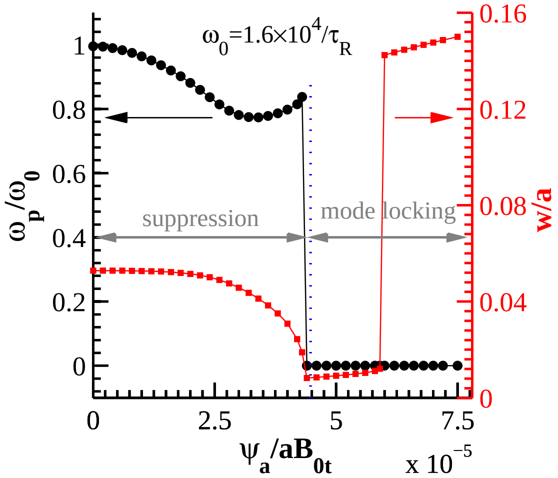

Fig.1 *Normalized mode angular frequency and island width versus ψ_a.*

(i) *Mode suppression regime* ($\psi_a<4.5\times10^{-5}aB_t$), in which the island width decreases with increasing RMP amplitude. It is interesting to note that the mode frequency decreases with increasing ψ_a for $\psi_a\leq3.1\times10^{-5}aB_t$ but increases for $3.1\times10^{-5}aB_t<\psi_a<4.5\times10^{-5}aB_t$. Such a frequency increase is likely to be caused by weaker electromagnetic force acting on the island with decreasing island width.

(ii) *Small locked island regime* ($4.5\times10^{-5}aB_t<\psi_a<5.9\times10^{-5}aB_t$), in which the mode is locked to the RMP as indicated by the zero mode frequency, while the island width is very small, being different from the usual mode locking with a large island width.

(iii) *mode locking regime* ($\psi_a>5.9\times10^{-5}aB_t$), beginning from a large jump in the island width. The mode frequency is also zero in this regime, but the island width is significantly larger than the original one without RMP.

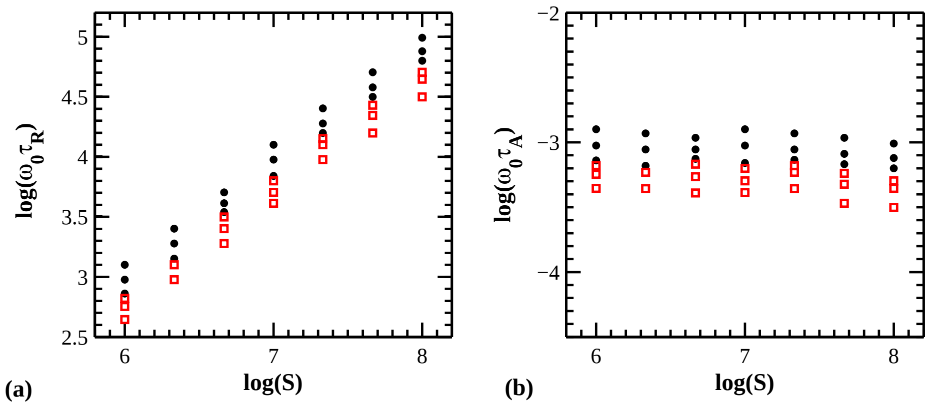

Fig.2 *(a) Required normalized original mode angular frequency, $\omega_0\tau_R$, for mode stabilization by RMP versus magnetic Reynolds number S. The solid circles (empty squares) show the cases for which there is (no) mode stabilization. (b) Same as (a) except that the vertical axis is $\log(\omega_0\tau_A)$.*

Figure 2(a) shows the required normalized original mode angular frequency $\omega_0\tau_R$ for mode stabilization by RMP versus magnetic Reynolds number S in the $\log(\omega_0\tau_R)\sim\log(S)$ plane. The solid circles (empty squares) show the case for which there is (no) mode stabilization. The required $\omega_0\tau_R$ for mode stabilization is proportional to S. When the mode angular frequency is normalized to the Alfvén time τ_A as shown in figure 2(b), however, the required $\omega_0\tau_A$ for mode stabilization is nearly a constant for different S values. The critical value is $\log(\omega_{0c}\tau_A)$=-3.18, and above which the 2/1 tearing mode can be stabilized by RMPs of moderate amplitude. Below this value no mode stabilization by RMPs is found. The value of $\log(\omega_{0c}\tau_A)$=-3.18 corresponds to $\omega_{0c}\tau_A=6.6\times10^{-4}$ or $f_{0c}=\omega_{0c}/2\pi=4.77$ kHz for typical J-TEXT experimental parameters ($\tau_A=2.2\times10^{-8}$s). For a lower Alfvén velocity the critical mode frequency for the mode stabilization by RMP is lower.

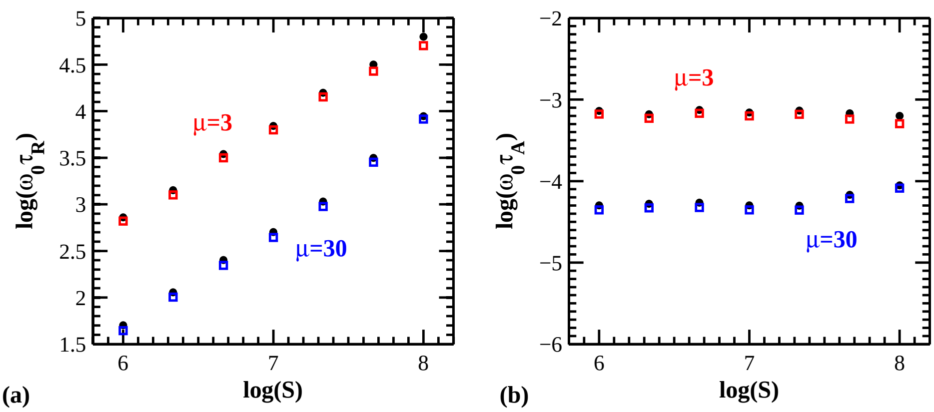

Fig.3 *Same as figure 2 except for the plasma viscosity $\mu=3a^2/\tau_A$ (red) and $\mu=30a^2/\tau_A$ (blue). A larger plasma viscosity enhances the mode stabilization.*

In figure 3, the required original mode angular frequency $\omega_0\tau_R$ for mode stabilization by RMPs is shown as a function of log(S), with the plasma viscosity $\mu=3a^2/\tau_A$ (red) and $\mu=30a^2/\tau_A$ (blue). For $\mu=3a^2/\tau_A$, the critical value is $\log(\omega_{0c}\tau_A)$=-3.18 as also seen from figure 2. For $\mu=30a^2/\tau_A$, the critical value is reduced to $\log(\omega_{0c}\tau_A)\approx-4.2$, which shows that the critical mode frequency is inversely proportion to plasma viscosity, indicating that a larger plasma viscosity enhances the mode stabilization by RMPs.

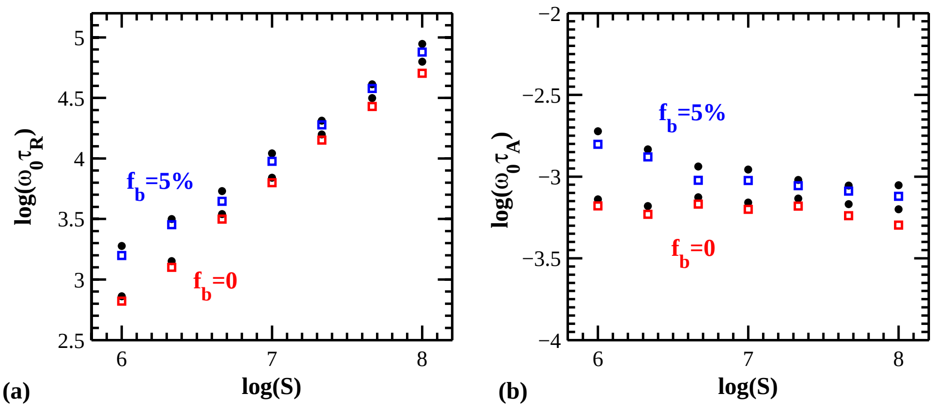

Fig.4 *Same as figure 2 except for the bootstrap current density fraction f_b=0 (red) and =5%. The bootstrap current perturbation reduces the stabilizing effect of RMPs on tearing modes.*

To study the effect of the bootstrap current perturbation, in figure 4 the required original mode angular frequency $\omega_0 \tau_R$ for mode stabilization by RMP is shown as a function of log(S) for f_b=0 (red) and f_b=5% (blue). The critical mode frequency for f_b=5% is much larger than that for f_b=0 at low S values. When S is larger than 10^7, the difference between these two cases is smaller. Further calculations with S=10^7 show that when f_b>8.5%, there is no mode stabilization by RMP.

In summary, nonlinear numerical modeling based on reduced MHD equations has been carried out. Both the mode locking and mode stabilization by RMPs are obtained from numerical modeling. In addition, it is found that the mode stabilization by RMP is possible for a sufficiently high island rotation frequency and a low Alfvén velocity. A larger plasma viscosity enhances the mode stabilization. This work is supported by the Ministry of Science and Technology (Contract No. 2010GB107004, 2011GB109001, and 2008CB717805,) and the Chang-Jiang scholar project of the Ministry of Education, China.

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