§2. Improvement of Nonlinear Three Dimensional Simulation Code for External MHD Modes

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For a stationary high beta tokamak plasma, it is important to control of resistive wall modes (RWMs), since the RWMs cause a plasma disruption and limit the plasma beta. The RWMs are also observed in low beta plasmas for rapid current ramp-up experiments. In JT-60U, small current quench occurs at the plasma edge as a result of destabilization of the current-driven RWM with $(m, n) = (3, 1)$ mode[1] and after that, plasma disruption occurs.

For analyzing the plasma disruption due to the RWM, we have developed nonlinear three-dimensional magnetohydrodynamic (MHD) simulation code which can be treated a free boundary problem. As mentioned the later, the calculation time for the free boundary problem is longer than the case for the fixed boundary problem. Hence, we improved our simulation code to obtain reliable results rapidly. In our simulation code, the following reduced MHD equations are solved numerically in the cylindrical coordinates;

$$\frac{\partial \psi}{\partial t} = -\mathbf{B}\cdot\nabla\phi + \eta J - E, \quad (1)$$

$$\frac{\partial U}{\partial t} = \mathbf{v}\cdot\nabla U - \mathbf{B}\cdot\nabla J + \nu\nabla_\perp^2 U, \quad (2)$$

$$\frac{\partial T}{\partial t} = \mathbf{v}_\perp\cdot\nabla T, \quad (3)$$

$$\mu_0 J = \nabla_\perp^2\psi, \quad U = \nabla_\perp^2\phi,$$

where ψ is the poloidal magnetic flux defined by $\mathbf{B} = -\nabla\psi\times\mathbf{e}_z + B_0\mathbf{e}_z$, ϕ is the stream function defined by $\mathbf{v}_\perp = \nabla\phi\times\mathbf{e}_z$, T is temperature, and Spitzer resistivity is assumed, i.e., $\eta \propto T^{-3/2}$. For treating external MHD modes, a highly resistive plasma is introduced in the vacuum region to use the pseudo-vacuum model. The ratio of the resistivity in the highly resistive plasma η_v to one at the center η_0 is chosen as $\eta_v/\eta_0 = 10^7$. The magnetic Reynolds number $S = \tau_a/\tau_r$ is set to be $S = 10^7$, where $\tau_a = R\sqrt{\mu_0\rho_0}/B_0$, $\tau_r = \mu_0 a^2/\eta_0$, ρ_0 is density at $r = 0$, R is major radius of the plasma and a is minor radius of the core plasma.

Since the resistivity of the pseudo-vacuum plasma is extremely high, we have to solve implicitly the diffusion term of the poloidal flux in eq.(1). Previously, we used the LU factorization method for a band matrix in order to solve the diffusion term. The CPU time for this method is proportional to the cubic of the number of modes, and it is not relevant for the large-scale simulation. Therefore, we adopted the BiCGSTAB method instead of the LU-factorization in this study. Furthermore, our simulation code has been parallelized using the MPI (Message Passing Interface). These improvements of our simulation code make us to carry out nonlinear simulation with the large number of modes.

Using the improved simulation code, we have studied the nonlinear phenomena of the current-driven RWMs with $(m, n) = (3, 1)$ mode. Figures show time evolution of magnetic energy of $(m, n) = (3, 1)$ and $(5, 2)$ modes, where the numbers in each figures are the number of modes used in the simulation. When the $(m, n) = (3, 1)$ mode shows the nonlinear growth, the growth of the (5,2) mode becomes to slow due to the mode coupling of the $(m, n) = (3, 1)$ and $(m, n) = (2, 1)$ mode. In the nonlinear phase, the dynamic of the (5,2) mode depends on the number of modes used in the simulation. In this study, the maximum number of modes is 618. However, it seems that 618 modes are not enough to carry out the simulation of external MHD modes. The convergence check of the numerical results using modes more than 618 modes, and the analyzing of the relation between the plasma disruption and the equilibrium profile by the large-scale simulation are future works.

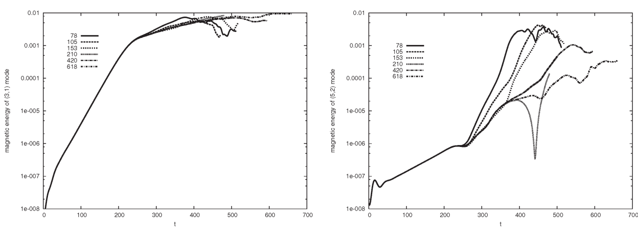

Figure 1: Dependence of time evolution of magnetic energies of (m, n) =(3,1) and (5,2) modes on the number of modes used in the simulations.

Reference

1) S.Takeji *et al.*, J. Plasma and Fusion Res., **78**, 447 (2001).