§10. Simulation Study of Nonlinear MHD Effects on Alfvén Eigenmode Evolution

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Nonlinear magnetohydrodymamic (MHD) effects on Alfvén eigenmode evolution were investigated via hybrid simulations of an MHD fluid interacting with energetic particles[1]. The investigation focused on the evolution of an n=4 toroidal Alfvén eigenmode (TAE) which is destabilized by energetic particles in a tokamak. In addition to fully nonlinear MEGA code, a linear-MHD version of MEGA code was used for comparison. The only nonlinearity in that linear code is from the energetic particle dynamics. No significant difference was found in the results of the two codes for low saturation levels, $\delta B/B \sim 10^{-3}$. In contrast, when the TAE saturation level predicted by the linear code is $\delta B/B \sim 10^{-2}$, the saturation amplitude in the fully nonlinear simulation was reduced by a factor of 2 due to the generation of zonal (n=0) and higher-n (n≥8) modes. This reduction is attributed to the increased dissipation arising from the non-linearly generated modes. The fully nonlinear simulations also show that geodesic acoustic mode is excited by the MHD nonlinearity after the TAE mode saturation.

The initial velocity-space distribution of the energetic ions is the slowing-down distribution with a maximum velocity $1.2\mathrm{v}_A$, where v_A represents the Alfvén velocity at the plasma center. The ratio of the energetic-ion Larmor radius to the minor radius a is 1/16 for the energetic-ion velocity equal to the Alfvén velocity. The aspect ratio is $R_0/a = 3.2$. We focus on the evolution of an n=4 TAE mode. The MHD nonlinearity generates fluctuations with toroidal mode numbers multiples of 4 (n=0, 4, 8, 12, 16, …), while they are restricted only to n=4 in the linear-MHD simulation. The energetic-ion effect on the MHD fluid is restricted only to n=4 mode to clarify the nonlinear MHD effects. Different central energetic-ion beta values β_{h0} were investigated with the spatial profile kept constant. The evolution of the m/n=6/4 harmonics of MHD radial velocity $\mathrm{v}_r/\mathrm{v}_A$ measured at the TAE peak location is compared in Fig. 1(a) between the linear-MHD simulation and the nonlinear MHD simulation for $\beta_{h0} = 1.7\%$ and viscosity, resistivity, and diffusivity $\nu = \eta/\mu_0 = \nu_n = 2.5\times10^{-7}\mathrm{v}_A R_0$. We see in Fig. 1(a) that the saturation level of $\mathrm{v}_r/\mathrm{v}_A$ for the nonlinear MHD case is reduced to half of the linear-MHD case. For cases where the instability growth is lower, the saturation level is $\mathrm{v}_r/\mathrm{v}_A \sim \delta B_r/B \sim 10^{-3}$, and the MHD nonlinearity does not play any important role.

To understand the underlying physics mechanism that reduces the TAE saturation level, we analyzed the time evolution of energy E_n and energy dissipation D_n for each toroidal mode number n. The energy dissipation in the MHD equations is the viscous heating and the Joule heating. We define the damping rate for each toroidal mode number using the energy and dissipation by $\gamma_{\mathrm{d\,n}} = D_\mathrm{n}/2E_4$ and also the total damping rate by $\gamma_{\mathrm{d\,ALL}} = \sum_\mathrm{n} D_\mathrm{n}/2E_4$. In Fig. 1(b) the evolution of $\gamma_{\mathrm{d\,n}}$ and $\gamma_{\mathrm{d\,ALL}}$ are compared with $\gamma_{\mathrm{d\,lin}} = D_4/2E_4$ in the relevant linear-MHD simulation. The total damping rate $\gamma_{d\,ALL}$, in the nonlinear MHD simulation, is clearly greater than the n=4 TAE damping rate $\gamma_{d\,\mathrm{lin}}$ in the linear-MHD simulation. This explains why the saturation level is reduced by the MHD nonlinearity. The nonlinear coupling increases the total energy dissipation leading to the lower saturation level. We observed the similar enhancement of the total damping rate and the consequent reduction of the saturation level for different dissipation coefficients. This suggests that the saturation level would similarly reduce by the nonlinear MHD effects even if the parameters for more realistic dissipation were taken into account. We have analyzed the spatial profiles and the evolution of the n=0 fluctuations in the nonlinear MHD simulation for $\beta_{h0} = 2.0\%$. The zonal flow and the pressure oscillate with the same frequency after the saturation of the instability. This oscillation is a GAM because the oscillation frequency and the coupling between the zonal flow and the 1/0 sine harmonic of the pressure fluctuation are consistent with the theory of GAM. It is evident that the GAM is excited through the MHD nonlinearity because the n=4 fluctuations of the energetic-particle current density retained in the simulations cannot directly drive the GAM.

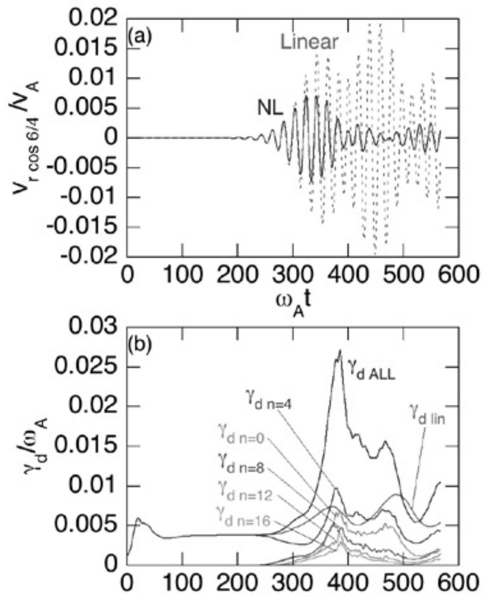

Fig. 1. Comparison of the radial velocity evolution for the linear-MHD and the nonlinear MHD runs using the cosine part of m/n=6/4 harmonics at r/a=0.42; (a), and evolution of damping rate for each toroidal mode number and total damping rate in the nonlinear MHD simulation, and damping rate in the linear-MHD simulation ($\gamma_{d\,\mathrm{lin}}$); (b) for $\beta_{h0} = 1.7\%$.

1) Y. Todo, H. L. Berk, and B. N. Breizman, Nucl. Fusion **50**, 084016 (2010).