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High-wavenumber ballooning-like modes with a finite parallel flow in LHD

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Fully three-dimensional, compressible and nonlinear MHD simulations are carried out to study nonlinear evolution of ballooning-like modes in LHD. A near-ideal dynamical evolution shows that growths of ballooning modes in brings about drastic deformations of the pressure. Another simulation which starts under a finite-amplitude flow parallel to the magnetic field lines suggests that the ballooning modes, which are obtained by the near-ideal simulation, are not sensitive to the parallel perturbation. In the nonlinear stage, only the parallel component of the velocity with $n = 1$ wavenumber survives the nonlinear saturation and the perpendicular velocity components become less energetic. Consequently, the saturated profile of the simulation with flow becomes more organized than that in the simulation without flow.

Keywords: MHD simulation, stability, parallel flow

1 Introduction

Study of magnetohydrodynamic (MHD) instability is one of the most basic and important subjects in the magnetic confinement research. In the Large Helical Device[1], pressure-driven instabilities are expected especially for the position of vacuum magnetic axis position $R_{ax} < 3.75m$ (*inward-shifted* magnetic axis position). Although some MHD signals are observed under an inward-shifted magnetic configuration (typically $R_{ax} = 3.6m$), the MHD activities do not bring about critical deterioration of the plasma profile and a high β-value of $\langle\beta\rangle \simeq 5\%$ has been been achieved.[2, 3, 4]

In order to clarify the mechanisms of a hot plasma to overcome the instabilities in LHD, we have been carrying out the fully three-dimensional, compressible and nonlinear MHD simulations by the use of the MHD In the Non-Orthogonal System (MINOS) code.[5, 6, 7, 8] The series of the MINOS simulations have revealed that there are some mechanisms which can reduce the impact of the instability, such as the profile modification (local fattenings) of the pressure, the release of the free-energy as the parallel kinetic energy, and the linear compressibility effect to reduce the growth rates of the unstable modes. However, we have also found that these mechanisms are not necessarily sufficient to suppress the high-wavenumber ballooning modes when the growths of them are near ideal.[8] Because of the overlapping of linear eigen-functions of the high-wavenumber ballooning modes, a local flattening of the pressure at one rational surface cannot stop growths of the multiple ballooning modes. In the simulations the considerable part of the free energy to drive the instability is released in the direction parallel to the magnetic field lines and the compressibility reduce the growth rates. However, these two mechanisms are not sufficient when the initial equilibrium is strongly unstable.

These results in conjunction with some simulations with the parallel heat conductivity suggest that the mild saturations in the LHD might be achieved through dissipative processes (including some sorts of turbulent viscosities caused by turbulence, which are out of scope of the single-fluid MHD), not through the processes in the frameworks of ideal MHD dynamics. Here we have to note that the suggestions or speculations are based on the simulations starting from an unstable equilibrium with very small random perturbations. While starting simulations from the equilibrium with small perturbations is basic and essential in the framework of the linear stability theory, it also makes senses to consider the plasma dynamics with finite-amplitude perturbations, or finite flows. In fact, the toroidal velocity in LHD experiments reaches to about 40~50 km/s[9], which is not negligible in comparison with the Alfvén velocity, though it is also pointed out in the reference that the flow velocity is not sufficient to stabilize the MHD modes.

Since the computations of the equilibrium with finite flows for fully three-dimensional configurations are not prepared sufficiently yet, it is still difficult to discuss the evolutions of unstable linear eigen-modes in the LHD now. Nevertheless, it may be worth carrying out MINOS simulations starting from the equilibrium with finite-amplitude perturbations, since such a computation can serve as a sort of numerical experiment to examine sensitivity of the linear eigen-modes without the flow to the strong perturbations. Here we concentrate on an initial flow in the direction parallel to the magnetic field lines, since the parallel flow is not directly related with the linear stability theory of the static equilibrium and thus we may be able to understand the time evolutions in the frame work of the stability theory of the static equilibrium. In the next section, we study numerical results of simulations with flows. The

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concluding remarks will be in §.3.

2 Nonlinear Simulation

A MINOS simulation with an initial finite-amplitude parallel flow is provided as follows. We make use of the numerical results of the near-ideal simulation in Ref.[8] as reference data. The number of grid points is $193 \times 193 \times 640$. Dissipative coefficients are set as the resistivity $\eta = 1 \times 10^{-6}$, the shear viscosity $\mu = 1 \times 10^{-6}$, the isotropic part of the heat conductivity $\kappa = 1 \times 10^{-6}$. We make use of a snap shot of the time evolution at $t = 64$ in the reference data as a part of the initial condition because the linear eigen-functions of the ballooning modes are formed at this time.[8] We perturb this initial data by adding a flow parallel to the magnetic field lines. The parallel flow is provided so that the velocity profile in the minor radial direction has the same profile as the pressure, for simplicity. It means $\mathbf{B} \cdot \nabla v_{//} = 0$ initially where $v_{//}$ is the parallel velocity. Then the most unsteady effect is expected in the centrifugal force. Here we set the maximum parallel velocity as the $\rho_0 v_{//}^2 / p = 1/1000$ at the position of the magnetic axis, where v_A is the Alfvén velocity and ρ is the mass density. Note that we have provided the initial equilibrium in the reference data with the peaked beta value $\beta_0 = 3.7\%$. A simple ordering of the right-hand-side terms of the momentum equation suggests that the centrifugal force of the parallel flow is quite smaller than the pressure gradient an the Lorentz force so that the parallel flow can be considered as a sort of the (finite-amplitude) perturbation to the equilibrium without flow.

In Fig.1, time evolutions of the (a)parallel and (b)sum of the normal and binormal components of the velocity with some specific poloidal (m) and toroidal (n) wavenumbers are shown. The wavenumbers are chosen so that the Fourier coefficients are the representatives of the linear eigen-functions. In Fig.1(a), many of the Fourier coefficients grow rapidly, while the $m/n = 0/0$ coefficients of the parallel component of the velocity has extremely large amplitude and stay almost constant. The $m/n = 2/1$ coefficient is perturbed initially due to numerical noise in the preparation of the perturbation. The perpendicular counter part of the $0/0$ coefficient in Fig.1(b) is only $1/10000$ of the parallel one, although it is also sufficiently large compared to the amplitudes of the other ($n \geq 1$) coefficients. A quick comparison of Fig.1 to Figs.2(b) and (c) in Ref.[8] reveals that the growth of the Fourier coefficients in Fig.1 are more rapid than those in Figs.2(b) and (c). Furthermore, the growths of the Fourier amplitudes in Fig.1 are slightly curved, suggesting the contributions of the nonlinear couplings through the dynamical evolutions.

In Fig.2, we see the radial profiles of the $n = 1$ pressure Fourier coefficients in the reference data and the perturbed simulation. It has been verified that the Fourier coefficients compose the linear eigen-function of the ballooning mode in Ref.[8]. We find that the Fourier coefficients in the perturbed simulation are very similar to that in the reference data.

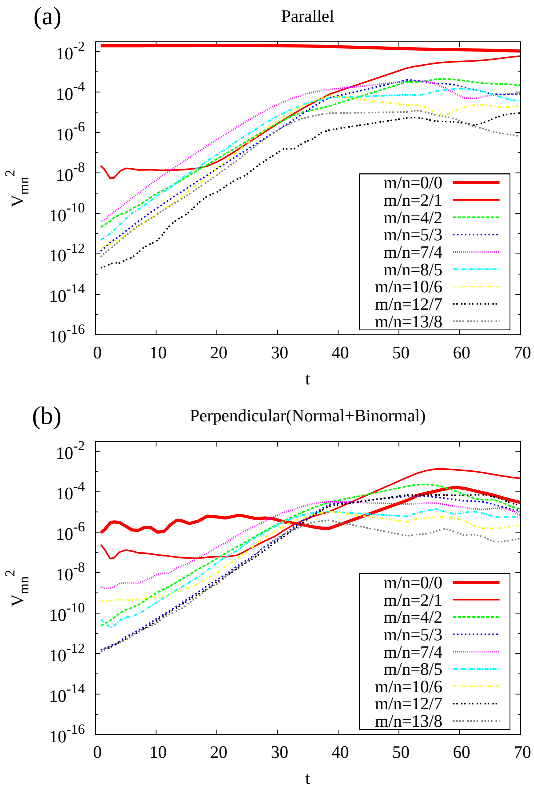

Fig. 1 Time evolutions of the Fourier amplitudes of (a)the parallel and (b)the perpendicular components of the velocity. The wavenumbers are selected as representatives of the linear eigen-modes of in the reference simulation.

In Figs.3 and Figs.4, we see the radial pressure profiles of the $n = 9$ and 15 modes respectively in the reference data and the perturbed simulation. The coefficients in Figs.3(c), (d) and Figs.4(c), (d) are the linear eigen-functions of the ballooning modes obtained in the reference data. Again we find that the Fourier coefficients in Figs.3(a), (b) and Figs.4(a), (b) are very similar to the linear eigen-functions. These observations suggest that the linear eigen-functions are not sensitive to the finite parallel perturbations and they might be good references to study the dynamical evolutions with the flow before the study of the stability theory for the equilibrium with flows are progressed.

In Fig.5(a), the three-dimensional view of the saturated state are shown. The isosurface and contours on a poloidal cross-section (left-hand-side to the paper) of the pressure are shown. The contours on a cross-section in the right-hand-side to the paper are for the pressure fluctuations. It is clear in the contour plots of the pressure fluctuations that the positive fluctuations are localized in the inner-side of the torus while the negative fluctuations are in the outer-side of the torus. The localization is mostly contributed by the $m/n = 2/1$ structure of the parallel ve-

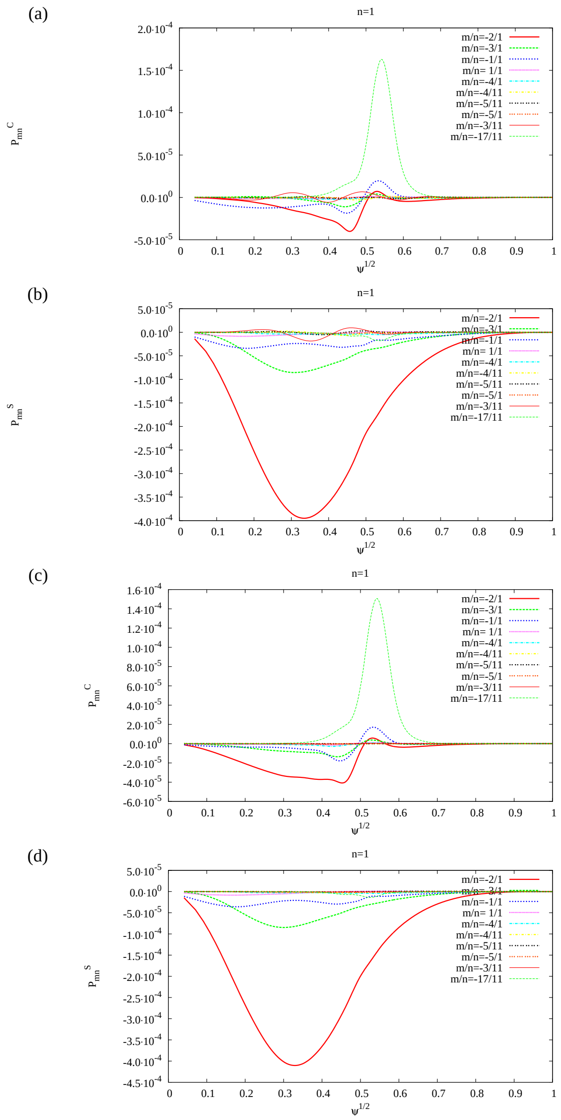

Fig. 2 Comparisons of the radial profiles of $n = 1$ Fourier coefficients. The (a)cosine and (b)sine parts of the Fourier coefficients in the perturbed simulations are compared to those in the reference simulation data (c) and (d), respectively.

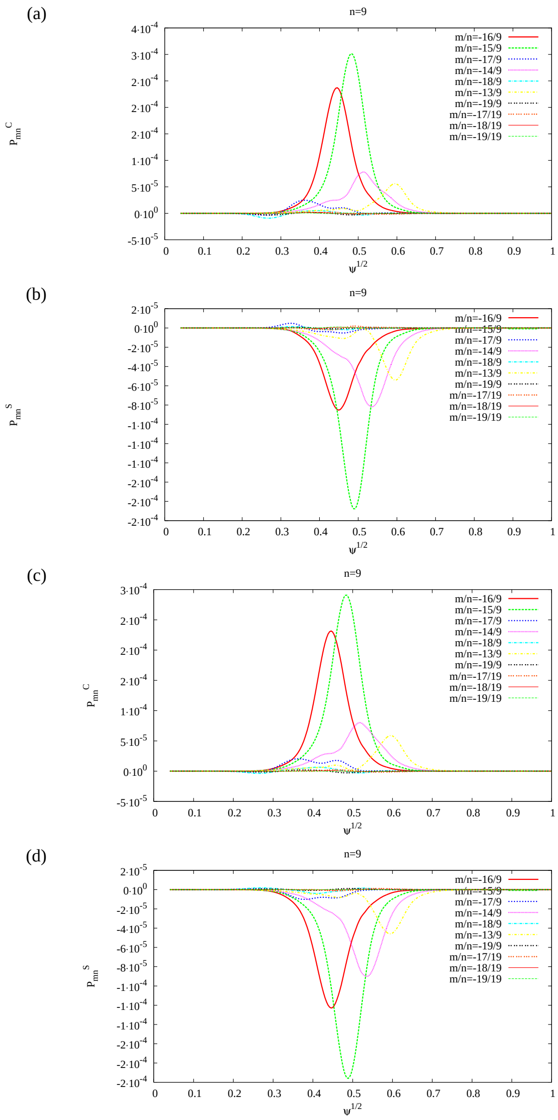

Fig. 3 The radial profiles of the pressure Fourier coefficients with $n = 9$ wavenumber. The(a)cosine and (b)sine parts of the Fourier coefficients in the perturbed simulations are compared to those in the reference simulation data (c) and (d), respectively.

locity as is seen in Fig.1(a) and the centrifugal force of the parallel motions appear being less important. In Fig.5(b), the $m/n = 0/0$ pressure profile of the perturbed simulation at the saturated time is compared to that in the reference data. Note that we have already seen in Ref.[8] that the local fattenings of the pressure can not stabilize the growths of high-wavenumber, near-ideal ballooning modes sufficiently and the $0/0$ profile of the pressure is drastically modified. However, it is easily found that the radial profile in the perturbed simulation is improved to that in the reference data.

3 Concluding Remarks

In this article, we have seen a very primitive view of an influence of the finite perturbations to the linearly-unstable MHD system. It appears that the linear stability theory of an equilibrium without flow can be a starting point to study the dynamical evolution with the parallel flow when neither an equilibrium with flow nor the stability analysis around the equilibrium for the three-dimensional helical configuration are prepared. Although the introduction of the initial parallel flow does not stabilize the instability sufficiently, the mean pressure profile appears better-organized than that in the near-ideal simulation without the parallel flow.

The numerical simulations in this articles have been

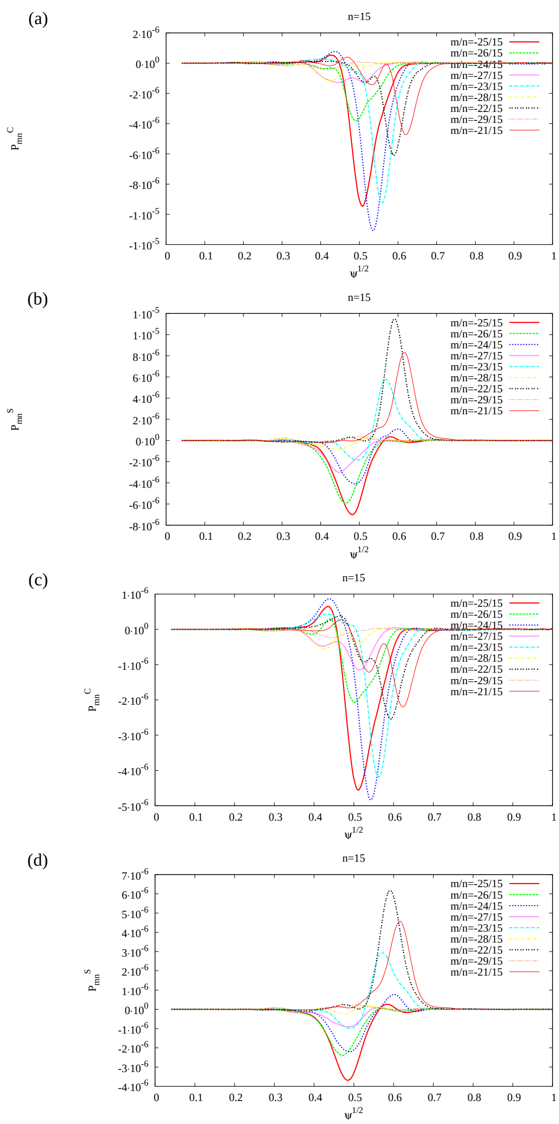

Fig. 4 The radial profiles of the pressure Fourier coefficients with $n = 15$ wavenumber. The(a)cosine and (b)sine parts of the Fourier coefficients in the perturbed simulations are compared to those in the reference simulation data (c) and (d), respectively.

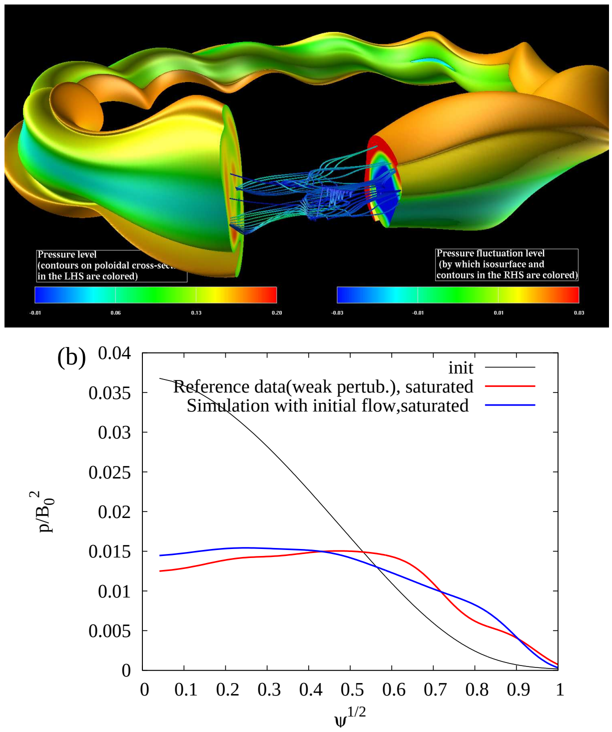

Fig. 5 (a)The three-dimensional view of the saturated state. The isosurface and contours on a poloidal cross-section of the pressure are shown. The contours on a cross-section in the right-hand-side to the paper are for the pressure fluctuations. (b) A comparison of $m/n = 0/0$ pressure profile between the reference data and the perturbed simulation.

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