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Simulation of resistive drift wave turbulence in a linear device

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Abstract. The three-field reduced magnetohydrodynamic (MHD) model is extended to describe the resistive drift wave turbulence in a linear device. Using this model, the linear eigenmode analysis has been performed to identify the unstable modes, which give an estimation of a necessary condition for the turbulence excitation in the Larger Mirror Device designed by Kyushu University. The parameter scan predicts the experimental condition for the excitation of the resistive drift wave turbulence. It is found that ion–neutral collision strongly stabilizes the resistive drift wave. A nonlinear simulation has also been performed to examine the saturation amplitude of the resistive drift wave turbulence.

1. Introduction

The anomalous transport in magnetically confined plasmas is attributed to plasma turbulence. Many works are devoted to the research of the drift wave turbulence (DWT) in high-temperature plasmas [1, 2]. Recently, plasma experiments in a rather simple configuration were revisited, and detailed measurements have been carried out to identify the wavenumber spectra of the DWT [3]. In addition, advanced data analyses such as that of bicoherence are providing quantitative information of the nonlinear wave interaction in DWT [4]. These results motivate the detailed simulation of a linear device for quantitative understanding of DWT. We have been developing a three-dimensional numerical simulation code called the 'Numerical Linear Device' (NLD), which simulates the DWT in a simple cylindrical plasma configuration. The comparisons of turbulence characteristics with experimental results, such as the nonlinear saturation amplitude of turbulence, wavenumber spectra and the balance of momentum transport, are possible by means of NLD. In this paper, the three-field reduced magnetohydrodynamic (MHD) model is extended to describe the resistive drift wave (RDW) turbulence in a simple mirror device. Using this model, the linear eigenmode analysis has been performed to identify the unstable modes, which give an estimation of a necessary condition for the turbulence excitation in the Larger Mirror Device (LMD) designed by Kyushu University. A nonlinear simulation has also been performed to examine the saturation amplitude of the RDW turbulence.

2. Model equations

For describing the RDW turbulence [5, 6] in a linear device, the continuity equation, the vorticity equation and Ohm's law can be used to obtain the fluctuating density, potential and parallel velocity of electrons:

$$\frac{dN}{dt} = -\nabla_{\|} V - V\nabla_{\|} N + \mu_{\mathrm{N}} \nabla_{\perp}^2 N, \tag{1}$$

$$\frac{d\nabla_{\perp}^2 \phi}{dt} = \nabla N \cdot \left(-\nu_{\mathrm{in}} \nabla_{\perp} \phi - \frac{d\nabla_{\perp} \phi}{dt} \right)$$
$$-\nu_{\mathrm{in}} \nabla_{\perp}^2 \phi - \nabla_{\|} V - V\nabla_{\|} N + \mu_{\mathrm{W}} \nabla_{\perp}^4 \phi, \tag{2}$$

$$\frac{dV}{dt} = \frac{M}{m_{\mathrm{e}}} \left(\nabla_{\|} \phi - \nabla_{\|} N \right) - \left(\nu_{\mathrm{ei}} + \nu_{\mathrm{en}} \right) V + \mu_{\mathrm{V}} \nabla_{\perp}^2 V, \tag{3}$$

where $N = \ln(n/n_0)$, $V = v_{\|}/c_{\mathrm{s}}$, $\phi = e\varphi/T_{\mathrm{e}}$, n is the density, n_0 is the peak density, $v_{\|}$ is the electron velocity parallel to the magnetic field, c_{s} is the ion sound velocity, φ is the electrostatic potential, T_{e} is the electron temperature, $d/dt = \partial/\partial t + [\phi, \quad]$ is the convective derivative, M and m_{e} are mass ratio of ion and electron, and ν_{ei}, ν_{in} and ν_{en} are ion–electron, ion–neutral and electron–neutral collision frequencies, respectively. μ_{N}, μ_{V} and μ_{W} are artificial viscosities and $\mu_{\mathrm{N}} = \mu_{\mathrm{V}} = \mu_{\mathrm{W}} = 1 \times 10^4$ are used in the following simulations. The ion cyclotron frequency Ω_{ci} and Larmor radius measured by the electron temperature ρ_{s} are used for the normalizations. In the low-temperature plasma, neutrals play an important role on the stability of the RDW, which is taken into account by ν_{en} and ν_{in}. The equations are solved in the cylindrical coordinate with spectral expansion in the azimuthal and axial (the direction parallel to the magnetic field line) directions assuming periodic boundary condition, where m and n are the azimuthal and axial mode number, respectively. The boundary condition in the radial direction are set to $f = 0$ at $r = 0, a$ when $m \neq 0$, and $\partial f/\partial r = 0$ at $r = 0$, $f = 0$ at $r = a$ when $m = 0$, where f implies $\{N, \phi, V\}$, and $r = a$ gives an outer boundary of the plasma column. In the experimental situation, end plates are placed at each ends of the axial direction, which give rise to the dissipative effect by the formation of a plasma sheath. This effect is not taken into account in the present study and should be investigated as future work.

3. Linear eigenmode

The linear stability of RDW has been investigated using the parameter set relevant to LMD designed by Kyushu University: Ar plasma, $T_{\mathrm{e}} = 2$ eV, filling pressure $p_0 = 1$ mtorr, magnetic field $B = 0.1$ T, plasma radius $a = 50$ mm and plasma length $\lambda = 3$ m. These parameters give the estimate $\rho_{\mathrm{s}} = 9$ mm and $\Omega_{\mathrm{ci}} = 2 \times 10^5$ rad s^{-1}, and the collision frequencies normalized by the ion cyclotron frequency are evaluated as $\nu_{\mathrm{in}} = 0.03$, $\nu_{\mathrm{en}} = 10$, $\nu_{\mathrm{ei}} = 400$. Since ν_{ei} is larger than ν_{en} in these parameters, we use ν_{ei} for the electron collision frequency. A Gaussian shape is assumed as the background density profile and the potential profile is set to be constant (i.e. no background potential gradient). Figure 1(a) shows the growth rate and frequency of $n = 1$ modes. Modes with low azimuthal mode numbers are found to be unstable. Modes $m = 1$–8 are unstable, and mode $m = 2$ has the maximum growth

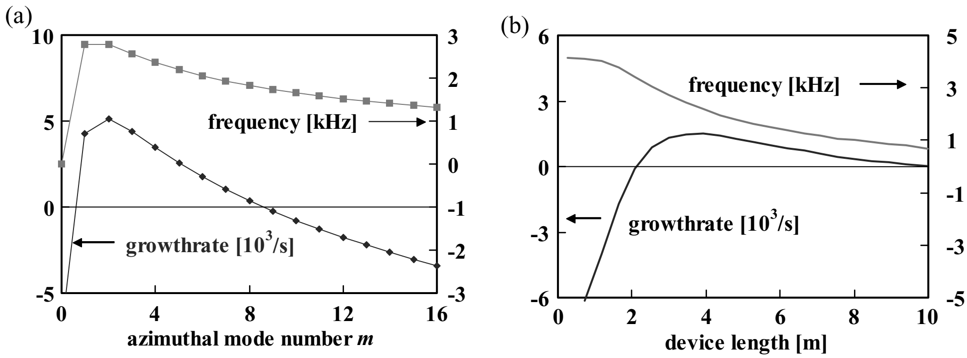

Figure 1. (a) Growth rate and frequency of linear eigenmodes. (b) Dependency of growth rate and frequency on the device length.

rate in this case. Dependencies of the mode growth rate and frequency on the device length, the magnetic field and the collision frequency, are evaluated. Figure 1(b) shows the dependency of the growth rate and frequency of $(m, n) = (1, 1)$ mode on the device length. The device length determines $k_\parallel$ of the modes, which is important to excite RDW. Figure 1(b) shows that the sufficient device length is needed for RDW excitation. The strength of the magnetic field should be also sufficient. In this case, $\lambda \sim 4$ m and $B \sim 0.1$ T is best for $(m, n) = (1, 1)$ mode to be most unstable. The electron collision destabilizes the drift wave, so that it should be large. Since the ion–neutral collision strongly stabilizes RDW, it should be suppressed. On the present experimental conditions in LMD, $\nu_{\rm in}$ is too large, therefore, a reduction of the neutral density and/or increase of the ionization ratio are necessary for excitation of RDW.

4. Nonlinear simulation

The nonlinear terms included in the set of equations of N, ϕ and V are advanced in time by using a predictor–corrector method. During the calculation, we have confirmed that the conservation of the total particle number is pretty good, which ensures the validity of the nonlinear simulation. It is found that no turbulent state is obtained for the standard parameter set given in the previous section. Only the limit cycle behavior of a few modes is observed and other modes are dumped out. Next, a more unstable case is investigated by reducing the neutral density ($\nu_{\rm in} = 0.01$ case). It is found that many modes have comparable amplitudes in the saturation phase. The saturation is attained by quasi-linear flattening, i.e. the $(m, n) = (0, 0)$ mode excited by nonlinear coupling (zonal structure formation) flattens the density profile, which makes modes stabilize and leads to the saturation. We also investigate the case without the $(0, 0)$ mode evolution of N using the first parameter set (a fixed density profile without quasi-linear flattening). This is equivalent to introducing an ideal source term preserving the initial density profile. Figure 2(a) shows the time evolution of each Fourier mode of the fluctuating density in the third case. Parameters are the same as those in Fig. 1(a). The (2,1) mode, which is most unstable in this case, is dominant, and the other less unstable modes also keep large magnitudes in the saturated state. Figure 2(b) shows the density and potential

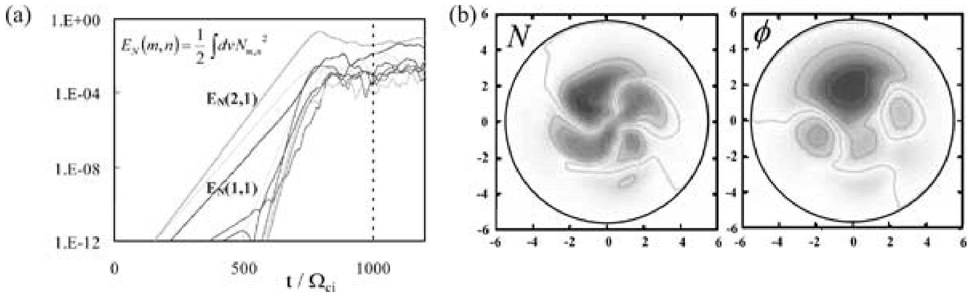

Figure 2. (a) Time evolution of the internal energy of each mode. (b) Density and potential profiles at $t = 1000$ of (a).

profiles at $t = 1000$ of Fig. 2(a). The self-sustained potential structure is formed by the nonlinear interaction as is shown in Fig. 2(b).

5. Conclusions

The progress of NLD, which is a three-dimensional numerical simulation code analyzing RDW turbulence in a simple cylindrical plasma configuration, has been described in this paper. The three-field (density, potential and parallel velocity of electrons) reduced MHD model with the effect of neutrals has been introduced. The linear eigenmode analysis predicts the experimental condition for RDW excitation. It is found that ion–neutral collision is an important parameter to control DWT. Steady turbulence is attained by the nonlinear simulation with small $\nu_{\rm in}$ or with a fixed density profile without quasi-linear flattening. In this way, the tool has been prepared for analyzing RDW turbulence in the linear device. In the next step, the analyses including a torque-generation mechanism will be carried out to clarify the self-sustained structural formation mechanism in the linear device. In this paper, the effect of background potential gradient (another instability source) has not been considered, and should be investigated in a future work.

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References

[1] Horton, W. 1999 *Rev. Mod. Phys.* **71**, 735.
[2] Diamond, P. H., Itoh, S.-I., Itoh, K. and Hahm, T. S. 2005 *Plasma Phys. Control. Fusion* **47**, R35.
[3] Burin, M. J. et al. 2005 *Phys. Plasmas* **12**, 052320.
[4] Nagashima, Y. et al. 2005 *Phys. Rev. Lett.* **95**, 095002.
[5] Hasegawa, A. and Wakatani, M. 1987 *Phys. Rev. Lett.* **59**, 1581.
[6] Schröder, C. 2003 *PhD Thesis*, Ernst-Moritz-Arndt-University, Greifswald.