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Generation mechanism of oscillatory zonal flows in MHD fluctuations and its implication in understanding turbulent transport

MHD揺動における振動帯状流の生成メカニズムと乱流輸送理解への示唆

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Oscillatory zonal flow (ZF) with finite frequency, e.g., the geodesic acoustic mode in a torus, is of importance in turbulent transport. This work reports on a new generation mechanism of the ZF oscillation in double tearing mode (DTM) with antisymmetric shear flows based on reduced resistive MHD model. Particularly, it is clarified that depending on shear flow amplitudes, which corresponds to different DTM eigen states, an oscillatory ZF can be driven by a cross coupling of different MHD eigenmodes located at different rational surfaces. Possible implication of such mechanism in understanding the ZF generation in microturbulence is discussed.

1. Introduction

Zonal flow (ZF) commonly occurs in micro-turbulence and also in MHD with flows, e.g., the drift tearing mode. Not only does the ZF not produce plasma transport but it can regulate the turbulence effectively so that the transport is reduced. The ZF is usually categorized into two types with low (nearly zero) or finite frequency. The generation mechanism of the former has been theoretically predicted through a secondary instability mechanism, which exists extensively in various plasmas [1]. It can remarkably regulate the turbulence through the effective shearing rate, which may quench the instability. On the other hand, the geodesic acoustic mode (GAM) is typical of oscillatory ZFs in a torus, whose shearing rate is much reduced due to the finite frequency [2]. Hence, the ZF frequency spectrum is an important index of the ZF dynamics in studying the transport.

Experimentally, the ZF frequency spectrum has been diagnosed with a distribution near the zero frequency except for the GAM peak in toroidal plasmas. Theoretically, the GAM has been well defined as an eigenmode due to the toroidicity. However, the ZF frequency spectral distribution has not been well understood yet. In this work, we report on an oscillatory ZF observed in the simulations of double tearing mode (DTM) in the presence of a radially anti-symmetric shear flow, a new generation mechanism of oscillatory ZFs is identified as the cross coupling of eigenmodes located at different rational surfaces in the plasma with shear flows including the ZFs themselves. The implication of such new mechanism in micro-turbulence is discussed.

2. Generation of oscillatory ZFs in DTM

The DTM is typical of MHD mode in double Harris current sheets configuration [3]. Linear DTM and its nonlinear evolution have been intensively investigated based on reduced resistive MHD model in slab geometry. The DTM is characterized by two static eigen states with symmetric or anti-symmetric static magnetic island. When a radially anti-symmetric shear flow $\upsilon_{eq} = \upsilon_0 \tanh(\kappa x)$ is embedded, the DTMs are stabilized or destabilized by weak shear flow below a critical amplitude υ_c through the island distortion. As the flow increases above υ_c but below the KH excitation, two eigen-modes tend to propagate oppositely along two rational surfaces with same growth rate, showing a tearing mode structure (referred to as STM-type DTM) due to the Alfven resonance occurring on each current sheet[4]. The time evolution exhibits an oscillatory increase of the ZF energy as well as turbulent energy, as shown in Fig. 1. The oscillation feature of the ZF kinetic energy looks to depend on the amplitude of shear flows [5]. In Fig.1(a), the ZF energy oscillation in the linear phase of DTMs behaves alternatively with both long and short periods whilst it becomes regular in Fig. 1(c).

The ZF oscillation can be elucidated using three-wave coupling or a modulation instability pumped by two different eigenmodes, namely, cross eigenmode coupling. Mathematically, the pump waves are assumed to be composed of two STM-type DTMs with same growth rate γ but different frequency $\omega_{R,L} = \pm k_y \upsilon_{xs}$, which results from the Doppler frequency shift. The sign $\pm$ indicates opposite propagation direction along the right (R) or left (L) rational surface. Mode coupling analysis based on the ZF equation from Eq.(1) is carried out by separating the mode coupling into self-coupling of individual eigenmode at each rational surface (R-R or L-L) and cross-coupling between two different eigenmodes along two rational surfaces (R-L). The resultant ZF equation can be derived as

$$\partial_t \nabla_\perp^2 \phi_{ZF} \approx [F_{R,L} + 2G^r_{RL}\cos(2k_y \upsilon_{xs} t)]e^{2\gamma} \quad , \qquad (2)$$

Here $F_{R,L}$ and G^r_{RL} terms correspond to the self-coupling (R-R or L-L) and the cross- coupling (R-L) contributions, respectively. The ZF kinetic energy can be expressed as [5]

$$\left\langle |\phi_{ZF}|^2 \right\rangle \propto \omega_{ZF}^{-2} k_{ZF}^{-4} \left\langle [F_{R,L} + 2G^r_{RL}\cos(2k_y \upsilon_{xs} t)]^2 \right\rangle e^{4\gamma} \quad , \qquad (3)$$

showing an oscillatory growth of ZF energy in the linear phase of DTMs. The relative magnitude of factors $F_{R,L}$ and G^r_{RL} determines the oscillation feature, which depends on the flow amplitude. For the shear flows slightly higher than υ_c, the Alfven resonance is weak so that the cross coupling of two STM-type modes is strong, namely, $F_{R,L} < 2G^r_{RL}$. The ZF energy oscillation evolves with alternative long and short periods. On the other hand, the Alfven resonance is enhanced by stronger flows. The cross coupling becomes weak, leading to $F_{R,L} > 2G^r_{RL}$. Hence the ZF energy oscillation becomes regular and the amplitude decreases.

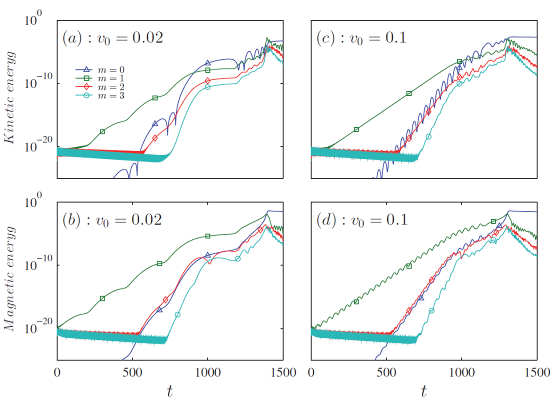

Fig. 1 Time evolution of kinetic ((a) and (c)) and magnetic ((b) and (d)) energies for four modes with m=0, 1, 2, 3.

3. ZF frequency in flowing ITG turbulence

The ZF occurs in various turbulent fluctuations due to asymmetric poloidal momentum transport. Motivated by the oscillatory ZF in the DTMs in a flowing plasma, we apply the same mechanism of finite ZF frequency to microturbulence, e.g. ion temperature gradient (ITG) mode to clarify the ZF frequency spectra measured extensively in various experiments. To match the corresponding modeling in ITG turbulence since each resonant mode is located near the rational surface, similar to the DTM, a sheared slab model with a radially periodic shear flow $\upsilon_{SF} = \upsilon_0 \sin(k_{SF} x)$ is employed to simulate the ZF evolution. The details on the ITG simulation has been well documented else [6]. The ZF evolution in simulations with and without external shear flow is plotted in Fig. 2. Comparison indicates that the shear flow gives rise to a low frequency ZF peak, which may correspond to the difference of the Doppler frequency shift between two rational surfaces, similar to the DTM case. Note that the ZF is rather strong in the ITG turbulence, it may infer that the ZF itself can back react on the ITG turbulence like the embedded shear flow so that the ZF frequency spectrum is synergetically determined by the total flows.

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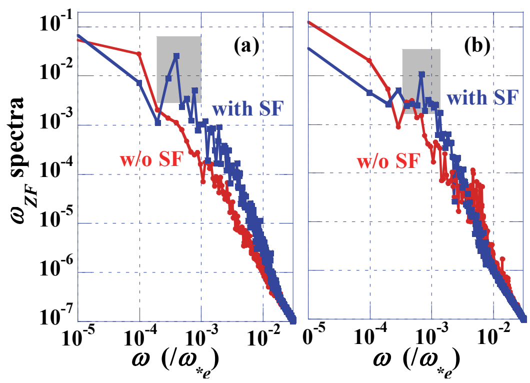

Fig.2 Averaged ZF frequency spectra in slab ITG simulations with and without shear flows (SFs). $\hat{s} = 0.1$(a), $\hat{s} = 0.2$(b). $\eta_i = 2.5$.