Modulational instability analysis of interaction between turbulence and zonal flow including mean plasma flow effect

Ken Uzawa[1]; Yasuaki Kishimoto[1]; Jiquan Li[2]

[1] none; [2] SWIP

Anomalous transport of particles and heat flux across the magnetic field line has been observed in almost all the magnetically confined fusion devices, such as tokamaks and stellarators. The temperature gradient and also the density gradient in magnetized plasmas work as a free energy source to drive micro-scale drift wave turbulence which gives rise to the anomalous transport. Recent theoretical works and numerical simulations have shown that the macro-scale structures such as zonal flows and streamers are nonlinearly generated from maternal turbulence through modulational instability process and play a crucial role in regulating the transport in tokamaks. Specifically, the zonal flows that show poloidaly and toroidally symmetric potential fluctuation have attracted much attention since they break up the turbulent vortices and suppress the heat flux. Similar structures are found in the atmosphere of Jupiter-like planets and also terrestrial planet (e.g. the westerlies and the Venusian super-rotation). Therefore such large structures are considered to be universal in the would. The generation mechanisms of such large scale structures have been intensively studied. The modulational process has been discussed as one of the plausible candidates of such generation mechanisms.

In addition to zonal flows, there are mean flows such as neo-classically driven flows and zonal flows driven by other scale fluctuations originating from different free energy sources. It is generally believed that the mean flow directly suppresses the transport through the decorrelation of turbulent vortices. Therefore, one of important factor governing transport is the external sheared mean flow.

In this work, we investigate the generation of zonal flow influenced by a mean flow having arbitrary spatio-temporal scales including the strong shearing regime. As an example, we consider the generation of zonal flow due to the electron temperature gradient (ETG) turbulence assuming that the mean flow originates from the ion temperature gradient (ITG)-driven zonal flow. A dispersion relation for the zonal flow instability with complex frequency of the zonal flow is derived. We have numerically solved the dispersion relation, and found that the growth rate of the zonal flow shows a decreasing tendency with respect to the wave number and energy of the mean flow. We note that the real frequency once crosses zero value and increases with the mean flow energy to the same order as the growth rate, suggesting that the mean flow suppresses the growth rate by having a large real frequency.

Next, we investigate the suppression mechanism of zonal flow generation due to a mean flow. We found that the pure forced oscillation to the side band due to the mean flow is related to the increase of real frequency of the zonal flow with respect to the mean flow energy and the resultant reduction/stabilization of zonal flow instability.

Finally, we have have confirmed validity of the modulational analysis by numerically solving the HM Eq. in the Fourier space. It is found that the damping rate of turbulence and reduction rate of zonal flow growth rate are in the same order. Furthermore, we have examined effects of the higher side bands that are truncated in the modulational analysis.

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