§7. Nonlinear Evolution of the Fishbone Instability

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The fishbone instability is a magnetohydrodynamic (MHD) instability driven by energetic particles. In tokamak plasmas, the primary harmonic of the fishbone spatial profile, which is located inside the q=1 magnetic surface, is m/n=1/1. Here, q is the safety factor, and m and n are the poloidal and toroidal mode numbers, respectively. Two theoretical explanations of the fishbone instability, the thermal ion diamagnetic drift fishbone and the precessional drift fishbone, were proposed. The frequency of the former is the thermal ion diamagnetic drift frequency, while that of the latter is close to the precessional drift frequency of the energetic ions. Although many theoretical researches have been made on the linear properties of the fishbone instability, the self-consistent nonlinear evolution of the fishbone instability has not been clarified yet. The finite resistivity and the MHD nonlinearity have not been taken into account in the previous nonlinear simulation study of the fishbone instability. We have investigated the nonlinear evolution of the precessional drift fishbone instability using a simulation code for MHD and energetic particles, MEGA.

We investigated the linear properties of the fishbone instability using the MEGA code[1]. The plasma parameters used are similar to those of the PDX tokamak where the fishbone instability was first observed. The MHD equilibria consistent with the energetic ion distributions where the trapped particles are dominant were constructed for the initial conditions of the simulations. In the initial conditions, the radius of the q=1 magnetic surface is 0.3 of the minor radius. When the energetic particles are absent, the kink instability takes place. We have carried out simulations for various energetic ion beta values. At a critical beta value of the energetic ions we see a transition in frequency from the kink instability to the fishbone instability. The frequency of the fishbone instability is close to 16 kHz for relatively high energetic ion beta values, while the kink instability has no rotation and the frequency is nearly zero for relatively low energetic ion beta values. Time evolutions of the MHD energy and the transferred energy were investigated. We have found that the instability is primarily driven by the energetic ions for relatively high energetic ion beta values. Moreover, the frequency of the instability is proportional to the beam injection energy. Thus, we can conclude that this instability is the precessional drift fishbone instability.

We have carried out five nonlinear simulation runs of the precessional drift fishbone instability with different parameters[1]. We can summarize the saturation process of the precessional drift fishbone instability.

1. At the linear growth phase, the energy transfer due to the Joule heating increases in proportion to the energy transfer from the energetic ions to the MHD fluid. The former is smaller than the latter by one order of magnitude. At the nonlinear phase, the increase in the energy transfer from the energetic ions to the MHD fluid stops, while the energy transfer due to the Joule heating increases to the level of the energy transfer from the energetic ions to the MHD fluid. The balance between the two energy transfers leads to the saturation of the instability.

2. As the instability grows, the magnetic reconnection takes place leading to a magnetic island formation. The overlap of the m/n=1/1 and 2/1 harmonics in the magnetic field fluctuation of the linearly unstable mode and the harmonics created by the nonlinear coupling, such as the m/n=3/2 harmonic, generates the stochastic regions of the magnetic lines of force.

3. The energetic ion orbit in the magnetic island and the stochastic regions of the magnetic lines of force is completely different from that in the initial equilibrium configuration. This reduces the number of the energetic ions that drive the fishbone instability, and also reduces the energetic ion pressure gradient. These stop the increase in the energy transfer from the energetic ions to the MHD fluid.

4. At the saturation of the fishbone instability, the energy transfer from the energetic ions to the MHD fluid keeps roughly a constant level. For the TAE instability, the energy transfer stops at the saturation due to the wave-particle trapping. Thus, we conclude that the wave-particle trapping is not important for the fishbone instability.

5. The estimated saturation level of the plasma displacement is the same order of magnitude as the radius of the q=1 magnetic surface ($r_{q=1}$). This is different from the previous simulation result of the diamagnetic drift fishbone instability where the saturation level of the plasma displacement is less than 10% of $r_{q=1}$[2]. In the previous simulation, the magnetic reconnection does not take place because neither the MHD nonlinearity nor the finite resistivity was considered. This leads to the difference from the results of the present work. Thus, we conclude that the MHD nonlinearity and the finite resistivity are needed to take account in the nonlinear evolution of the fishbone instability.

6. At the saturation of the instability the frequency shifts downward. The frequency downshift is accompanied by the radial transport of the energetic ions.

7. In all of the cases the safety factor q is below unity at the magnetic axis. Then, the fishbone instability investigated in this work is driven not only by the energetic particles but also by the plasma current. As the safety factor q at the magnetic axis is closer to unity, the properties of the current-driven instability becomes weaker. The estimated saturation level of the plasma displacement is the same order of magnitude as $r_{q=1}$.

References

1) Shiozaki, Y., Ph.D. Thesis (2005, Graduate Univ. Advanced Studies, in Japanese).
2) Candy, J. et al., Phys. Plasmas **6**, 1822 (1999).