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Zonal flow damping simulation in non-circular tokamaks by a fluid closure model based on collisionless gyrokinetics

無衝突運動論的クロージャー流体モデルに基づく、非円形断面トカマクにおけるゾーナル流減衰シミュレーション

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Simulation study of zonal flow (ZF) damping is done by using a fluid model based on the collisionless gyrokinetics [H. Sugama et al., Phys. Plasmas **14**, 022502 (2007)]. The residual zonal flow level is discussed in tokamaks with various shapes of the magnetic surfaces, whose MHD equilibria are obtained numerically by VMEC code. For circular toakamak, it is shown that our fluid model gives a residual level predicted by Rosenbluth-Hinton (R-H) formula [M. N. Rosenbluth et al., Phys. Rev. Lett. **80**, 724 (1998)]. For non-circular tokamaks, the ellipticity is an increasing effect for ZF. On the other hand, the triangularity is more weak effect. These simulation results are also compared with some ZF theories. Effects of finite initial parallel flow are also considered. It is shown that the toroidal component of initial parallel flow is not damped while the poloidal component is damped as R-H formula shows, and resulting perpendicular flow can be kept with high level. The quasi-linear results are also shown by considering the linear ion temperature gradient modes and trapped electron modes as the nonlinear sources for the fluid variables.

1. Intoroduction

It is known that the zonal flow (ZF) component of E x B flow plays an important role for the determination of the anomalous transport level via the turbulence suppression. This means that the zonal flow itself should be treated accurately.

The fluid model has an advantage that it needs much smaller computation resources than those the kinetic model needs. However, it has come to realize unfortunately that the zonal flow is not treated accurately in the classical fluid models. Hammett and Perkins (H-P) [1] improved the fluid model to include the effect of kinetic Landau damping. This introduces the transient response of the potential in the short time (so-called GAM oscillation), and fluid simulation studies with this model have been developed [2,3]. However, it was pointed out that even with H-P model, the fluid model cannot reproduce the residual ZF level predicted by the kinetic equations [4]. To improve the discripancy, an attempt was made [5]. In consideration of these results, a new fluid closure model is developed to reproduce the kinetic ZF level in the long time limit, based on the collisionless gyrokinetics [6].

In this work, we use the model of Ref.[6] for the simulation study of the zonal flow damping. The residual ZF level is discussed in tokamaks with various shapes of the magnetic surfaces, whose MHD equilibria are obtained numerically by an MHD code, VMEC [7]. For circular toakamak, it is shown that our fluid model gives a residual level predicted by Rosenbluth-Hinton (R-H) formula [4]. For non-circular tokamaks, the ellipticity is found to have an increasing effect on ZF. On the other hand, the triangularity is more weak effect. These simulation results are also compared with some ZF theories. Effects of initial parallel flow are also investigated. It is shown that when resultant vector of initial parallel flow and perpendicular E x B flow is in the toroidal direction, the flow, potential, density, are not damped at all.

2. The fluid model

The model fluid equations are given in eqs. (48)-(51) of Ref.[6] with quasi-neutrality condition. Four fluid variables δn, $u_{//}$, $\delta p_{//}$, and $\delta p_{\perp}$ are solved. The closure is introduced to the parallel and perpendicular energy flux along the field line, $q_{//}$ and $q_{\perp}$. These are divided into two parts, short and long time terms,

$$q_{//}=q_{//}^{(s)}+q_{//}^{(l)},$$
$$q_{\perp}=q_{\perp}^{(s)}+q_{\perp}^{(l)}. \quad (1)$$

The short time term $q^{(s)}$ is assumed to be H-P model, while the long time term $q^{(l)}$ is given by eq.(57) of [6]. The typical simulation results in the circular tokamak are shown in Fig.1. If the energy flux q is dropped entirely, the potential is oscillating and not converged. If only the short time closure is considered (H-P model), the initially given potential is GAM-damped and it becomes negligibly small in the long time limit. In the case that both $q^{(s)}$ and $q^{(l)}$ are included, the finite level of residual zonal flow is obtained, for which we can confirm that the residual level reproduce the R-H result.

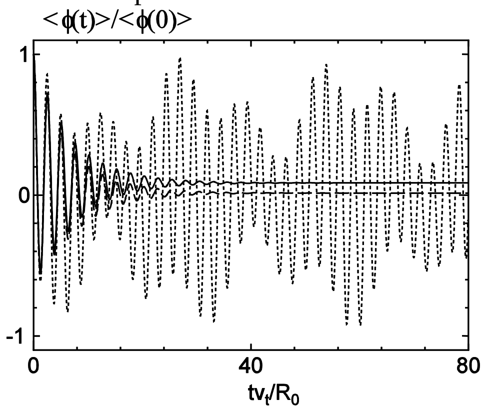

Fig.1: q=0(dot), $q=q^{(s)}$ (dash) and $q=q^{(s)}+q^{(l)}$ (solid)

3. Shaping effects on the residual zonal flow

Here the effects of the ellipticity and triangularity of the magnetic surfaces on the residual zonal flow are investigated. Here $a/R_0=1/3$ and $q=1+2\rho^2$ are fixed, and a surface $\rho=0.6$ and $\varepsilon\sim0.2$ is considered. The radial wave number is assumed to be $k_r a_i=0.01$. The R-H formula, $f(\infty)/f(0)=1/(1+1.6q^2/\varepsilon^{1/2})$, is obtained for the circular tokamaks so that it does not change as the ellipticity or triangularity changes (dashed lines). On the other hand, the simulation result (marks) increases with the ellipticity. A formula from Ref.[6] in the low k_r limit is also shown (solid lines), which coincides with the simulation results very well. The effect of triangularity on the residual ZF level is found to be weak. These tendencies are roughly consistent with theories [8,9] (dotted, dot-dashed lines).

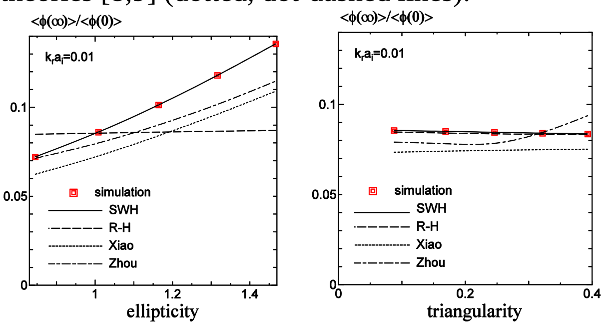

Fig.2: Residual potential as a function of the ellipticity (left) and triangularity (right).

4. Effects of finite initial parallel flow

Effects of finite initial parallel flow have not been discussed so much in the past. Here we discuss finite $u_{//}(0)$ cases. In fig.3, three cases are considered: (i)$\phi(0)=1$ and $u_{//}(0)=0$, (ii) $\phi(0)=0$ and $u_{//}(0)=-iKv_t^2/B$, and (iii) $\phi(0)=1$ and $u_{//}(0)=-iKv_t^2/B$, where $K=k_\perp B_t/\Omega_p$. In the case (i), $\phi(0)=1$ at t=0 is damped as usual, and the residual potential becomes the R-H level. On the other hand, we assume only finite $u_{//}(0)/v_t=-iKv_t/B$ in case (ii). Here this $u_{//}(0)$ corresponds to the first term of eq.(A7) of [6], in which case total flow ($u_{//}\mathbf{b}+\mathbf{u}_\perp$) is in the toroidal direction. Since we consider linear systems, a solution is linear combination of cases with different initial value. Thus the case (iii) is expected to be the sum of case (i) and case (ii), and we see that the potential ϕ at t=0 is not damped at all. This is expected because in this case, balance equation eq.(66) of [6] is satisfied for $k_r a_i=0.01<<1$, which forces ϕ, δn and $u_{//}$ to be fixed in time simultaneously without nonlinear source. This is one example, and we can choose function form of $u_{//}(0)$ freely. The effects of quasi-linear density or flows, derived from linear gyrokinetic modes (ITG, TEMs, etc.) will be discussed.

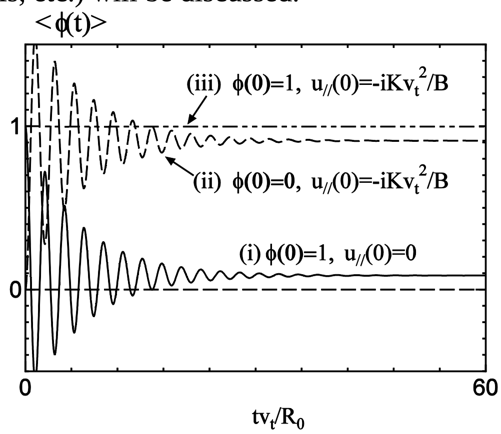

Fig.3: Residual potential with finite $u_{//}(t=0)$.

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