Nonlinear Properties of the Kelvin-Helmholtz Instability in Compressible Plasmas

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In this paper, we first focus on the weak reversed magnetic shear configuration and give a rather complete picture of the flow profile-dependence of the KH instability. Then, we check the role of the flow profile. We use the compressible resistive MHD model with weak shear magnetic field and shear flow of the hyperbolic tangent profile with the plasma flow being sub-sonic flow. The time evolution of the averaged norm of the perturbed magnetic field is employed for measuring the growth rate of the instability. We mainly concentrate on the nonlinear phase of the instability.

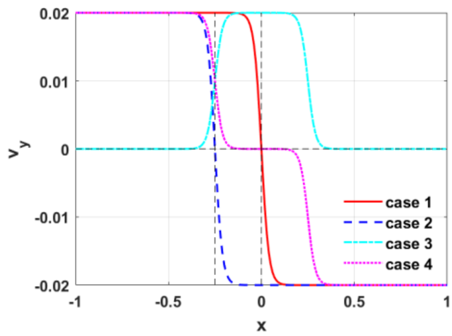

Figure 1. Radial profiles of shear flow (v_y) for case 1 and case 2.

To compare with the previous result of DTMs, we applied a monotonically equilibrium shear flow [1]. The profile function can be written as $u_0(x) = V_0 \tanh\left[\kappa\left(x - x_0\right)\right]\hat{y}$, where V_0 and κ are the strength and shear factor of the flow, respectively. For case 1, the flow shear on the two resonant surfaces is zero, while the strong flow shear at $x = 0$ is applied to study the effect of flow shear on the KH instability in weak reversed magnetic shear plasmas. For case 2, to compare with case 1, the local strong flow shear is imposed at left resonant surfaces.

For the DTMs, the shear or relative velocity ($\tilde{v} \equiv |v_{s1} - v_{s2}|$) between the two resonant surfaces, plays important roles on suppression of the mode. To further identify whether $\tilde{v}$ is the dominant effect on excitation of KH instabilities, we introduce the case 3 and 4 in figure 9(a) and 9(b), respectively. For case 3, the velocity and shear strength on both of resonant surfaces is same, then $\tilde{v}$ is zero. For case 4, the shear strength of two resonant surfaces is same, while their velocity is contrary with $\tilde{v} = 0.02$.

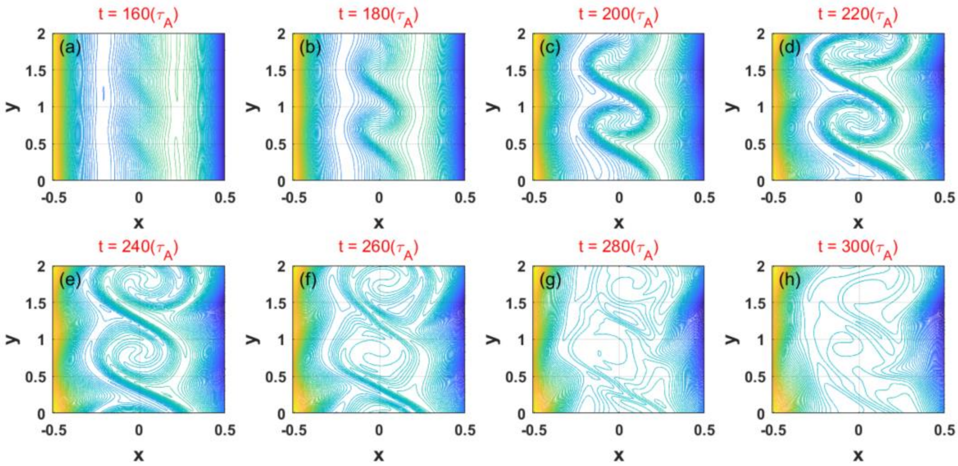

Figure 2. Time evolution of 2D structures of the total magnetic flux of the KH instability for case 1.

To show the mode structure, we plot the 2D contour of magnetic flux (ψ) in figure 2, with $\vec{B} = \nabla\psi \times \hat{z}$. Though the flow strength (~ 0.02) is much smaller than the sonic velocity (~0.5), the magnetic field lines are curled significantly between two resonant surfaces due to the strong flow shear. This suggests that the mode may be a non-resonant mode in the absence of resonant surfaces at $x = 0$. At the end of linear growth ($t \sim 220$), however, the resonant tearing-like instability can also be driven by KH-induced plasma flows on resonant surfaces, similar to a process of forced magnetic field reconnection [2, 3]. It is different from the strong shear case [4, 5], after all, here not strong coupling of both KH and tearing instabilities is found, i.e. the KH instability always plays a dominate role in the nonlinear magnetic field reconnection dynamics. After a long-time evolution, the MHD nonlinearity finally leads to the generation of turbulence-like structures.

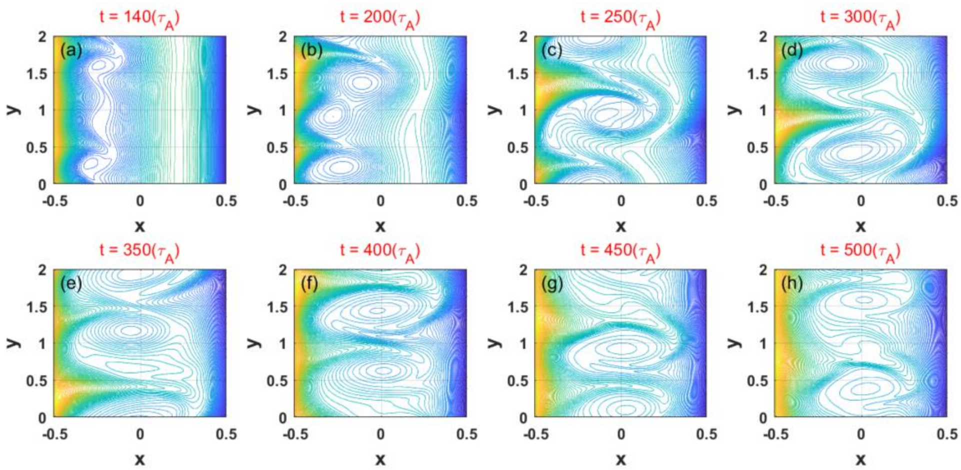

Figure 3. Time evolution of 2D structures of the total magnetic flux of the KH instability for case 2.

It is found that the position of flow shear plays an important role in the formation of KH and tearing modes. On one hand, a high mode harmonic of the island on left resonant surface is induced by wavy magnetic field and flow field, islands grow quickly and bring about the coalescence of mode harmonics. It should be noted that unlike previous simulations of KH-coupled tearing modes [4-7], in this case the KH mode always dominates the dynamics process of instability rather than tearing mode, which suggests a crucial effect of the weak reversed magnetic shear on formation of the KH structure in the small flow regime of $V_0 << u_A$. On the other hand, a rotating island generated on right resonant surface keeps interlocking with KH modes in the nonlinear stage of $200 < t < 350$ and eventually overlaps each other.

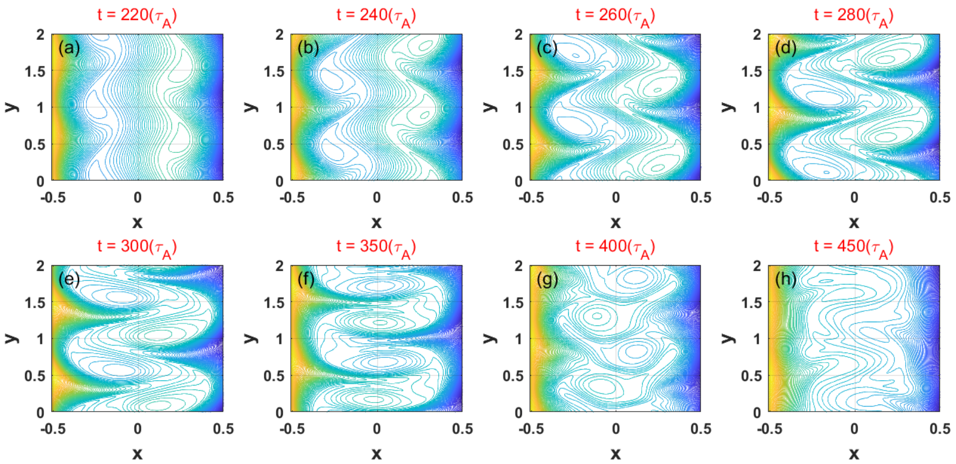

Figure 4. Time evolution of 2D structures of the total magnetic flux of the KH instability for case 3.

Here, the wave number is dominated by $k_y \sim 2$ and larger than $k_y \sim 1$ of general DTMs with similar simulation parameters in strong magnetic shear cases. It is indicated that the KH-induced modes can also drive each other, meanwhile, they are rotating in the y direction but without the relative motion, which result in an asymmetric forced driven magnetic reconnection configuration to be well remained. In the nonlinear saturated stage, the field lines between the resonant surfaces will be reconnected, the two modes are overlapping as similar to the general DTMs.

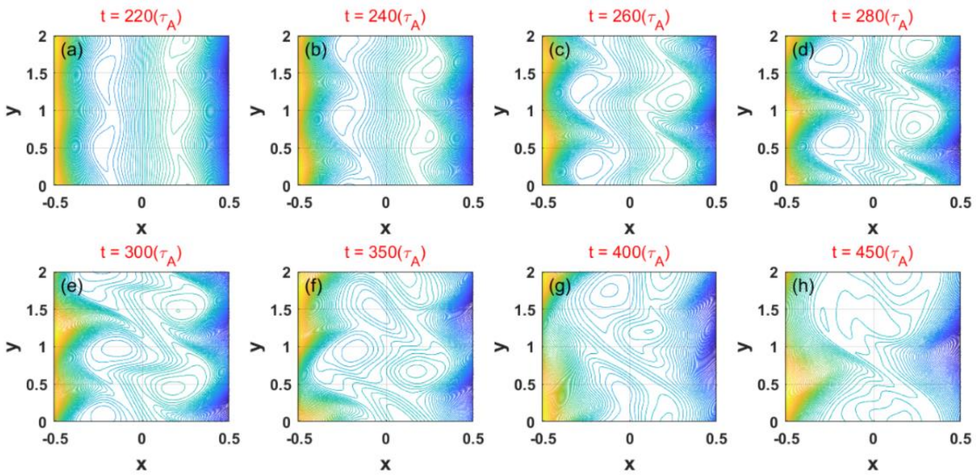

Figure 5. Time evolution of 2D structures of the total magnetic flux of the KH instability for case 4.

The interlocking process of the two KH instabilities shown in figure 5 supports a picture to understand the mechanism of nonlinear fast reconnection in weak magnetic shear regimes. Unlike the interlocked DTMs, we can find that the deformation of KH modes results from the effect of both flow shear and mode coupling. In the nonlinear stage, the interaction of two KH modes induces brake of islands and then twists together between the two resonant surfaces. Thus, the model including compressible effect are more suitable to study interlocking of KH modes in the weak magnetic shear configuration than the reduced MHD model, particularly for a super-sonic flow.

Acknowledgments

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