Interaction between non-uniform vortex sheet and bulk point vortices

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The interaction of vortices with unstable interface plays an important role in a wide range of engineering, geophysics, and astrophysical flows. However little research has been done on nonlinear interaction of unstable velocity-shearing interface with bulk vortices. The Richtmyer–Meshkov instability (RMI) is a shock-induced density-stratified interfacial instability and it is important in astrophysics and inertial confinement fusion.[1] RMI differs from other instabilities in that there are non-uniform velocity shares at the unstable interface and vortices are generated in bulk behind the shocks. [2, 3] The nonlinear interaction between bulk point vortices and a nonuniform vortex sheet is investigated theoretically and numerically with use of the vortex sheet model (VSM)[4]. RMI also causes the amplification of magnetic field in super nova remnant.[5]

We consider here an interface that has initially sinusoidal velocity shear with the maximum values of the difference of tangential velocity between the lower and upper fluids, $2v_{\text{lin}}$, with wavenumber k, where v_{lin} corresponds to the linear growth rate in a weak shock limit RMI. Time is normalized as $kv_{\text{lin}}t$, therefore the model can be applied for any values of the linear growth rate. Figure 1(a) shows interfacial structure with the colored scale of the vortex strength and the velocity field at normalized time of $t = 5$ without bulk vortices. [6]

The nonlinear evolution of RMI is investigated within VSM, taking the nonlinear interaction between the interface and the bulk vortices into account. The vorticity and position of the bulk vortices obtained from the compressible linear theory [4] were applied as initial conditions of the bulk point vortices in VSM. The suppression of RMI due to the bulk vortices is observed in early stage and its reduction is quantitatively evaluated and compared with the compressible linear theory. In the fully nonlinear stage strong bulk vortices behind the transmitted shock however enhanced the growth of spike, supplying flow from spike root to its top and mushroom umbrella.[7]

More generally as the point vortices approach the nonuniform vortex sheet due to their nonlinear interaction, they increase the local sheet strength of the vortex sheet forming a vortex core depending on the sign of their circulation of point vortices. At the vortex core the velocity shear takes its maximum value in absolute values. For example, as shown in Fig. 2, when the circulation of a point vortex is the opposite sign of the local sheet strength, it induces a new type of vortex pair with a local enhanced sheet vortex. The new vortex core causes different types of interface deformation. Under certain conditions, the vortex core and the point vortex form a pseudo-vortex pair on the interface. The pair creates a local satellite mushroom as shown in Fig. 2. It is also seen in Fig.2 that the pseudo-vortex pair creates finer structures such as satellite bubbles or satellite spikes on the interface in the fully nonlinear stage.

Fig. 1 (b) and (c) show interfacial structure at $t = 5$ with point vortices and loci of point vortices, where open symbols indicate their initial position. The obtained results indicate that the complexity of the interface structure is enhanced if the bulk vortices exist.

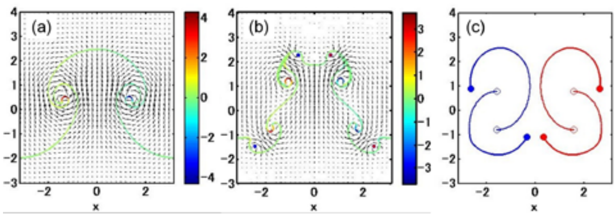

Fig.1. Interfacial structure with the colored scale of the vortex sheet strength and the velocity fields at normalized time $t = 5$ for a vortex sheet corresponding to pure RMI (a), vortex sheet with point vortices (b) and loci of point vortices (c).

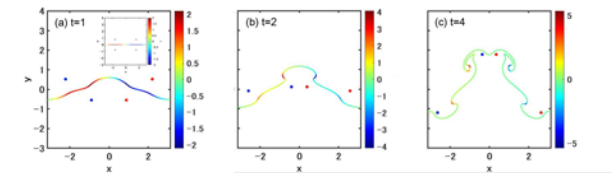

Fig.2. Interfacial structure with the colored scales of the vortex sheet strength at normalized time of $t = 1$, 2 and 4 from left to right. Insertion is initial structure.

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References

[1] R. D. Richtmyer, Commun. Pure Appl. Math, **13**, 297 (1960); E. E. Meshkov, Fluid Dyn. **4**, 101 (1972); Y. Zhou, Phys. Rep. **720-722**, 1 (2017).
[2] K. Nishihara *et al* Philos. Trans. R. Soc. A **368**, 1769 (2010).
[3] F. Cobos-Campos *et al*. Phys. Rev. **E93**, 053111 (2016).
[4] C. Matsuoka *et al*. Phys. Rev. **E73**, 026304 (2006).
[5] T. Sano *et al* Astrophys. J. **758**, 126 (2012).
[6] C. Matsuoka *et al* Phys. Plasmas, **27**. 052305 (2020).
[7] C. Matsuoka *et al* Phys. Plasmas **27**, 112301 (2020).