§57. Interaction between a Columnar Vortex and External Turbulence

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The interaction between a columnar vortex and external turbulence is investigated numerically. As the columnar vortex, the Lamb-Oseen vortex is used. The columnar vortex is immersed in an initially isotropic homogeneous turbulence field, which itself is produced by a direct numerical simulation of decaying turbulence. Using visualization techniques, we investigate the formation of inhomogeneous fine turbulent eddies around the columnar vortex, the vortex-core deformations and the dynamical evolution in the passive scalar field.

We investigate the dynamical evolution of the vortex structure and the passive scalar structure, appeared due to the isotropic homogeneous turbulence interacting with the columnar vortex. The characteristics of the flow field are analyzed by using several flow-visualization techniques. The statistics of the turbulence around the columnar vortex are investigated by computing the two-point energy spectrum tensors, and they are compared with the results of a linear rapid distortion theory (RDT) [1]. The growth of the velocity and vorticity disturbances are proportional to $t^{0.9}$ and t^1 respectively. Although the results are qualitatively consistent with RDT, that do not agree quantitatively with the prediction of RDT($\propto t^2$).

We solve the Navier-Stokes equation for incompressible fluids and the transport equation for the passive scalar (such as a passive temperature field or a dye) under periodic boundary conditions with period 4π. A spectral method is used to solve the equations. The time integration is performed using the fourth order Runge-Kutta-Gill method. The simulations are done with resolutions of 256^3 and 512^3. The columnar vortex is immersed in an initially isotropic homogeneous turbulence field, which itself is produced numerically by a direct numerical simulation of decaying turbulence.

As the columnar vortex, we use the Lamb-Oseen vortex. In cylindrical coordinates, the velocity components of the Lamb-Oseen vortex are defined by

$$U_r = 0 \quad (1)$$

$$U_\theta = \frac{\Gamma_0}{2\pi r}\left\{1 - \exp\left(-\frac{r^2}{r_0^2}\right)\right\}, \quad (2)$$

$$U_z = 0, \quad (3)$$

where U_r, U_θ and U_z are the radial, azimuthal and axial components of the velocity field.The initial circulation Γ_0 is an arbitrary parameter, so we set the circulation strong enough to dominate the vortex dynamics of the flow field

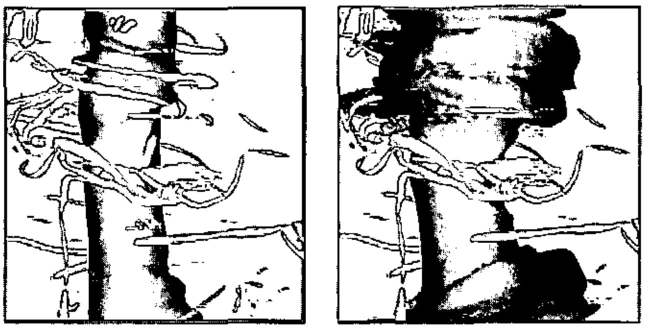

Figure 1: Isosurfaces of the passive scalar (Gray) and the columnar vortex (white) of Case 1(Left) and 2(right) at $t/T = 5.2$.

as

$$\Gamma_0 = 40 r_0^2 \omega_{r.m.s.} \quad (4)$$

where $\omega_{r.m.s.}$ is the root mean square of the vorticity of the initial turbulence. Then the Reynolds number of the columnar vortex Γ_0/ν becomes about 20,000 to 80,000.

In the case that the columnar vortex corresponds to the Lamb-Oseen vortex, the vortex undergoes a deformation due to the interaction, and the vortex wraps worms around its surface in a spiral structure. On the surface, external velocity disturbances are blocked by the vortex and they cannot penetrate into the vortex core directly ('blocking effect'), whereas various types of vortex waves (Kelvin waves) are excited. The disturbances in the axial direction were suppressed. This result is consistent with the Taylor-Proudman's theorem.

The initial scalar field is initialized with the profile $s_0(z)$, which depends only on the axial component of z. In the Case 1, the profile $s_0(r)$ has a Gaussian profile. On the other hand, the profile $s_0(r)$ proportional to $r^2 \exp(-r^2)$. The instantaneous snapshot of the scalar field shows noticeable advection of the passive scalar field around the surface of the vortex core (Fig. 1). This phenomenon may be due to the fact that the blocking effect of the velocity field is excited where the mean axial gradient of the scalar field is large. Another characteristic advection is observed separated from the vortex core. The coherent fine scale structure (worm) wraps the passive scalar; i.e., the only swirling motion of the vortical structure becomes important in the scalar advection.

References

[1] Miyazaki, T. and Hunt, J. C. R.: Linear and nonlinear interactions between a columnar vortex and external turbulence, *J. Fluid Mech.* **402**: 349, 2000.

[2] Takahashi, N., Ishii, H. and Miyazaki, T.: The Influence of Turbulence on a Columnar Vortex, *Phys. Fluids* (submitted), 2003.