Mechanisms of Core Perturbation Growth in Vortex-Turbulence Interaction

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The interaction between a large-scale vortex column and fine-scale ambient turbulence is studied through direct numerical simulation (DNS) of the incompressible Navier Stokes-equations. Turbulence outside the vortexcore is stretched by the vortex's induced azimuthal motion into numerous fine-scale vortex filaments(threads) which are then organized into vortex dipoles, whereas core fluctuations evolve as a superposition of waves. The self-induced motion of the thread dipoles transports mean momentum radially outward, resulting in an overshoot of the mean angular momentum profile. The most prominent effect of the turbulence is to induce strong core perturbations, whose amplitude exceeds the external turbulence levels. Trends of core perturbation growth with increasing Reynolds number (Re)suggest the likelihood of core transition manifesting as accelerated vortex decay at Re values prevailing inpractical flows, such as the aircraft trailing vortex. Three potential mechanisms of core transition are examined: (i) centrifugal instability resulting from a mean circulation overshoot, (ii) resonant forcing of core dynamics (Kelvin waves) by ring-like structures wrapping the column's core, and (iii) the nonlinear growth of optimal transient perturbations. It is found that while centrifugal instability can enhance turbulence production, vortex decay is arrested by the dampening of the instability due to the "turbulent mixing" caused by instability-generated azimuthal vortical structures. In (ii) we find ring-vortex wave resonance even for relatively weak rings. Resonance leads to strong core dynamics, resulting in sheath-like structures in the core, known to be unstable to a Kelvin-Helmholtz-type insta- bility. The nonlinear evolution of modes experiencing transient growth, however, appears to be the most plausible explanation for core fluctuation amplification. Transient growth is manifested by the appearence of bending waves in the core, consistent with prior observations of turbulent vortices. A single bending wave mode reproduces features of turbulent statistics obtaining in vortex interaction with fully developed turbulence, including dipole formation and circulation overshoot. Simulations suggest that the induction of optimal transient modes would result in accelerated vortex decay which should be of interest for prospective flow control.