THREE-DIMENSIONAL VORTEX BREAKDOWN IN SWIRLING JETS AND WAKES

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Summary DNS simulations of swirling jets and wakes exhibiting vortex breakdown are discussed. The basic form of vortex breakdown is found to be axisymmetric, and the transition to helical and double helical breakdown modes is shown to be caused by a sufficiently large pocket of absolute instability in the wake of the primary breakdown bubble.

Vortex breakdown of nominally axisymmetric, swirling incompressible flows with jet- and wake-like axial velocity distributions issuing into a semi-infinite domain is studied by means of direct numerical simulations. By selecting a two-parametric velocity profile for which the steady, axisymmetric breakdown is well studied (Grabowski and Berger 1976), issues are addressed regarding the role of three-dimensionality and unsteadiness with respect to the existence, mode selection, and internal structure of vortex breakdown, in terms of the two governing parameters and the Reynolds number. Low Reynolds numbers are found to yield flow fields lacking breakdown bubbles or helical breakdown modes even for high swirl. In contrast, highly swirling flows at large Reynolds numbers exhibit bubble, helical (figure 1) or double helical (figure 2) breakdown modes. Here the axisymmetric mode is promoted by a jet-like axial velocity profile, while a wake-like profile renders the flow helically unstable and ultimately yields non-axisymmetric breakdown modes. It is shown that a transition from super- to subcritical flow, as defined by Benjamin (1962), accurately predicts the parameter combination yielding breakdown, if applied locally to flows with supercritical inflow profiles. Thus, the basic form of breakdown is axisymmetric, and a transition to helical breakdown modes is shown to be caused by a sufficiently large pocket of absolute instability in the wake of the bubble, giving rise to a self-excited global mode. Two distinct eigenfunctions corresponding to an azimuthal wavenumber m=-1 (figure 3) and m=-2 have been found to yield a helical or double helical breakdown mode, respectively. Here the minus sign represents the fact that the winding sense of the spiral is opposite to that of the flow.

References

[1] Grabowski, W., Berger, S. Solutions of the Navier-Stokes equations for vortex breakdown. J. Fluid Mech. **75**, 525-544, 1976.
[2] Benjamin, T. Theory of the vortex breakdown phenomenon. J. Fluid Mech. **14**, 593-629, 1962.

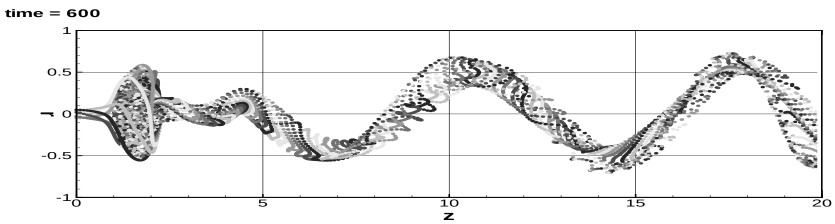

Figure 1: Visualization of flow field with streaklines. Starting from a columnar vortex, a quasi-steady state is reached. It becomes unstable to helical disturbances in the wake of the bubble, so that a helical breakdown mode results.

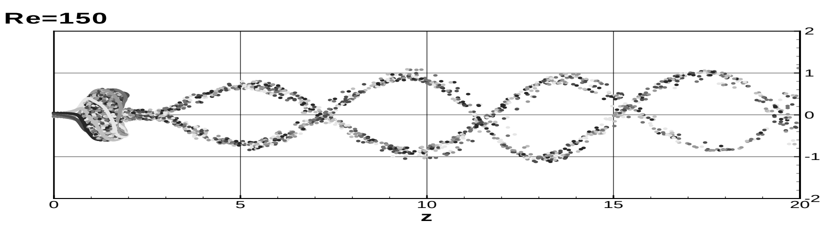

Figure 2: The double helical breakdown mode.

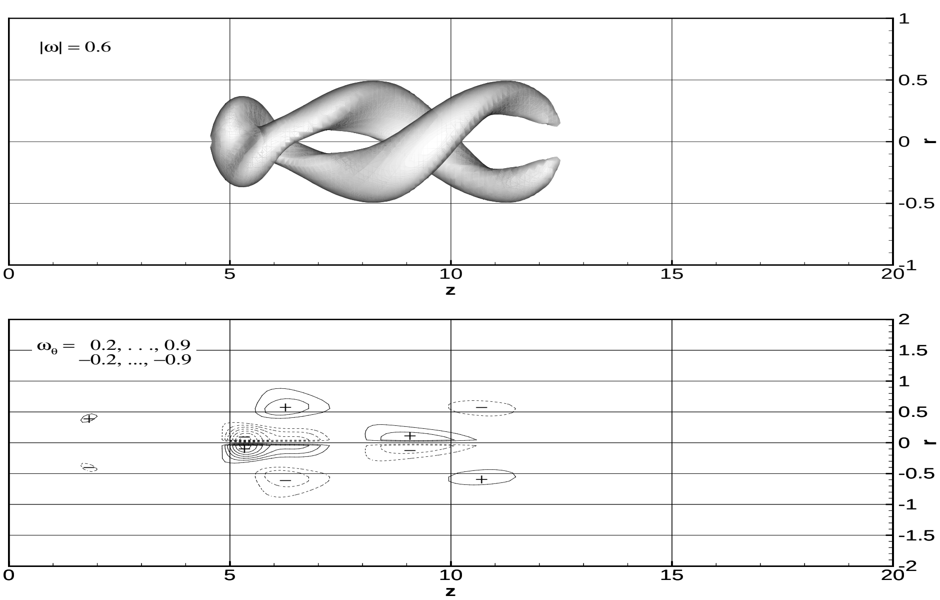

Figure 3: Eigenfunctions of the helical instability mode. The iso-surface of the vorticity (upper frame) reveals an $m = -1$ instability mode which corresponds to alternating signs of the azimuthal vorticity (lower frame).