On late stage mechanisms of transition in round jets

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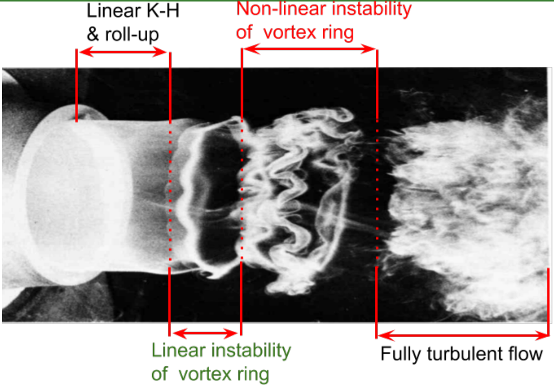
Stages of instability and transition in round jets



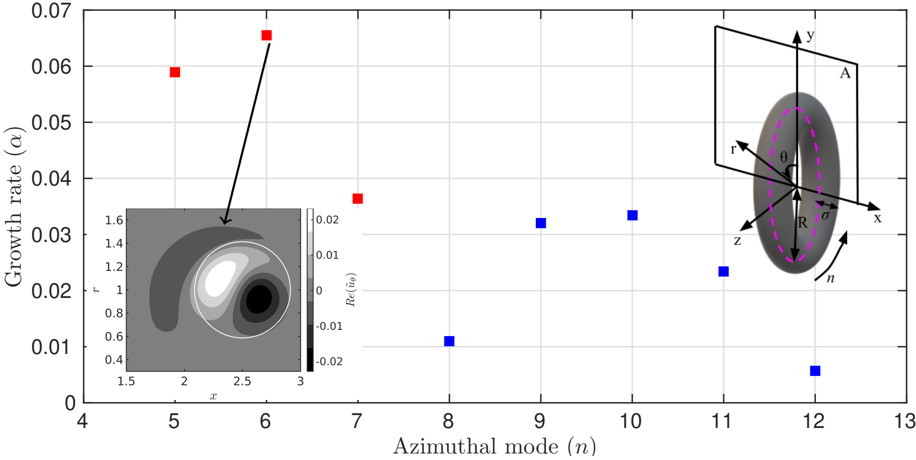
Different stages of instability in round jet at Reynolds number of 13,000 Photograph by R. Wille and A. Michalke, courtesy of H.Fiedler*

1. Shear layer undergoes Kelvin-Helmholtz-like instability → rolls up into vortex rings
2. Linear instability of vortex rings (azimuthal)†
3. Non-linear effects creep in → transition to turbulent flow

*Van Dyke M., An Album of Fluid Motion (The Parabolic Press, Stanford, 1982)

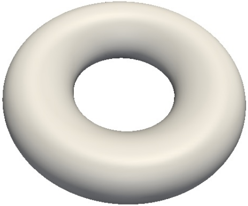
†Balakrishna et al., J. Fluid Mech. - under review

*Linear global stability of vortex ring with $\sigma/R = 0.41$ and $Re = 5500$**

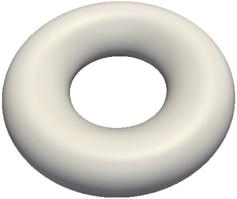


*Balakrishna et al., J. Fluid Mech. - under review

Linear stability, n = 6

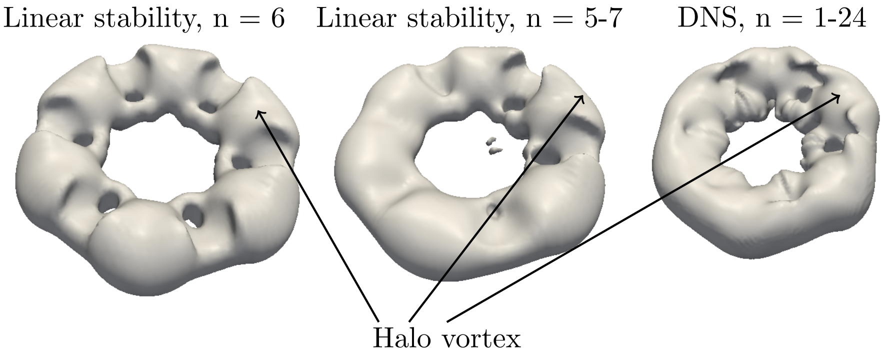


Linear stability, n = 5-7

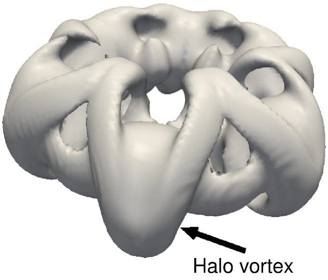


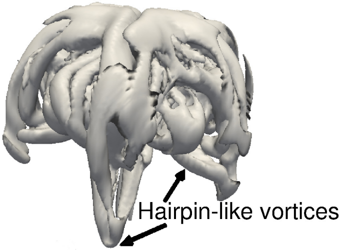
DNS, n = 1-24

Transition of vortex ring



Motivation for the present study

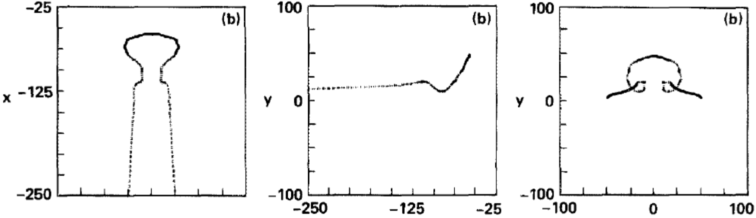




- Number of halo and hairpin-like vortices is a function of dominant azimuthal mode, n
- Any hairpin vortex in the wake is in the induced velocity field of ring and other hairpin vortices
- Transition is modelled with simplified models of increasing complexity
  1. Isolated hairpin vortex
  2. Isolated hairpin vortex in a uniform shear flow
  3. Multiple hairpin vortices
  4. Multiple hairpin vortices with a vortex ring

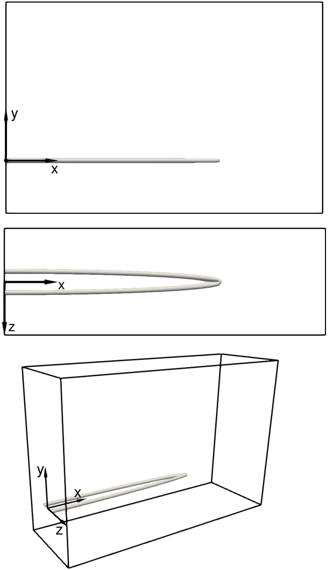
Evolution of an isolated hairpin vortex - previous studies

- Evolution of an isolated parabolic vortex filament was studied using
  - Local-induction approximation*
  - Biot-Savart line integral†
- Evolution has the following stages
  - Lift-up of the hairpin tip due to self-induced velocity
  - Increase in radius of curvature at the tip
  - Legs of hairpin comes close to each other upstream of the tip leading to pinch-off
- Presence of uniform shear retards pinch-off



*Hama, Phys. Fluids (1962)

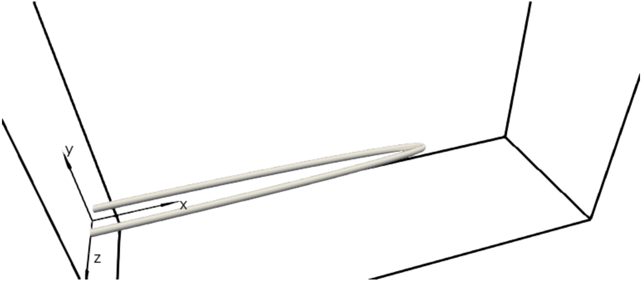
†Moin et al., Phys. Fluids (1986)



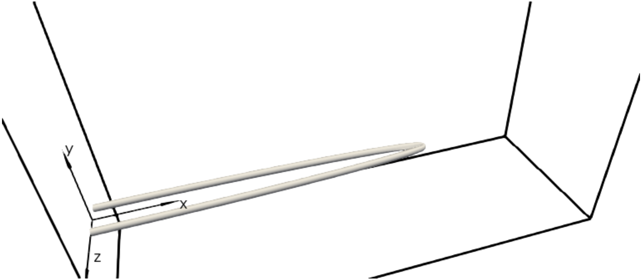
- Hairpin vortex modelled as semi-ellipse
- Elliptic cylindrical coordinates
- Gaussian vorticity distribution
- Initial velocity field obtained from vorticity field
- Length and time scales are b and b^2/Γ
- $Re = 1500$, $\sigma = 0.2$ and $\mathrm{AR} = 20$
- $L_x \times L_y \times L_z = 30 \times 20 \times 10$
- $N_x \times N_y \times N_z = 769 \times 513 \times 256$
- Boundary conditions
  - Free slip wall and periodic in y and z
  - At $x = L_x$ convective boundary condition
  - At $x = 0$, $u = 0.02y + 0.1$
- Incompact3D*

*Laizet and Li, Int. J. Numer. Methods Fluids (2011)

Evolution of an isolated hairpin vortex

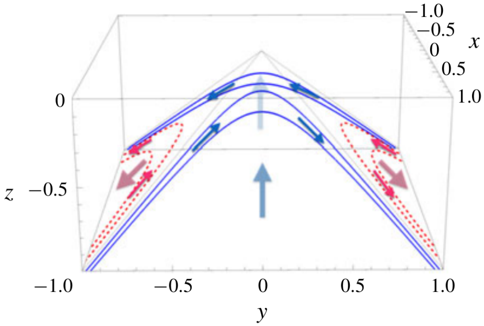


Without shear



With uniform shear

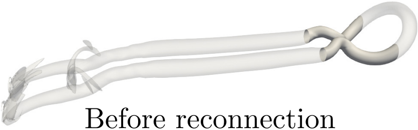
Pyramid-reconnection process



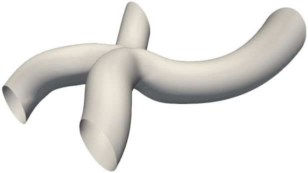
Solid blue - initial and surviving vortex

Dotted red - reconnected vortex

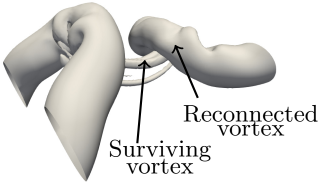
Dark and light arrows - vorticity and propagation direction*



Before reconnection



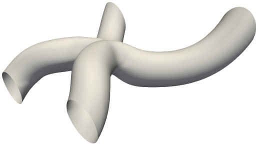
After reconnection



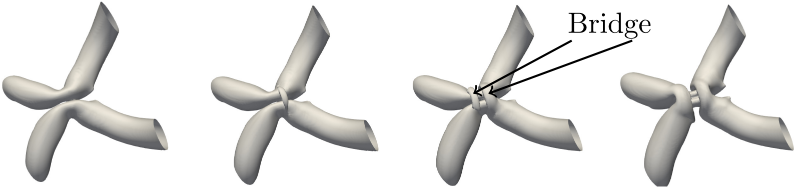
* Moffatt & Kimura, J. Fluid Mech. (2019)

Different stages of reconnection

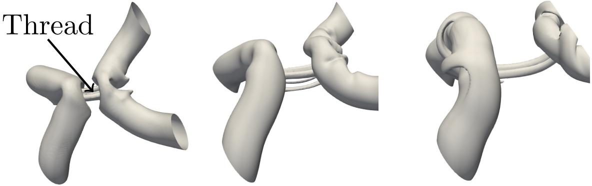
Inviscid advection



Bridging



Threading



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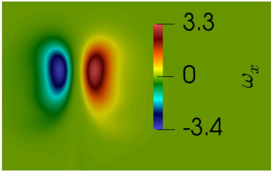

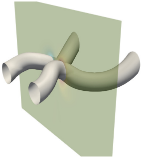

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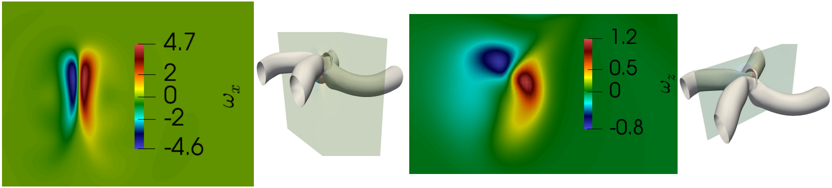

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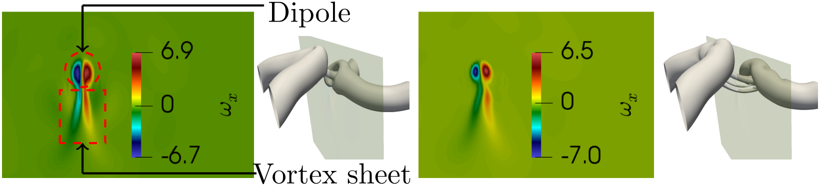

Summary and ongoing work

- Summary
  - Evolution of an isolated hairpin vortex is similar to the works of Moin et al. (1986) till pinch-off
  - Legs of hairpin undergoes pyramid-reconnection process at pinch-off leading to formation of vortex ring and smaller hairpin
  - Three stages of vortex reconnection formulated by Melander & Hussian (1988) are shown
- Ongoing work
  - Evolution of multiple hairpins distributed along the circumference of the ring is being studied with and without ring.
  - Significance of reconnection process during the breakdown of halo vortices

Thank you!