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Title : Comparative Study of the Vorticity
Field in Turbulent Flows: Theory,
Experiments and Computations

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I. Coherent Structure Interactions and Vortex Dynamics

a) Experiments in Elliptic jets

We have carried out a comprehensive study of unexcited and excited elliptic jets, addressing the effects of initial conditions, aspect ratio, excitation frequency, and excitation amplitude. We have studied the dynamics of the preferred mode structure and interactions of coherent structure in the near field of elliptic jets. The dynamics of elliptic jets are quite different from the extensively studied plane and circular jets -- owing mainly to the fact that the azimuthal curvature variation of a vortical structure causes a nonuniform self-induction and hence complex three-dimensional deformation. Such deformation, combined with properly selected excitation, can substantially alter entrainment and other turbulence phenomenon, thus suggesting a preference for the elliptic shape in many jet applications. In the following, we mention a few key results (for detailed results, see Hussain & Husain, 1989; Husain & Hussain, 1991).

Response to controlled excitation reveal that, similar to circular jets, elliptic jets are characterized by the preferred and the stable pairing modes. The corresponding frequencies are $St_{De} (\equiv fD_e/U_e) \approx 0.4$ and 0.85 , where D_e is the equivalent diameter of the elliptic nozzle exit, f is the excitation frequency and U_e is the exit velocity. While the preferred mode structures do not interact mutually, excitation at $St_{De} \approx 0.85$ produces periodic pairing of the structures at the same streamwise location.

When the vortex sheet rolls up in an elliptic jet, the plane of the vortex ring formed is parallel to the nozzle exit plane. Subsequently, the high curvature causes the major axis sides to move ahead of the minor-axis sides. The forward inclination of the major-axis sides forms folds in the initial minor-axis sides. As a results, the induced velocity on the minor-axis sides, now directed outward, increases, and the minor-axis sides moves outward. Consequently, the vortex ring again takes an elliptic shape, but by now the initial major and minor axes have switched. Such inward and outward motions of elliptic structures produces greater engulfment of ambient fluid and subsequently increased entrainment and mixing than those in circular jets. As the aspect ratio of the jet is increased from 2:1 to 4:1, the major-axis sides move ahead of the minor-axis side and towards

the jet centerline much faster because of the greater curvature on the major-axis side. After the first switching of axes, the major-axis sides continue to move farther toward the jet centerline instead of reversing back to start another axes switching. This causes the original major-axis sides to come close enough at the centerline to touch each other. The resulting interaction produces two nearly circular vortices via vortex reconnection. Due to the growth of two side-by-side, nearly circular structures, the 4:1 jet experiences a large increase in the jet width in the initial minor axis plane and an overall increase in the jet cross-sectional area. Vortex reconnection and the resulting jet bifurcation produces enhanced mixing -- both small scale and large scale -- considerably greater than in circular jets. Bifurcation of the 4:1 jet occurs for initial excitation levels of $u'_e/U_e \geq 5\%$; no bifurcation occurs in the 2:1 jet even at $u'_e/U_e = 15\%$, the highest excitation level in our facility.

Pairing interactions are found to be quite different from those in an axisymmetric jet. Because of nonplanar advection of structures, pairing of elliptic vortices does not occur uniformly around the entire perimeter. Merger occurs only in the initial major-axis sides through an entanglement process, while in the minor-axis sides, the trailing vortex rushes inside the leading vortex without pairing and breaks down violently. These motions produce considerably greater entrainment and mixing in elliptic jets than in circular and plane jets. From the measures of dynamical properties over the extent of coherent structures, the production mechanism is related to the longitudinal vortices connecting the elliptic structures.

Ref.: Hussain, F. and Husain, H.S., "Elliptic Jets. Part 1. General Characteristics of Unexcited and Excited Jets," *J. Fluid Mech* **208**, pp. 257-320 (1989).

Husain, H.S. & Hussain, F., "Elliptic jets. Part 2. Dynamics of coherent Structure Pairing," *J. Fluid Mech.* **233**, pp. 439-482 (1991).

b) Coherent Structures, Vorticity and Helicity

Helicity is a conserved dynamical and topological quantity which is an indicator of nonlinear interactions in a flow. Although helicity density by itself is not an invariant in a flow, and some studies have claimed that it may not be relevant, our study (Hunt & Hussain, 1989) has shown how information about helicity density can be used. We have found it to be important in light of its possible

relationship with the entrainment of ambient fluid at a boundary between turbulent and non-turbulent motions, which occur in jets, wakes, mixing layers, etc. Our analysis has shown that in the regions with relatively large modulus of helicity in a turbulent flow, the production of velocity fluctuations and vorticity diffusion has been found to be small, and therefore the entrainment is weak. This is observed in the regions of a mixing layer where the streamwise vortices or "ribs" connect with the spanwise "rolls". On the other hand, we find that helicity of small-scale turbulence is weak in the presence of large-scale straining (as at the saddle points in mixing layers), there is stretching of small-scale vorticity and strong velocity fluctuations normal to the small-scale vorticity. Entrainment is large here because these large normal velocity fluctuations diffuse mean vorticity, and high gradients of amplified vorticity also amplify its viscous diffusion.

Ref.: Hunt, J.C.R. and Hussain, F., "Helicity Associated with Flow around Fluid Lumps and with inhomogeneous Turbulence" in *Topological Fluid Mechanics* (eds. H.K. Moffatt & A. Tsinober), Cambridge U. Press pp. 727-742 (1990).

Hunt, J.C.R. & Hussain, F., "A Note on Velocity, Vorticity and Helicity of Inviscid Fluid Elements," *J. Fluid Mech.* **229**, pp. 569-587 (1991) .

c) Vortex Reconnection

Studies on vortex reconnection have been motivated by the speculation that reconnection is a frequent event in turbulent flows and that it plays a crucial role in mixing, and generation of helicity, enstrophy and aerodynamic noise. We have considered several simple configurations of vortex rings and tubes to simplify our study and focus on the underlying physics of the flow. In the following, we briefly report our results (for details, see Kerr and Hussain, 1989; Melander and Hussain, 1990 & 1991; Kida *et al.*, 1991).

(i) Two Antiparallel Vortex Tubes

Direct numerical simulation of the reconnection of two antiparallel vortex tubes was carried out using 3-D incompressible Navier-Stokes equations. A detailed study of the dynamically important quantities, such as enstrophy, enstrophy production, helicity, kinetic energy dissipation, has led to many useful insights. The simulations reveal in detail the mechanisms in vortex cross linking of the

two viscous vortex tubes. The reconnection process is found to have three characteristic phases: (i) inviscid advection followed by core flattening and stretching; (ii) bridging - *i.e.* annihilation and subsequent accumulation of vortex lines ahead of the interacting vortices; and (iii) threading - *i.e.* the stretching of the remnants with inverse curvature of the initial pair between the two bridges as they pull apart. These phases and the roles of threading and bridging in the mixing and enstrophy cascade have been explained. The entire mechanism has been found to be insensitive to asymmetries.

Ref.: Melander, M.V. and Hussain, F., "Topological Aspects of Vortex Reconnection" in *Topological Fluid Mechanics* (eds: H.K. Moffatt & A. Tsinober), Cambridge U. Press pp. 485-499 (1990).

Melander, M.F., Husain, H.S. & Hussain, F., "Coherent Structures, Vortex Reconnection and Turbulence Mixing," in *New Perspectives in Turbulence* (ed. L. Sirovich) Springer pp. 195-228 (1991).

Melander, M.V. & Hussain, F. "Coherent Structure Dynamics: Interaction between large and fine scales," *8th Symp. Turb. Shear Flow*, pp. 28-5-1 -28-5-5, Munich, Sept. 9-11 (1991).

(ii) High resolution simulations using symmetries

The reconnection of two antiparallel viscous vortices were simulated in a periodic domain for Reynolds numbers ranging from 1600 to 3200. Symmetries were used along with increased resolution in the direction normal to the dividing plane to considerably reduce the computational requirements. An increase of Reynolds number shows a significant increase in the peak vorticity though a corresponding increase in enstrophy is not observed. This observation is consistent with the singularity of the three-dimensional, incompressible Euler equations in a finite time. This is contrary to expectations from analytical models which suggest that there is a singularity of the enstrophy integral.

Ref.: Kerr, R.M. and Hussain, F., "Simulation of Vortex Reconnection," *Physica D*, 37, pp. 474-484 (1989).

Kerr, R.M., Virk, D. & Hussain, F. "Effects of Incompressible and Compressible Vortex Reconnection" in *Topological Fluid Mechanics* (eds. H.K. Moffatt & A. Tsinober), Cambridge U. Press pp. 500-514 (1990).

(iii) Reconnection of Vortex Rings

The reconnection of two vortex rings is a phenomenon extensively studied in experiments though without the necessary ability to make accurate measurements of crucial events. We have studied the interaction of two circular vortex rings evolving from a side-by-side configuration, and have explained the detailed mechanism of reconnection by examining the 3D vorticity field. If the two vortices collide head-on, reconnection is not possible and the two rings annihilate themselves. However, collisions at angles show vortex reconnection similar to the one between two counter-rotating vortices. The vortices undergo two successive reconnections while their shape changes from the original rings. We have examined the dependence of the reconnection process on initial conditions as well as viscosity and have compared the spatial structure of enstrophy, energy-dissipation, enstrophy-production and helicity density fields. It was found that the domains of high energy dissipation and high enstrophy production overlap and are highly localized in space as compared to the regions of concentrated vorticity. The high helicity density and the high energy dissipation regions also overlap significantly although their peaks do not always do so. Additionally, we have estimated the time scale of the process and its role in the enstrophy cascade and noise generation. It was also shown that the time evolution of a passive scalar is quite different from that of the vorticity field, confirming our assertion of not relying too heavily on flow visualization in laboratory experiments for studying vortex dynamics and coherent structures.

Ref.: Kida, S., Takaoka, M. and Hussain, F., "Reconnection of Two Vortex Rings" in *Topological Fluid Mechanics* (eds. H.K. Moffatt & A. Tsinober), Cambridge U. Press. pp. 525-534 (1990)

(d) Dynamics of point vortices in a rotating frame

As part of our mathematical approach to understanding coherent structure dynamics, we have studied the evolution of a mathematically tractable system of point vortices (Kunin, *et al.*, 1990). Point vortices are important as they model the behavior in real flows where vortex patches, sheets, etc., play an important role.

We have reduced the number of degrees of freedom of the Hamiltonian system of N -point vortices to $(N-1)$ leading to symmetric, easy to handle

governing equations. A special rotating frame (SRF) was found in which the relative motion of the point vortices is simpler, had minimum energy, and reveals dynamical features which are otherwise not discernible in the usual fixed reference frame. Examples of periodic, quasiperiodic and chaotic motions in the SRF show that : (a) periodic orbits are closed lines and not space filling as in a fixed frame, (b) quasiperiodic orbits form steady patterns, and (c) chaotic motions create asymptotic symmetries that reflect the permutation symmetry of the Hamiltonian. In addition, the kinetic energy of relative motion is the minimum in the SRF.

Ref.: Kunin, I., Hussain, F., Zhou, X. & Kovich, D., "Dynamics of Point Vortices in a Special Rotating Frame," *Int. J. Engr. Sci.* 28, pp. 965-970 (1990).

(e) Symmetry breaking

Diverging fluid motions occur frequently in technologically relevant flows and, in particular, in energy devices such as combustion chambers, fuel atomizers, diffusers and thrusters. The possibility of an azimuthal instability splitting the flow into a few branches, internal and near wall separation, and generation of strong azimuthal oscillations are some of their intrinsic features relevant to practical applications.

We have shown that a new kind of inertial instability, different from the well-known Kelvin-Helmholtz, Rayleigh, Taylor and Heisenberg-Lin instabilities, develops due to unfavourable pressure gradients and deceleration of the flow caused by the divergence of streamlines (Goldshtik, *et al.*, 1991). This is most clear and convincing for the simplest case studied by us – planar flow from a point source. This flow has no jumps, inflection points, swirl or shear required for the above mentioned instability mechanisms. The simplicity of vortex-source and Jeffery-Hamel flows permits advanced analyses to obtain secondary solutions resulting from the primary and secondary instabilities.

Thus, the stability and bifurcations associated with the loss of azimuthal symmetry of planar flows of a viscous incompressible fluid, such as vortex-source and Jeffery-Hamel flows, were studied by employing linear, weakly nonlinear and fully nonlinear analyses. We have addressed the stability of steady self-similar solutions of the Navier-Stokes equations to spatially developing

disturbances. By considering bifurcations of a potential vortex-source flow, we have found secondary solutions. They include asymmetric vortices which are generalizations of the classical point vortex to vortical flows with nonaxisymmetric vorticity distributions. Another class of solutions relates to transition trajectories that connect new bifurcation-produced solutions with the primary ones. Such solutions provide far-field asymptotes for a number of jetlike flows. In particular, we have considered flows which are combinations of a jet and a sink, a tripolar jet, a jet emerging from a slit in a plane wall, a jet emerging from a plane channel and reattachment phenomenon in the Jeffery-Hamel flow in divergent channels.

Ref.: Goldshtik, M. Hussain, F. & Shtern, V., "Symmetry Breaking in Vortex-Source and Jeffrey-Hamel Flows," *J. Fluid Mech.* **232**, pp. 521-565 (1991).

f) Kinematic Separation

Separation of heavy particles from a fluid by centrifugal forces or by barodiffusion is quite well known. However, continuum hypothesis would suggest that the separation of a homogeneous mixture of very fine particles in a fluid is impossible. Our experiments in a vortex breakdown chamber have indicated the contrary. We have observed spontaneous segregation of smoke particles from air in an initially uniform mixture, when a rotational flow is induced in the medium (Goldshtik, *et al.*, 1992).

This observed separation has significant technological implications in pollution control and isotope separation processes. An explanation for this separation is not obvious. Analysis of the observed phenomena has led to a tentative explanation based on flow kinematics. We are currently making a detailed experimental and numerical study of all the forces that act on the particles in the flow which could lead to the separation.

Ref.: Goldshtik, M., Husain, H.S. & Hussain, F. "Kinematic Separation of Mixtures," *Phys. Rev. A* **45**, 8611-8616 (1992).

Goldshtik, M., Husain, H. S. & Hussain, F., "Loss of Homogeneity in a suspension by Kinematic Action," *Nature* **357**, 141-142 (1992).

II. Topology and Dynamics of Mixing Layers

a) Multi-rake Hot-wire system and 9-wire vorticity probe

A primary objective of our experimental research is to obtain quantitative data in turbulent shear flows to study the dynamics of coherent structures. Vorticity is the defining quantity in turbulent flows, and with this in mind, we have focussed on the development of innovative measurement techniques to educe coherent structures. We use multiple rakes of hot-wires to estimate and a 9-wire vorticity probe to directly measure the vorticity in a flow.

During the period of the grant, we have acquired the necessary hardware and made it operational. A set of 70 channels of constant temperature anemometers and a 9-wire vorticity probe were purchased while a micromanipulator/micor-welding apparatus was assembled in-house. Also a special computer-controlled traverse for use in pitch/yaw calibration of the probe was designed and built in-house. A significant effort was spent on the development of a software package for the calibration, data acquisition and conversion of raw voltage values into velocity and gradients for use with the vorticity probe.

Working from the basic calibration scheme developed by Vukoslavcevic, Balint & Wallace (1989), we now use fourth order Chebyshev polynomials to resolve the velocity components from the measure wire voltages. Additionally modifications were made to account for the response nonlinearities due to electrical cross talk in the probe, non-orthogonality of the wires, etc. to make the calibration more efficient. The calibration was validated in the potential core of a circular jet and velocity and vorticity statistics were computed in the shear layer of the jet.

b) Eduction of coherent structures in a plane turbulent wake

The experimental study of the dynamics of coherent structures (CS) in a plane turbulent wake was carried out using several combinations of appropriately spaced X-wires. Vorticity distributions in the spanwise and transverse planes were measured in the intermediate region ($10d \leq x \leq 40d$) of the plane turbulent wake of a circular cylinder at a Reynolds number of 13000 based on the cylinder diameter d .

CS are detected from instantaneous, spatially phase-correlated vorticity field using certain criteria based on size, strength and geometry of vortical structures. The study indicates that the organized structures in the nominally two-dimensional wake exhibits significant three-dimensionality even in the near field (Hayakawa & Hussain, 1989). Frequent concentrations of transverse vorticity with scales and strengths of the order of spanwise vorticity were found in the flow. The dominant configuration of the distorted rolls was found to be a horseshoe-like-vortex inclined at an angle of 30° to the y-axis.

Ref.: Hayakawa, M. and Hussain, F., "Three Dimensionality of Organized Structures in a Plane Turbulent Wake," *J. Fluid Mech.* 206, pp. 375-404 (1989).

c) Numerical Simulations of a Mixing Layer

A new mechanism for small-scale transition in a mixing layer, which is not reliant on the presence of secondary longitudinal vortices, or 'ribs' was developed and analyzed. Using linear stability analysis of the Stuart vortex row solution, we studied the linear evolution and dynamics of 'bulging' instability eigenmodes, which produce amplifying oscillations of a spanwise core size nonuniformity of the primary vortices, or 'rolls'. Through direct numerical simulation, we extended these dynamics into the nonlinear regime for evolution up to two roll pairings. To mimic a general perturbation environment in an unforced experimental flow, all 2D and 3D instability modes were initialized with the same initial energy content. We found that the twisting and untwisting of roll vortex lines associated with the bulging instability eventually results in an internal reconnection of vortex lines within the roll between the first and second pairings, thereby generating small-scale 'threads' of vorticity which is reflected by a sharp rise in the dissipation rate. The core oscillation dynamics are not disrupted by the presence of collapsed ribs or their engulfment within pairing rolls, which indicates that the bulging instability can operate alongside the evolution of the standard rib and roll flow structures. In fact, the dynamics of roll vorticity in the standard flow are dominated by the bulging instability, which indicates that it governs the generation of small scales if it experiences an excitation level comparable to that of the ribs in the initial conditions or upstream flow. The roll oscillation causes the ribs to evolve nonuniformly along the span, which constitutes a potential mechanism for rib rescaling.

We have also shown that the bulging instability can be excited by a pairing, and have proposed a scenario of transition from low initial 3D disturbance levels based on an oblique mode with a sufficiently long streamwise wavelength to generate a required level of 3D saturation energy. We observe that the vortex core dynamics are insensitive to vortex geometry and require only an external strain rate for amplification, thus constituting a possible transition mechanism in other shear flows.

List of Publications Supported by DOE Grant No. DE-FG05-88ER13839

1. Hussain, F. and Husain, H.S., "Elliptic Jets. Part 1. General Characteristics of Unexcited and Excited Jets," *J. Fluid Mech* 208, pp. 257-320 (1989).
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3. Hunt, J.C.R. and Hussain, F., "Helicity Associated with Flow around Fluid Lumps and with inhomogeneous Turbulence" in *Topological Fluid Mechanics* (eds. H.K. Moffatt & A. Tsinober), Cambridge U. Press pp. 727-742 (1990).
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5. Bridges, J., Husain, H.S. & Hussain, F., "Wither Coherent Structures?" in *Whither Turbulence? Turbulence at the Crossroads* (ed. J.L. Lumley) Springer-Verlag, pp. 132-151 (1990).
6. Melander, M.V. and Hussain, F., "Topological Aspects of Vortex Reconnection" in *Topological Fluid Mechanics* (eds: H.K. Moffatt & A. Tsinober), Cambridge U. Press pp. 485-499 (1990).
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9. Melander, M.V. & Hussain, F., Basu, A. "Breakdown of a Circular Jet into Turbulence," *8th Symp. on Turb. Shear Flow*, pp. 15-5-1 - 15-5-6, Munich, Sept. 9-11 (1991).
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13. Kida, S., Takaoka, M. & Hussain, F., "Formation of head-Tail Structure in a Two-Dimensional uniform Staining flow," *Phys. Fluids A* **3**, pp. 2688-97 (1991).
14. Kunin, I., Hussain, F., Zhou, X. & Kovlich, D., "Dynamics of Point Vortices in a Special Rotating Frame," *Int. J. Engr. Sci.* **28**, pp. 965-970 (1990).
15. Goldshtik, M. Hussain, F. & Shtern, V., "Symmetry Breaking in Vortex-Source and Jeffrey-Hamel Flows," *J. Fluid Mech.* **232**, pp. 521-565 (1991).
16. Goldshtik, M., Husain, H.S. & Hussain, F. "Kinematic Separation of Mixtures," *Phys, Rev. A* **45**, 8611-8616 (1992).
17. Goldshtik, M., Husain, H. S. & Hussain, F., "Loss of Homogeneity in a suspension by Kinematic Action," *Nature* **357**, 141-142 (1992).
18. Hayakawa, M. and Hussain, F., "Three Dimensionality of Organized Structures in a Plane Turbulent Wake," *J. Fluid Mech.* **206**, pp. 375-404 (1989).

and a large number of conferences proceedings, invited lectures and seminars.

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