Numerical Study of Subsonic Twin Round Jets using LES based on Explicit Filtering

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Introduction Twin Jets

- the jets interact and merge into a single jet downstream
- have different jet plume development and noise directivity characterstics compared with single jet

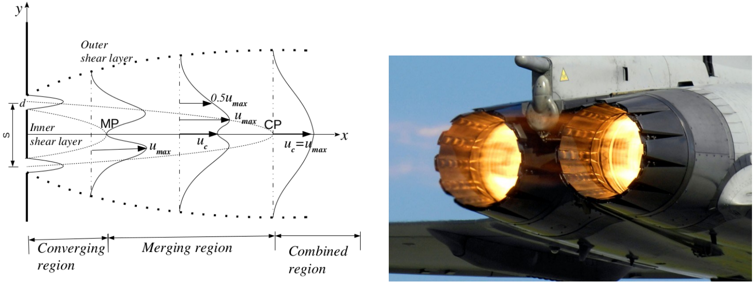

Figure 1: Schematic and an image[1] of the flow of twin round jets

image[1]

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[1] **Google**.

Governing Equations

The Navier-Stokes are the model equations of the flow,

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0$$

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j}$$

$$\frac{\partial(\rho E)}{\partial t} + \frac{\partial[(\rho E + p)u_i]}{\partial x_i} = \frac{\partial(u_j \tau_{ij})}{\partial x_i} + \frac{\partial q_i}{\partial x_i}$$

where $E = p/(\gamma - 1) + \frac{1}{2}\rho(u^2 + v^2 + w^2)$

Numerical Scheme

The **LES** with **explicit filtering**, Mathew *et al.*[2] as its **subgrid model** implemented here, requires

- high resolution spatial discretization schemes
- high resolution low-pass spatial filter
- filtering is done at every time step

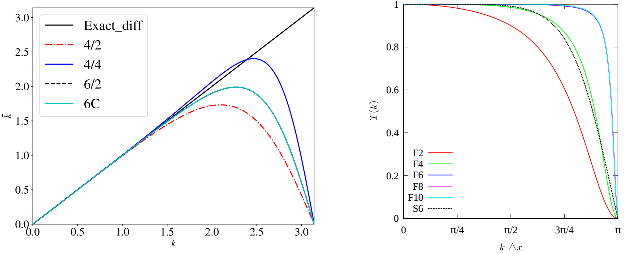

Figure 2: Compact schemes wavenumber resolution capabilities

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[2] Joseph Mathew et al. "An explicit filtering method for large eddy simulation of compressible flows". In: *Physics of Fluids* 15 (8 2003).

Code Validation - Single Round Jet

An isothermal turbulent round jet at $Re = 11000$ and Mach number 0.9 and $d = 0.061m$

- computation domain is $16d \times 75d \times 16d$
- with $363 \times 471 \times 363 \approx 62$ million grid points
- statistics collected after 30 flow-throughs

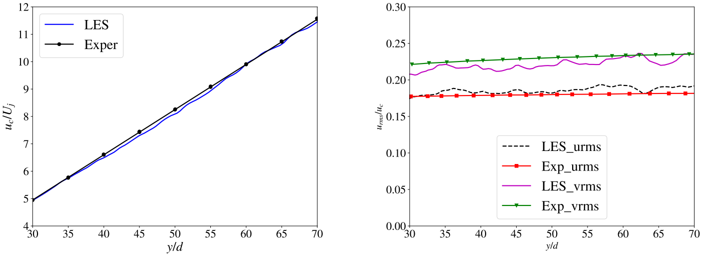

Figure 3: Inverse centerline velocity and turbulence intensities

Experimental data[3]

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[3] Panchapakesan N. R. and Lumley J. L. "Turbulence measurements in axisymmetric jets of air and helium. Part 1 Air jet". In: *J. Fluid Mechanics* 246.197 (1993).

Simulation of Twin Circular Jets

- jet diameter $d = 0.07\text{m}$, $Re = 2.3 \times 10^5$
- nozzle spacing $S/d = 5$
- same initial condition for velocity at the inflow plane

$$\frac{u(r)}{U_j} = \frac{1}{2} + \frac{1}{2}\tanh\left(\frac{r_0 - r}{2\delta_\theta}\right)$$

- size computation domain is $21d \times 54d \times 21d$
- with $441 \times 401 \times 441 \approx 80$ million grid points
- additional points inside the buffer zone

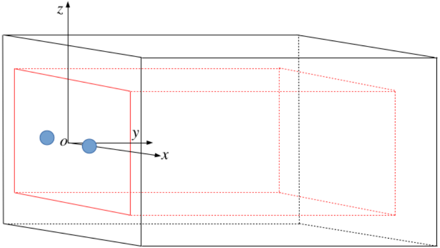

Figure 4: Computational domain

Velocity Flow Field

- iso-surfaces of a snapshot of Q indicating the development of the interaction
- mean velocity contour plots showing the merging of the two inner shear layers

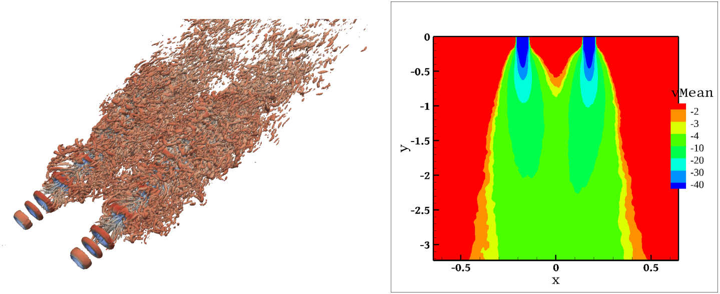

Figure 5: Iso-surfaces of a snapshot of Q and mean velocity contour plot at mid-plane $z = 0$

Mean Velocity Profiles

Initially the velocity in the center of the $xy-$ plane is zero but at downstream distance $y/d = 10$ it appears in the centerline.

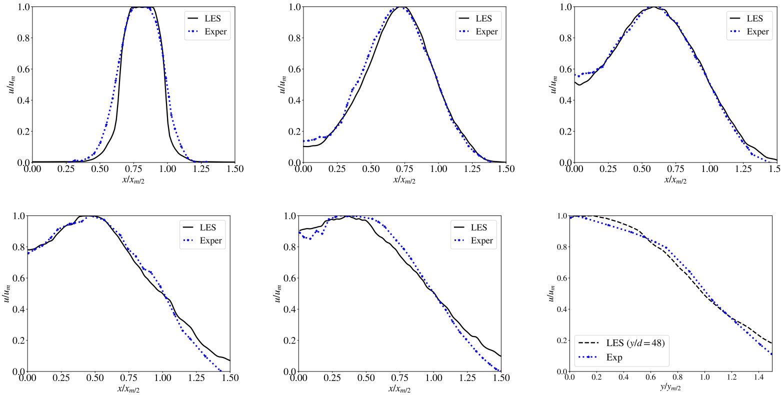

Figure 6: Mean velocity profiles normalized by local maximum velocity

Experimental data[4]

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[4] T. Okamoto et al. "Interaction of twin turbulent circular jet". In: *Bulletine of JSME* 28.238 (1985).

Contd ...

- the interaction becomes stronger when the velocity in the symmetry plane gradually increases
- The position of the maximum velocity shifts from the center of the respective jets toward the symmetry plane

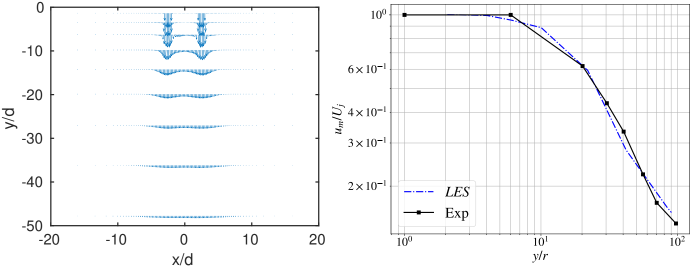

Figure 7: Max mean velocity shift and decay along downstream distances

Growth of the Jet Half-Width

- almost a linear growth rate is observed for the jet spreading
- The spread of the jets computed based on the velocity ratio, $u/u_m = 0.1$,

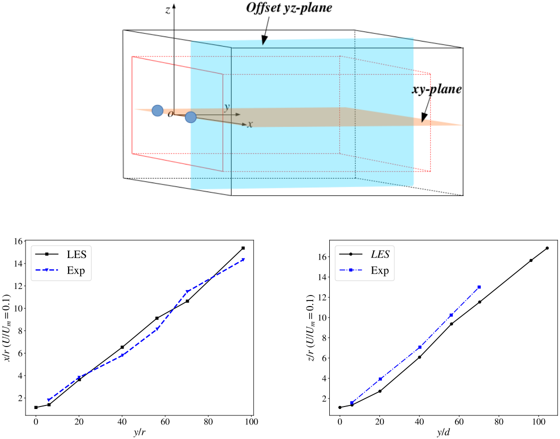

Figure 8: Spread of twin jet on the *xy*- and offset *yz*-plane through the nozzle

Static pressure profiles

- The static pressure distribution increases with downstream distance
- gradual shift in position of the minimum pressure toward the mid point between the jets is observed

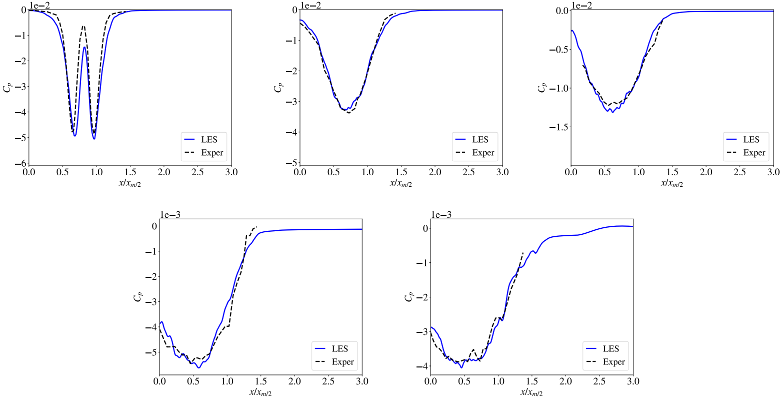

Figure 9: The variation of static pressure profiles at different downstream distances

Turbulence Intensity and Reynolds Shear stress

- difference in the streamwise turbulence intensity in the inner and outer shear layer regions is observed for $y/d \geq 20$
- the peak value of the Reynolds shear stress in the inner shear layer to be smaller than the outer one at $y/d \geq 20$

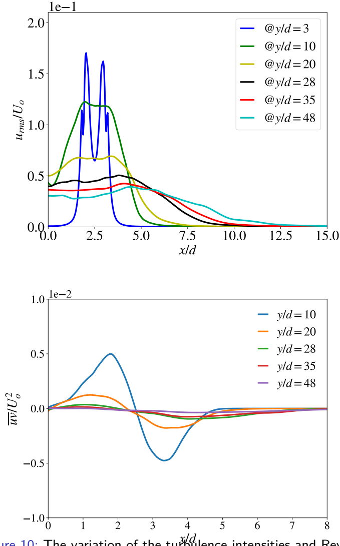

Figure 10: The variation of the turbulence intensities and Reynolds shear stresses at different downstream distances

Axis Switching

At far downstream the contour profile switching was observed.

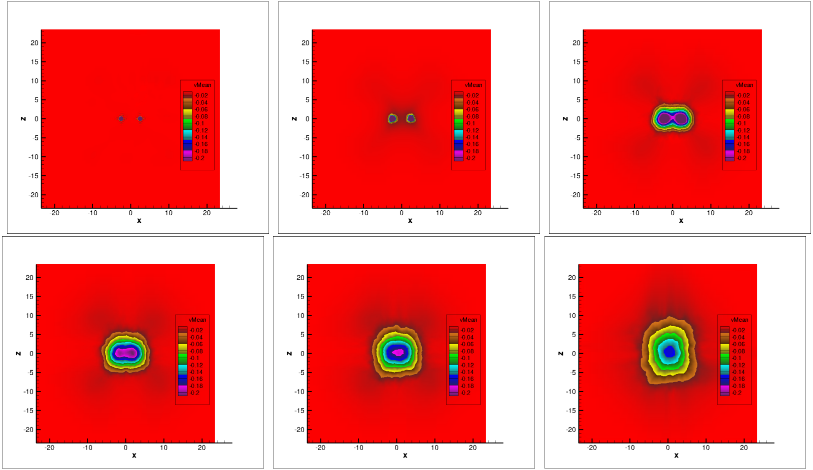

Figure 11: Iso-velocity curves of the mean velocity at different downstream cross-sections ($y/d = 0, 10, 20, 28, 35$ and 48)

Conclusion

The current LES of twin parallel circular-nozzle jets has shown

- the shift in position of the maximum velocity and minimum pressure toward the axis of symmetry of the jets
- the flow-field spread almost in a linear fashion in the *xy* plane
- Contour profiles at different downstream cross-section showed the presence of an axis switching
- magnitude of the streamwise turbulence intensity at the inner shear layer, for $y/d \geq 20$, are smaller compared to the outer shear layer region
- similarly the magnitude of the peak value of the Reynolds shear stress in the inner shear layer to be smaller than the outer one at $y/d \geq 20$

Thank You!