Inlet Conditions for LES of Swirl Flows

Mohammad Baba-Ahmadi, Gavin Tabor

SECaM, University of Exeter

August 12, 2008

Large Eddy Simulation

Turbulence : need to reduce d.o.f. in problem –

- implement some form of averaging,
- simulate 'mean' flow
- model 'turbulent' fluctuations

RANS – time/ensemble averaged mean flow. All quantities static or slowly varying.

LES – volume averaging via filter

$$u(t) = \overline{u}(t) + u'(t) \qquad \text{where} \quad \overline{u}(t) = \int G(x - x')u(x', t)\; d^3x$$

GS quantities stochastically varying – causes significant problems at inlets

Inlet boundaries

Very important – many flows affected by turbulence at inlet.
LES inlet must contain some stochastic component due to GS turbulence.
Required properties :

- stochastically time-varying
- on scales down to filter scale
- compatible with the N-S equations
- ‘looks’ like turbulence
- specify turbulent properties (length scales, turbulent magnitudes etc.)

Simply adding on random fluctuations does not work.

Standard approaches :

- **Synthesis** Construct pseudo-random field from base functions (e.g Fourier, digital filters etc) and attempt to match required properties.
- **Library lookup** Perform separate calculation to generate turbulence data and map to inlet

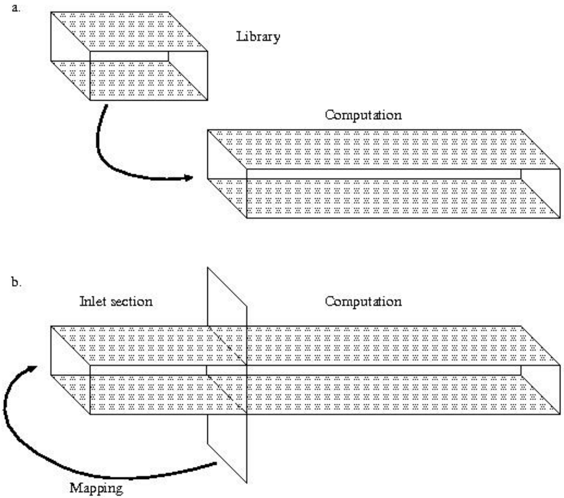
OpenFOAM also includes mapping method; sample flow downstream and map back to inlet.

OpenFOAM

C++ class library for finite volume CFD on arbitrary unstructured grids, developed by H.Weller and H. Jasak (Imperial College, Nabla Ltd, now OpenCFD Ltd, Wikki Ltd and U.Zagreb)

Multi-purpose library with well-validated LES capability using 2nd order schemes, CG solvers, PISO and a range of SGS models (Smag, 1 equation, dynamic models).

Implements LES inlet condition based on internal mapping on main domain


a.
Library
Computation
b.
Inlet section
Computation
Mapping

Inlets with swirl

We wish to manipulate inlet to specify mean flow profile – eg. swirl – also turbulence profiles.

Swirl particularly important as this is difficult to model with RANS due to streamline curvature effects.

Previous attempts; mean flow plus fluctuations (Huang and Yang 2005, Wang *et al.* 2007), library lookup (Wang and Bai 2005, Schlüter *et al.* 2004) based on cyclic channel with fixed body force (Pierce and Moin 1998).

Our approach; mapping on main domain with appropriate forcing and control algorithms :

1. Apply control algorithm to driving body force to generate correct mean (and swirl) profile

$$\overline{\mathbf{F}} = \frac{V_b}{L}\left[\alpha(\mathbf{v}_{des} - \langle \overline{\mathbf{v}} \rangle) + (\mathbf{v}_{des} - \overline{\mathbf{v}})\right], \qquad (1)$$

2. Apply velocity corrections with control algorithm within mapping section

$$\overline{\mathbf{v}}^* = \mathbf{v}_{des} + (\overline{\mathbf{v}} - \langle \overline{\mathbf{v}} \rangle) \times \left(\frac{(R_{des})_{ii}}{R_{ii}}\right)^{1/2}, \qquad (2)$$

Cylindrical pipe

Swirling flow in a cylindrical pipe length $10D$ (pipe diameter $D = 2\ \mathrm{m}$)

Mesh resolution 448 cells across section, 30 cells/metre of length.

Swirl S defined

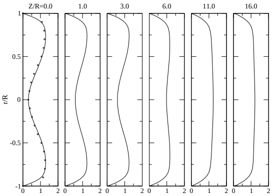
$$S = \frac{1}{R_0} \frac{\int_0^{R_0} r^2 \langle v_z \rangle \langle v_\theta \rangle dr}{\int_0^{R_0} r \langle v_z \rangle^2 dr} \tag{3}$$

here, $S = 0.6$ at $\mathcal{R}e = 30,000$.
Case run for $4000\ \mathrm{s}$ – 60 transits through domain

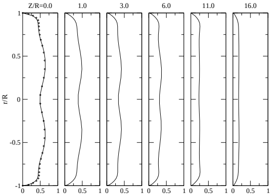
Target profile from averaged LES on short cyclic domain.

Results

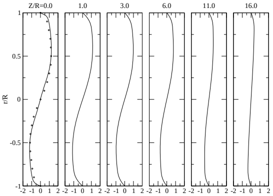
Axial mean velocity



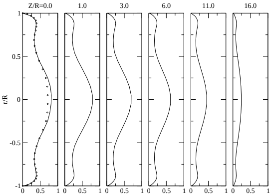
$v'_{z,rms}$



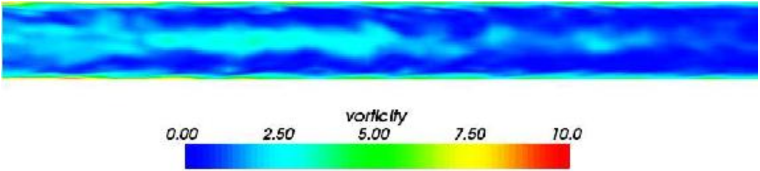
Tangential mean velocity



$v'_{\theta,rms}$



Vorticity



Sudden Expansion

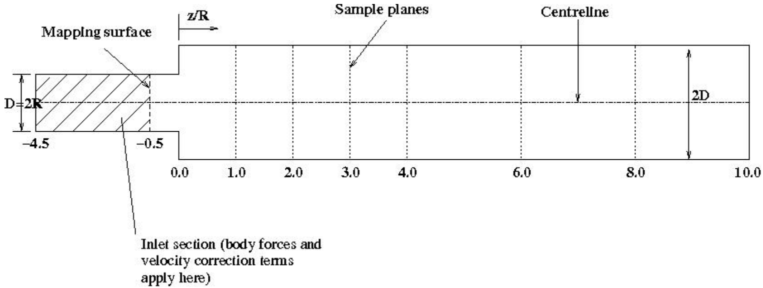
Test case; sudden expansion jet flow with/without swirl

Measurements in Turbulent Swirling Flow through an Abrupt Axisymmetric Expansion. Dellenback, Metzger, Neitzel. *AIAA.J.* **26#6** (1988)

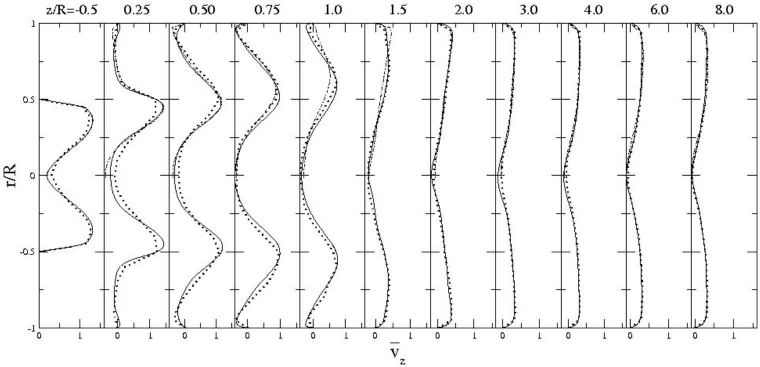
Experimental data for $\mathcal{R}e = 30,000$, $S = 0, 0.6$. $S > 0.25$ creates central recirculation, vortex breakdown – turbulence production within domain. Still need to generate correct inlet conditions.

1.5 million cells; $y^+ = 16$ upstream of expansion.

Compare with experimental and literature LES (Schlüter *et al.*)

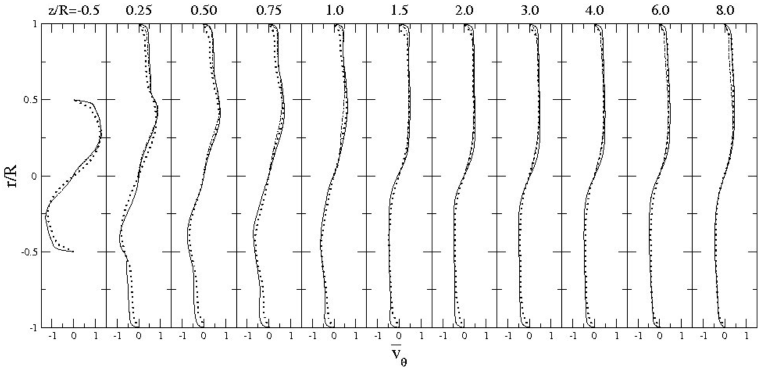

Mapping surface
z/R
Sample planes
Centreline
D=2R
2D
−4.5
−0.5
0.0
1.0
2.0
3.0
4.0
6.0
8.0
10.0
Inlet section (body forces and velocity correction terms apply here)

Axial mean velocity



Dotted lines: experimental, Solid lines: LES, Dot-dash: Schlüter

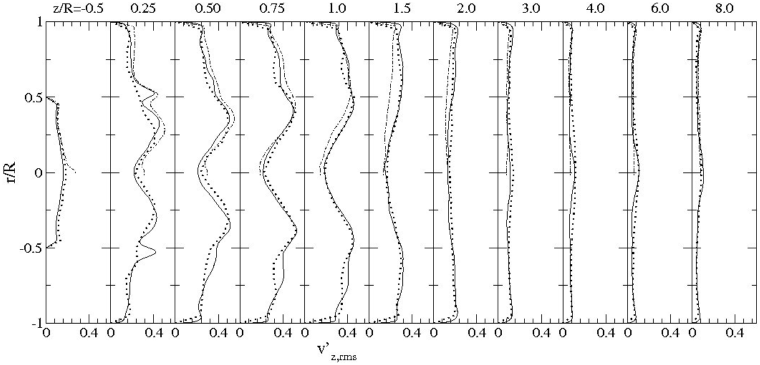
Tangential mean velocity



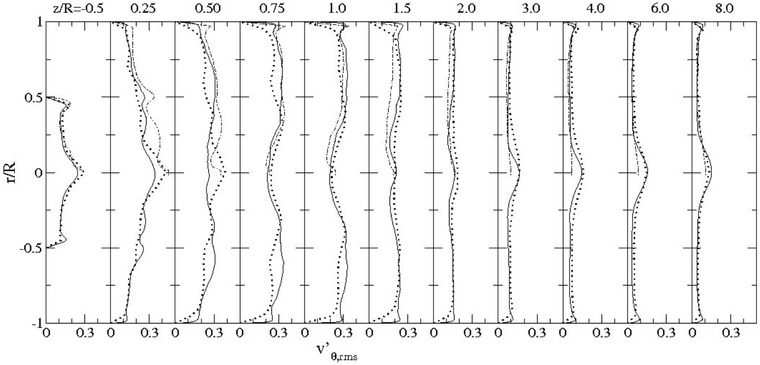
$v'_{z,rms}$

Inlet Conditions for LES of Swirl Flows

Mohammad Baba-Ahmadi, Gavin Tabor

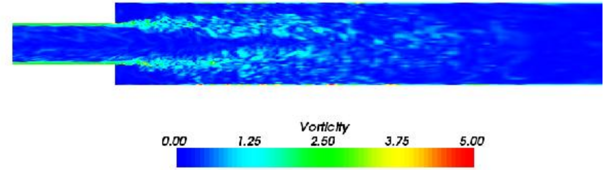


$v'_{\theta,rms}$

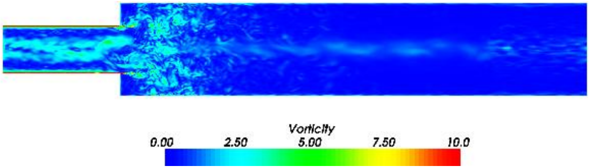


Vorticity

No swirl:



Swirl number 0.6:



Discussion

Pipe case

- Used to develop methodology – no comparison with reference data
- Turbulence generated at inlet behaves much as expected :
  - Flow field uniform across mapping plane
  - No unphysical behaviour in mapping section or downstream
  - No significant periodicity in solution

Sudden expansion

- Good comparison with experimental and literature LES data; mean flow well reproduced; for all properties results at least as good as lit LES data.
- No need for turbulence to develop (cf. synthesis methods)
- High swirl cases less sensitive to inlet turbulence, but actual bulk swirl needs to be reproduced.

Conclusions

- Mapping method can be adapted using bulk forces, velocity corrections, and feedback control to generate desired mean and turbulent profiles
- Profiles from experimental data or pre-computation (possibly from RANS)
- Method performs better than synthesis methods, at least as well as library methods
- and is more elegant, simpler

Acknowledgements

Prof Hrvoje Jasak, Henry Weller, Dr Eugene de Villiers
EPSRC grant no. GR/R27495/01

References :

"Inlet Conditions for LES of gas-turbine swirl injectors", M.H.Baba-Ahmadi, G.Tabor, *AIAA.J.***46#7** pp.1782 – 1790 (2008)

"Inlet Conditions for LES using Mapping and Feedback Control", M.H.Baba-Ahmadi, G.Tabor, Submitted to :*Computers and Fluids*

"Construction of Inlet Conditions for LES of Turbulent Channel Flow", G. Tabor, M. H. Baba-Ahmadi, E. de Villiers, H.Weller, *ECCOMAS 2004 Congress*, Finland (2004)