Hybrid LES Approach for Practical Turbomachinery Flows

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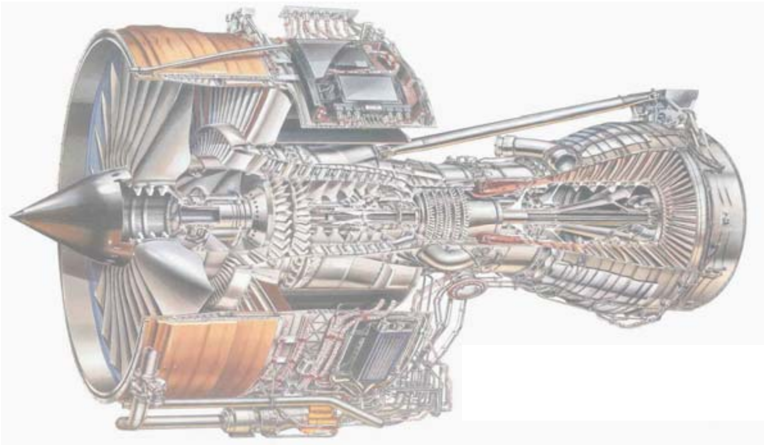

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Summary

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- LES computational cost discussed
- LES hierarchy is proposed → LES model last !!
- Practical hybrid LES approach is proposed
- Applied to predict canonical flows: HDT, free shear flow, wall shear flows (+TS), ribbed passage; convex surface impingement
- Consider turbine and compressor endwall flows; fan blade section; jets; cutback trailing edge; idealized high pressure compressor drum cavity
- Encouraging results. Challenges remain for complex BL physics …..
- Need for best practices, better validation data discussed

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What is LES, MILES, NLES …?

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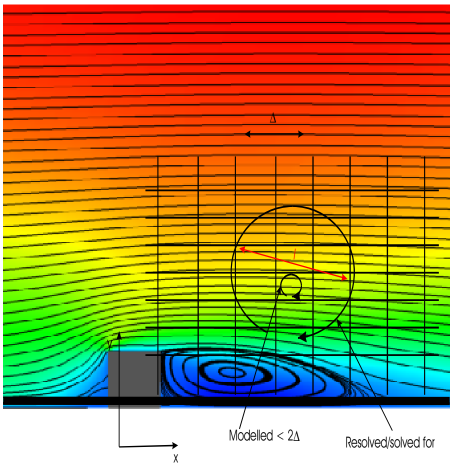
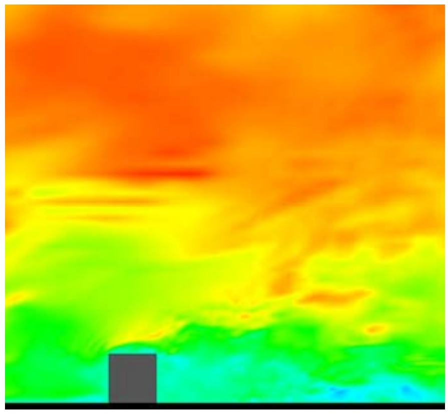
RANS = Resolve time average of flow, all modelling



LES = Resolve all large eddies 10% modelling



•Practical LES (DeBonis)

•Rigorous LES

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KEY LES PROBLEM

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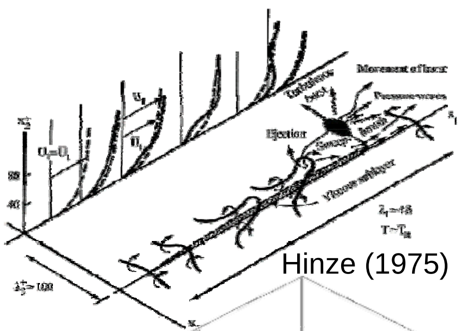
•Resolving streaks $\Delta z^+ \approx 100$

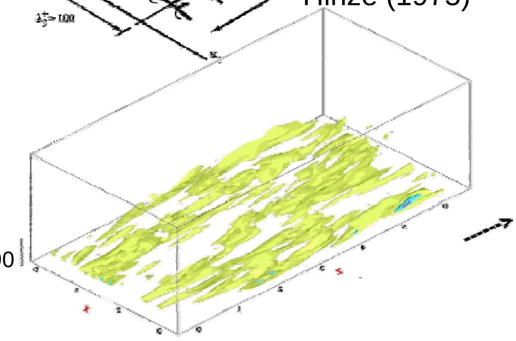
•Trent 1000 fan at cruise 10^7

•LES Cost α $Re^{2.5*}$

•Hybrid LES-RANS Cost α $Re^{0.5}$



Hinze (1975)



*Piomelli, AIAA-2008-396

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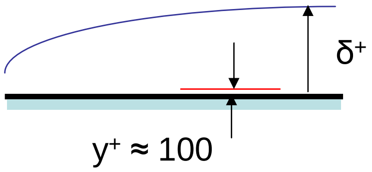
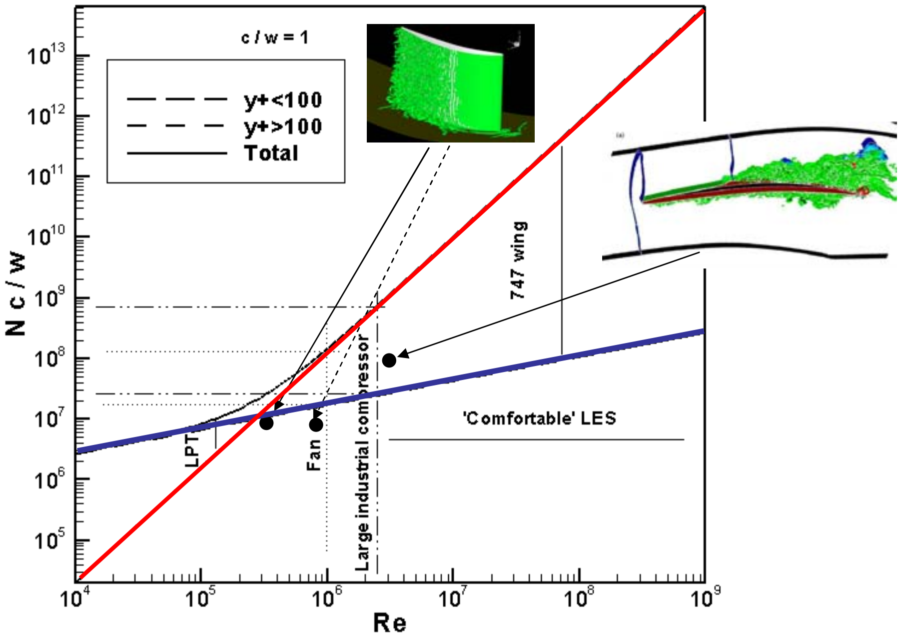
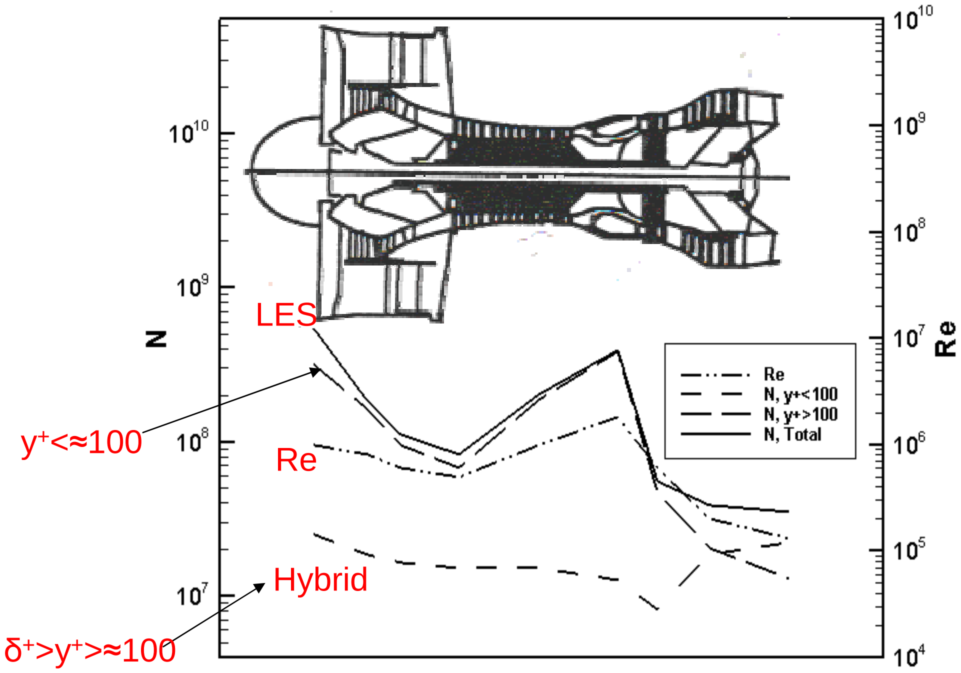
LES Resolution Requirements





Adapted from Leschziner (2009), Piomelli and Balaras (2002)

Grid Requirements



NUMERICS/SGS SENSITIVITY

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Range of Solvers

Code	Description	Order of Φ_{ctr}	Smoothing
HYDRA	Cell Vertex	2	4th order
BOFFS	Curvilinear	2-6	3-7th order
FluxP	Cell Centered	2	4th order
TBLOCK	Cell Vertex	2	4th order
CHYDRA	Cell Vertex	2	f(wiggles)
Vu40	Staggered Grid	2-8	Smag. Model

Range of LES Models

Model	Components
Smagorinsky	L
Yoshizawa	L
Clark	L+NL
Kosovic	L+NL
LANS-α	L+NL
Leray	L+NL
VMS	Uses Smag. Model

Liu, Y., Tucker, P. and Kerr, R. Linear and nonlinear model large-eddy simulations of a plane jet. *Computers and Fluids*, 37(4): 439-449, 2008

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Homogenous decaying turbulence

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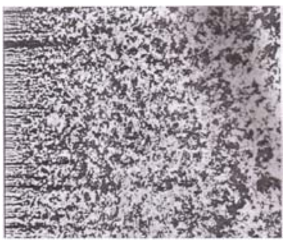

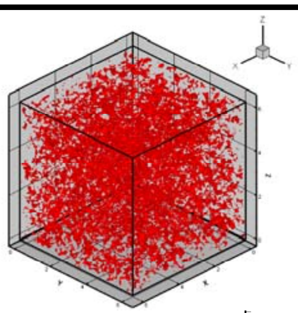

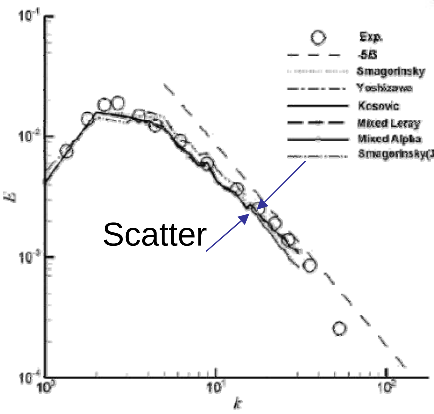

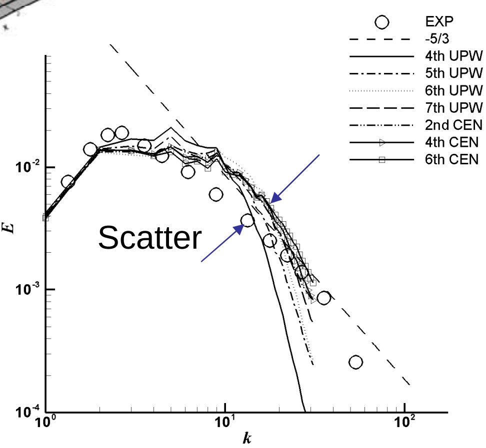

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LES model

Numerical parameters

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Shear Layers – significant numerical influence

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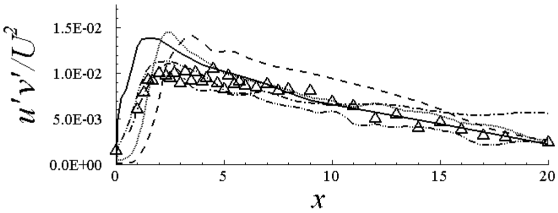
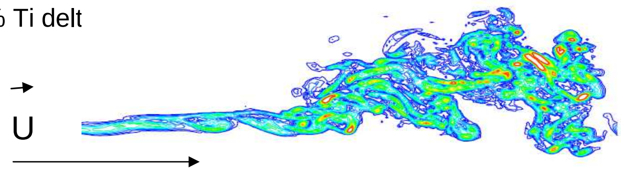
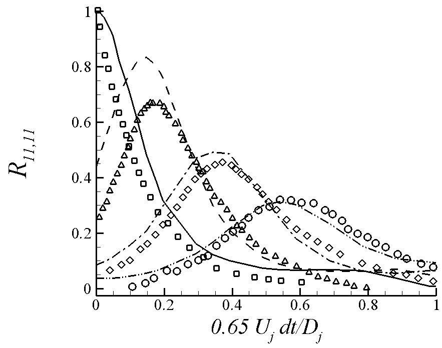
- Average predicted shear stress error for five LES models, five numerical schemes and 10% Ti delt inflow





	Std. Dev.	Ave. error
LES model	4 %	12 %
Numerical scheme	19 %	14%
Inflow (Ti = 10%)	-	4 %



For NLES N/Re$^{0.4}$ - 3.5 time higher i.e. better resolved

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Shear Flow - Significant Numerical Influence

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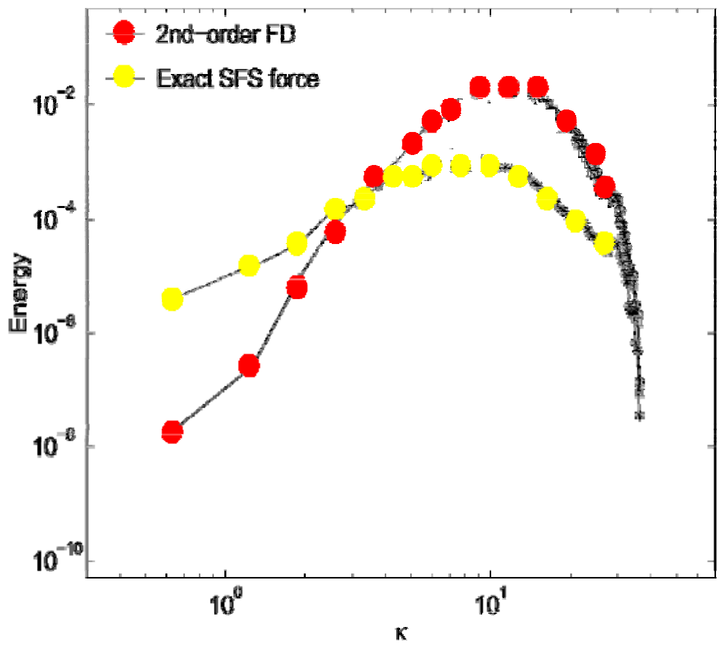
Chow and Moin JCP (2003) – numerical error



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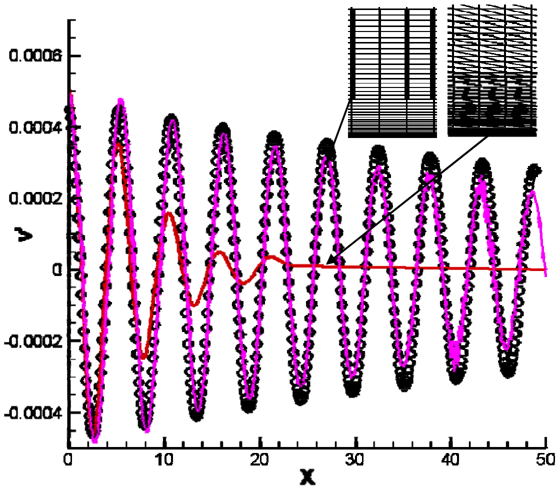
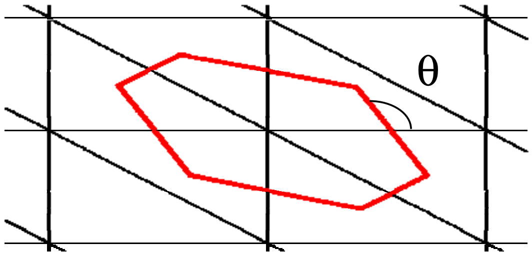
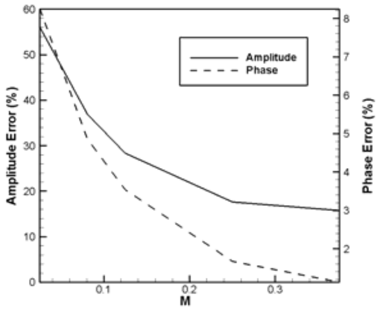
TS Wave in Shear Flow - Grid-Solver Compatibility/Sensitivity



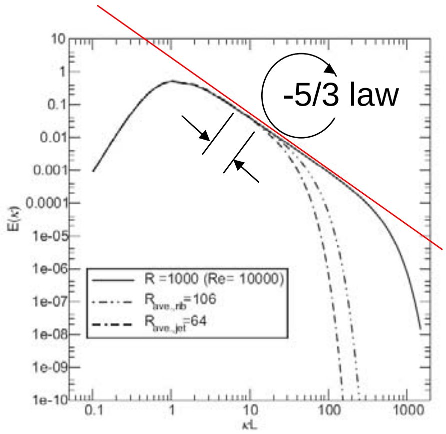


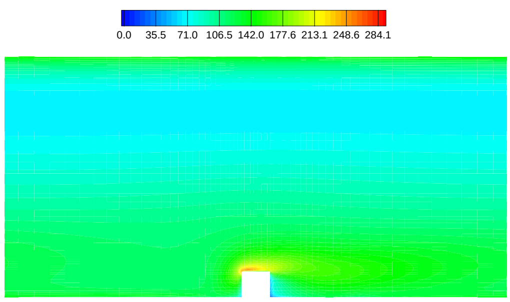


OMIT LES MODEL TO LESSEN DISSIPATION?

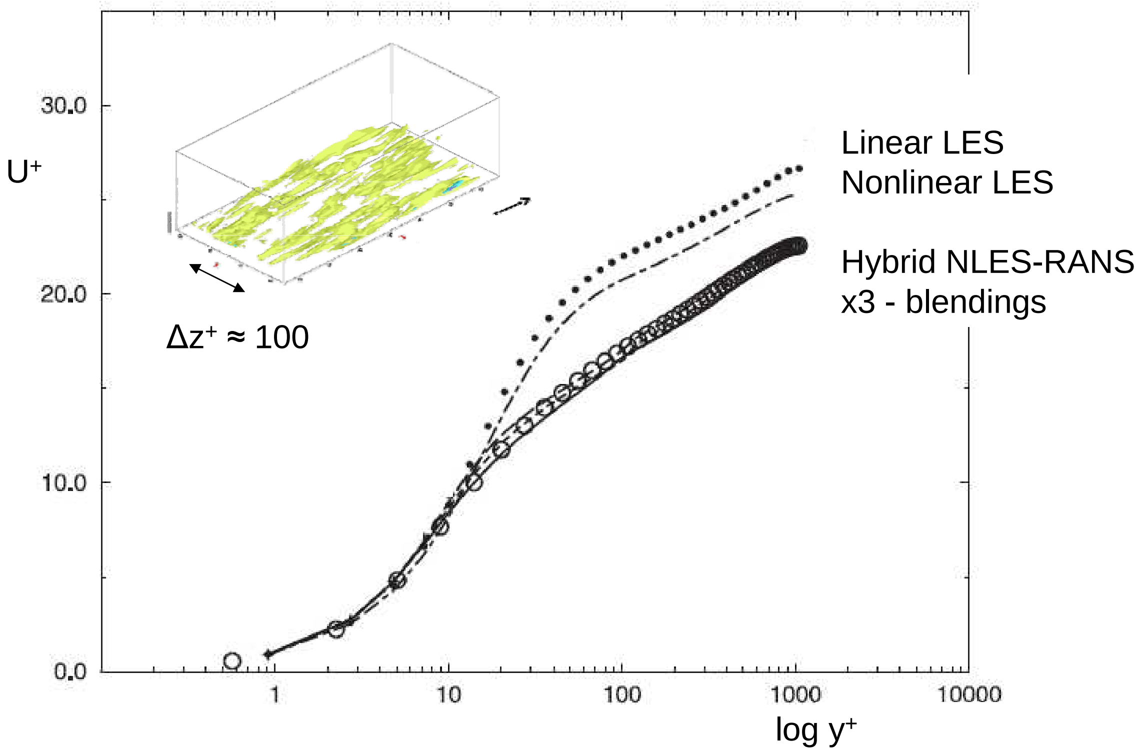
LES Model Validity? Omit?

- Smagorinsky model erroneously drains energy from all scales (AIAA ban)
- It provides no backscatter
- Eddy viscosity alters the effective Reynolds number and so alters the fine scales (non-linear LES models OK?)
- Existence of Kolmogorov -5/3 region in turbomachinery? If not new LES model needed

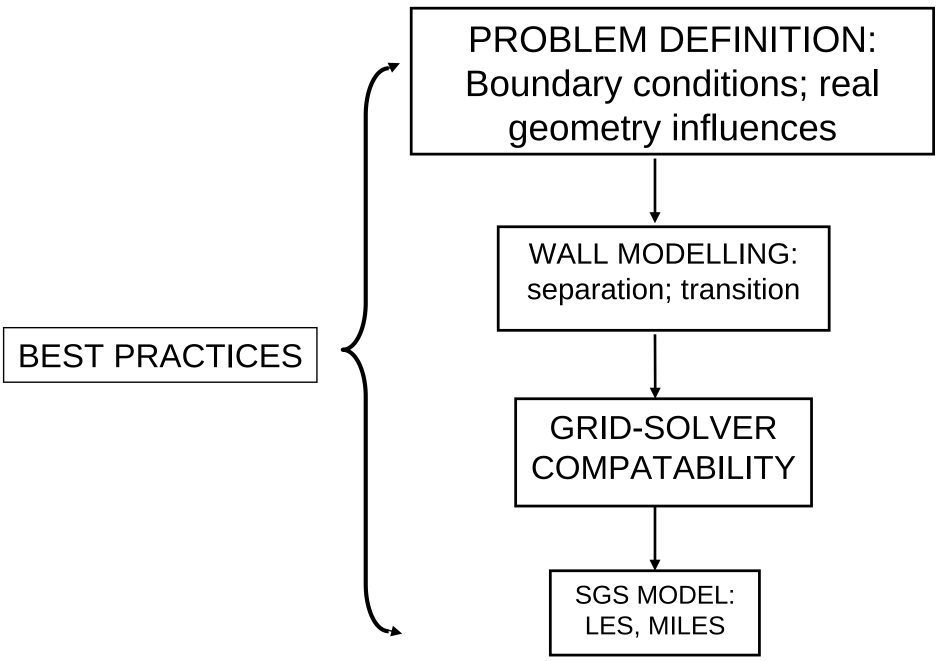




‘Law of the wall’ for under-resolved LES grids



Industrial Turbomachinery LES Hierarchy



ENGINEERING MODELLING APPROACH – RANS-NLES Blending

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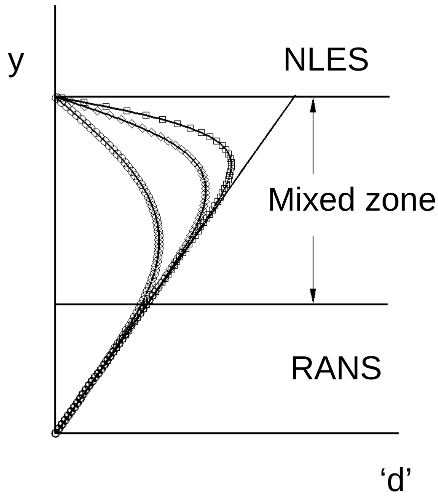
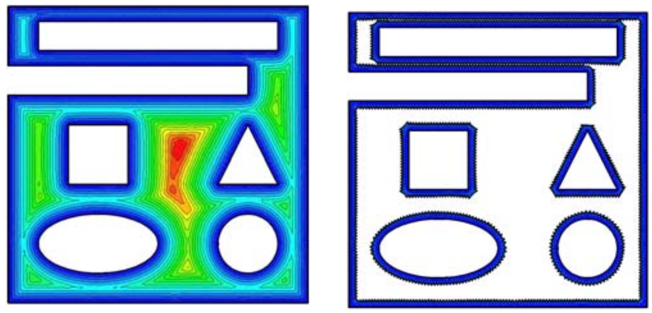
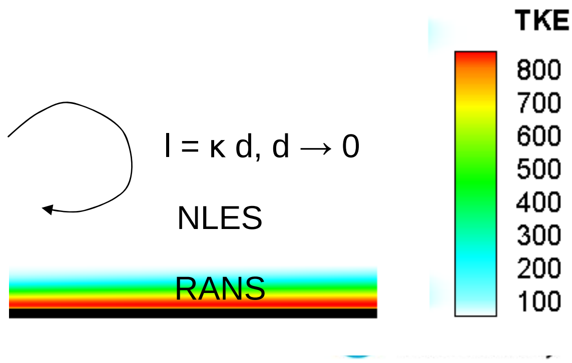




$$|\nabla\phi| = 1 + f(\phi)\,\nabla^2\phi + g(\phi)$$

$$f(\phi) = \varepsilon_0\phi,\; g(\phi) = \varepsilon_1(\phi/L)^n$$



Ribbed channel (Re = 14,000)

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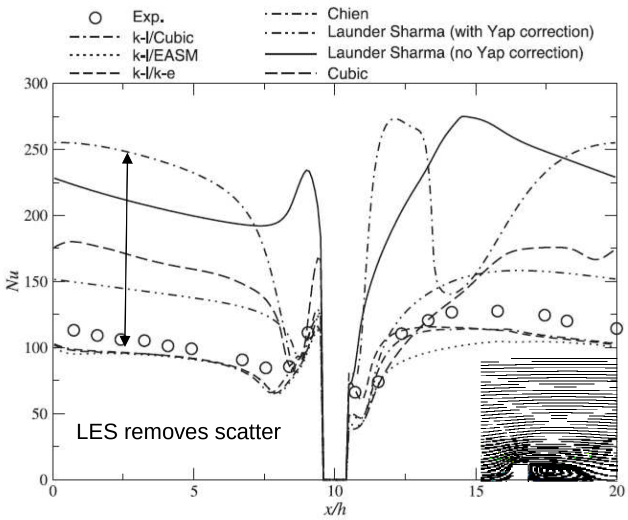

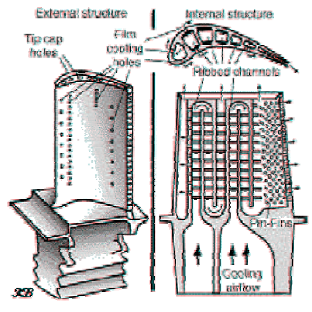

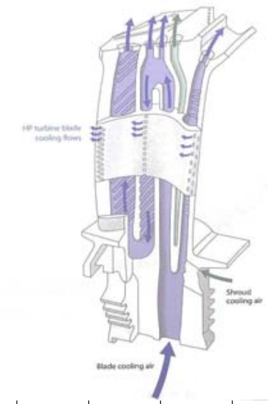

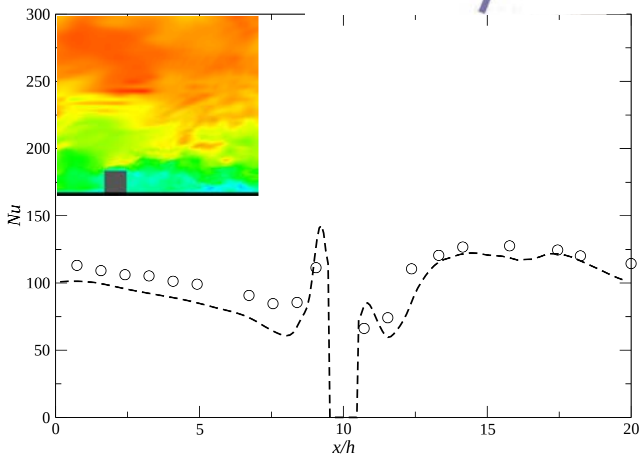

Impinging Jet Flow – Re = 23000

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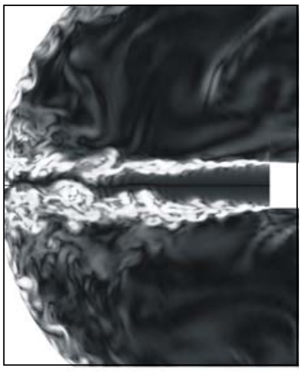

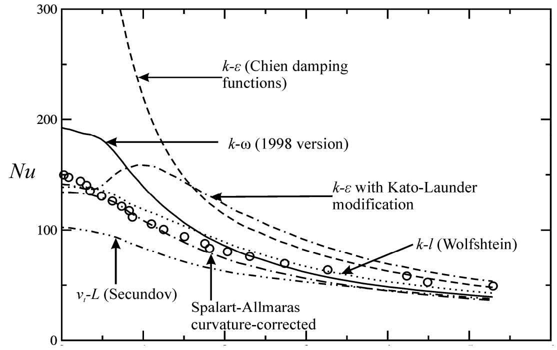

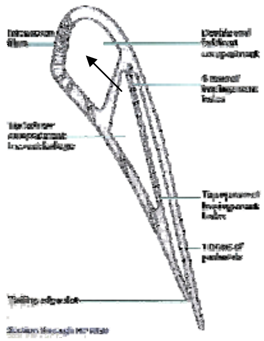

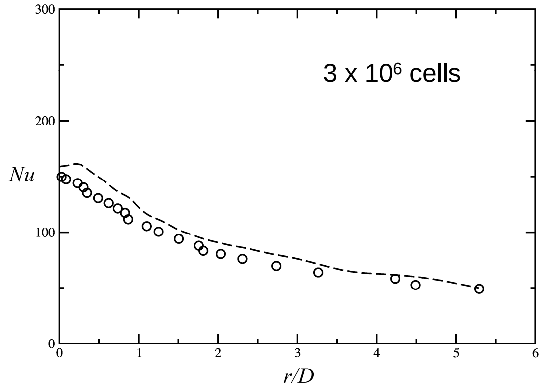

Compressor Blade – End Wall

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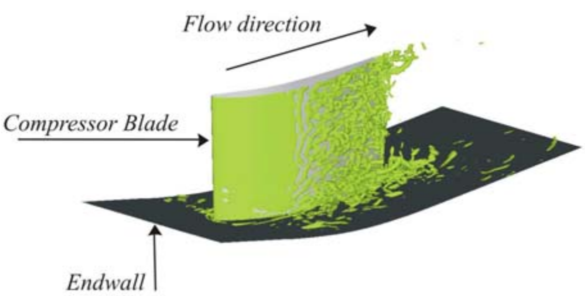
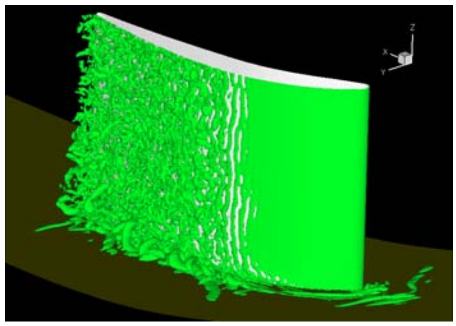
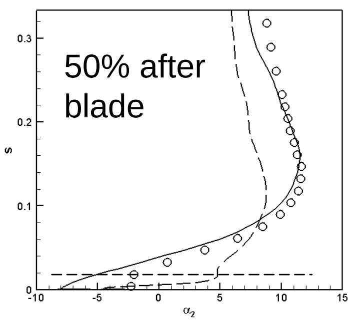
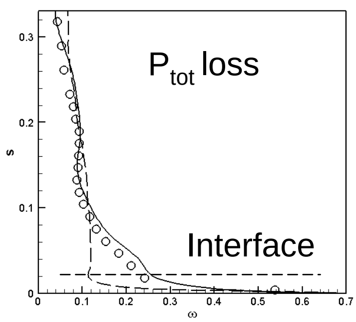




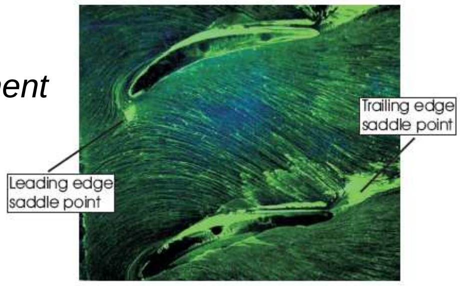




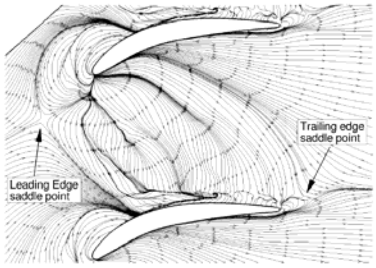
Re ≈0.25 million, N = 5 million

Streamlines at Endwall - Compressor

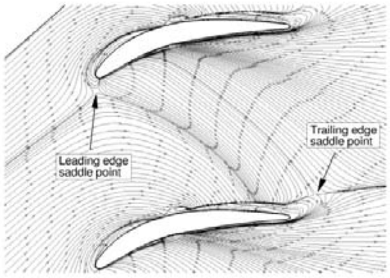
Experiment



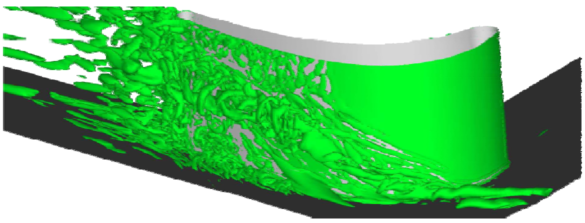
NLES



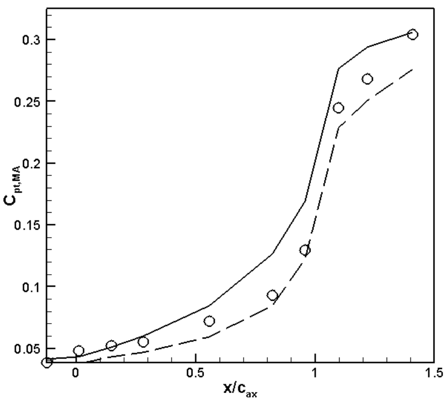
Hybrid NLES-RANS

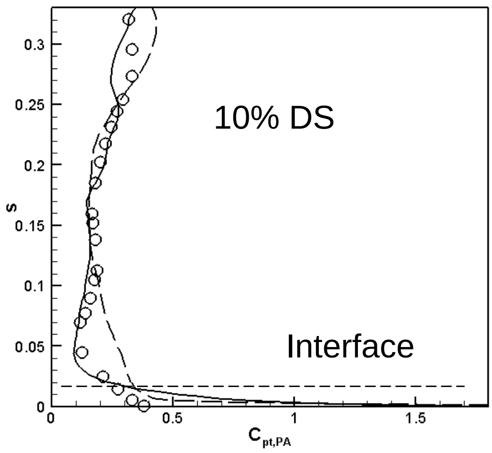


Averaged Total Pressure Loss Coefficient



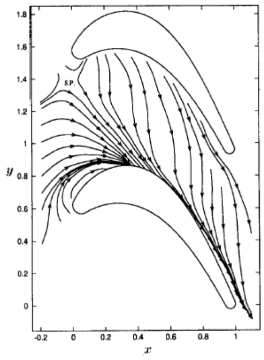
Re ≈ 0.6 million, N > 5 million



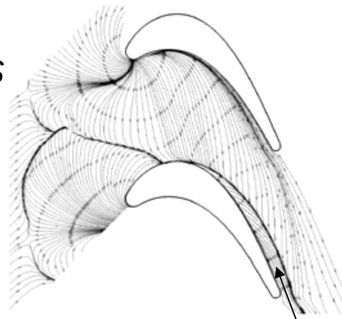


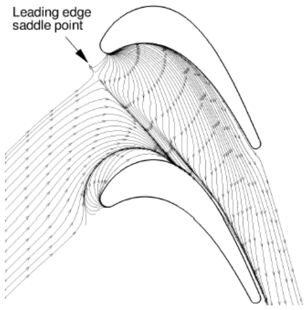
Streamlines at Endwall - Turbine

Experiment



NLES

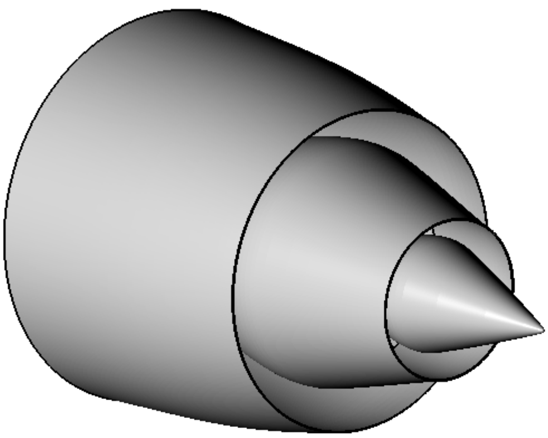


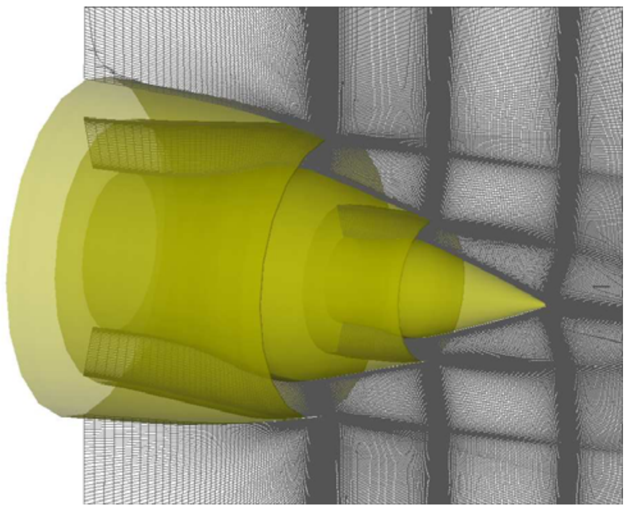


Excessive separation

Hybrid NLES-RANS

Coaxial Nozzle





Re = 300,000, 5<N< 50 (million)

HJ Equation Distance Function

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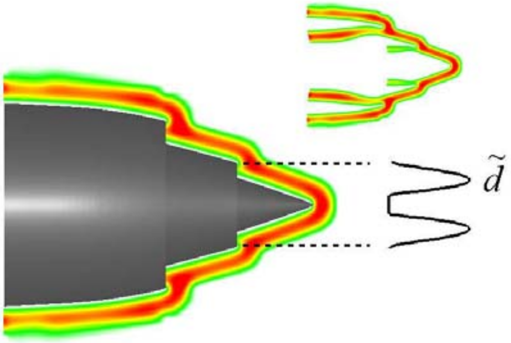

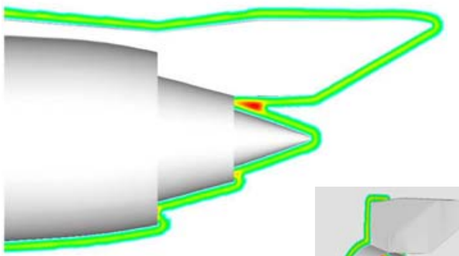

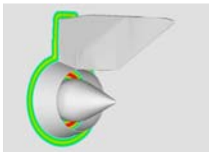

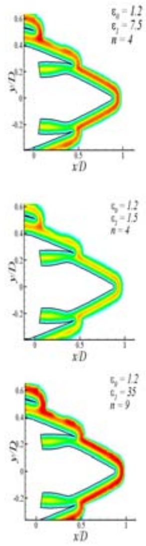

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Vorticity Contours

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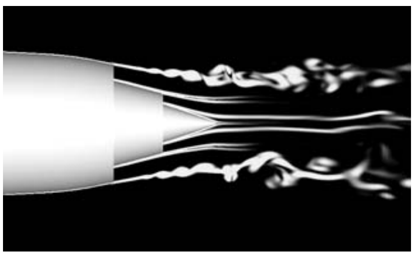

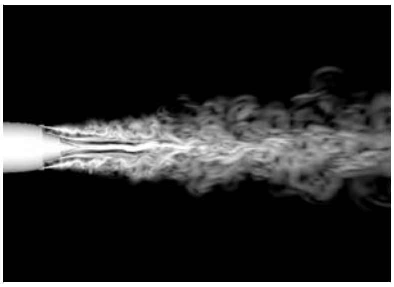

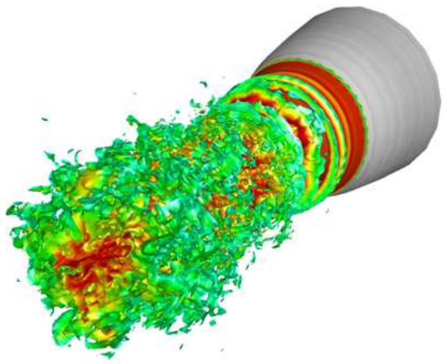

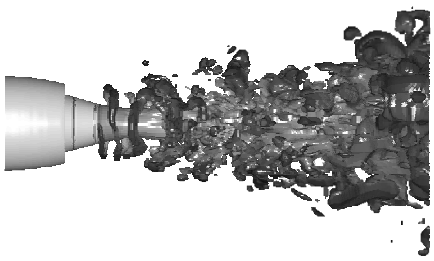

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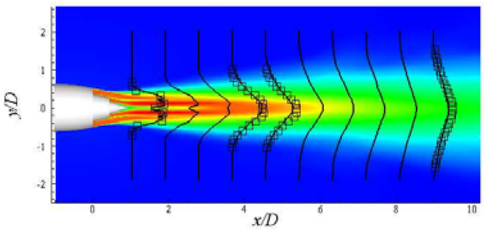
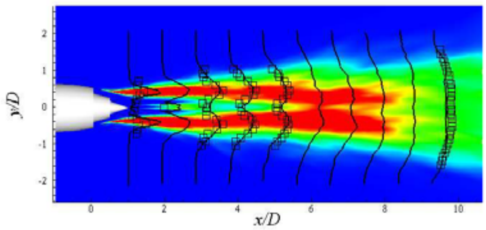
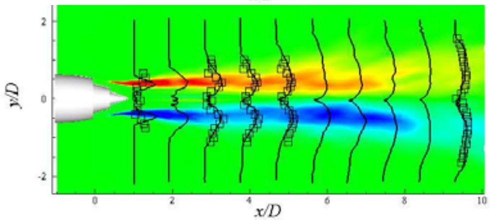
Statistics



Time averaged streamwise velocity.

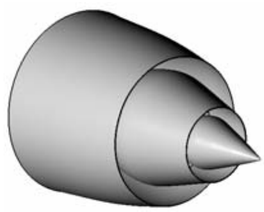


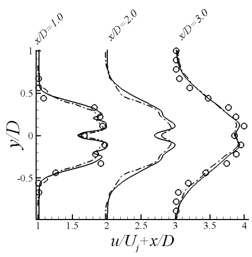
Normal stress, u'u'

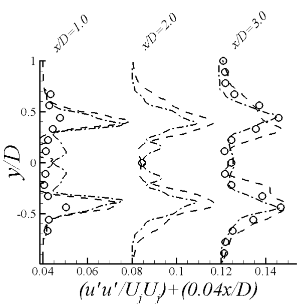


Shear stress, u'v'

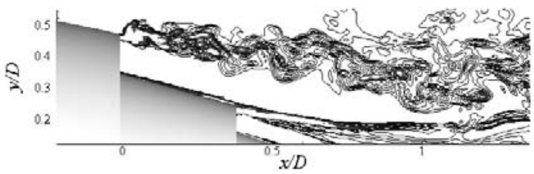
Grid Sensitivity



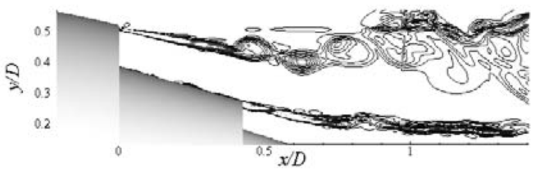




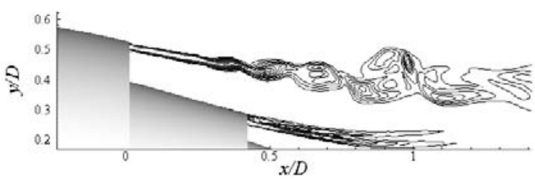
50M



12M



6M



SENSITIVITY TO REAL INFLOW/ GEOMETRY

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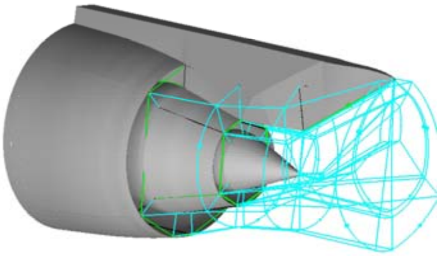
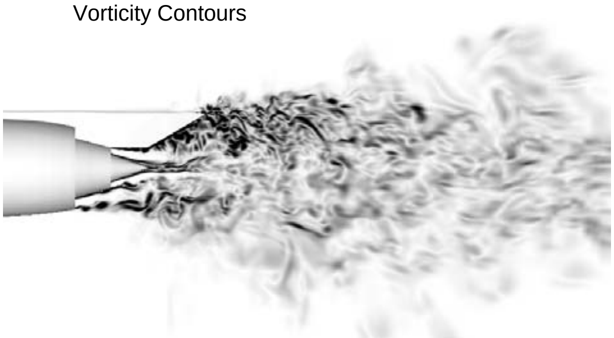
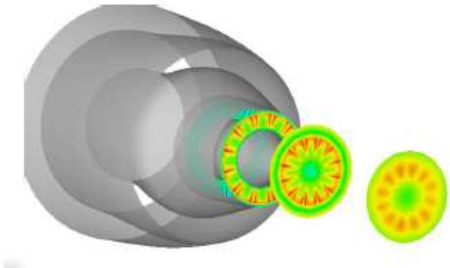
Geometry and Blocking Structure



Vorticity Contours



Axial velocity



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Turbulence profiles for pylon and nozzle with internal geometry

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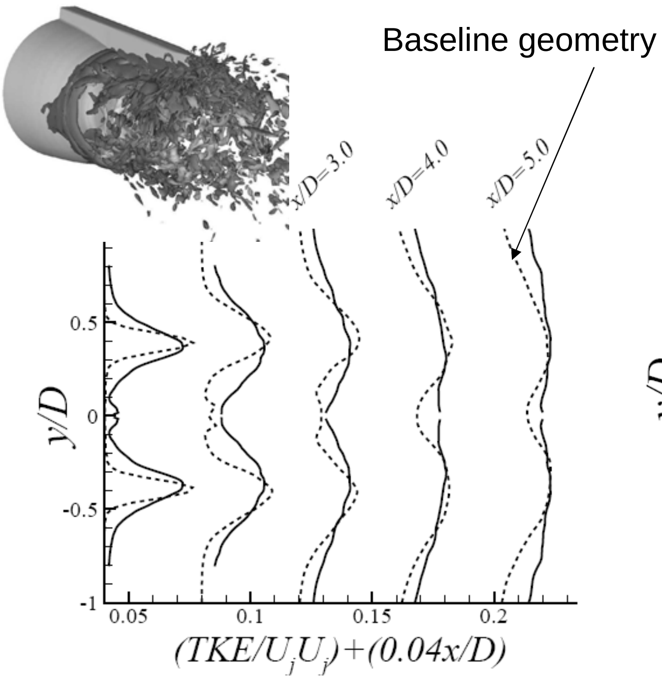
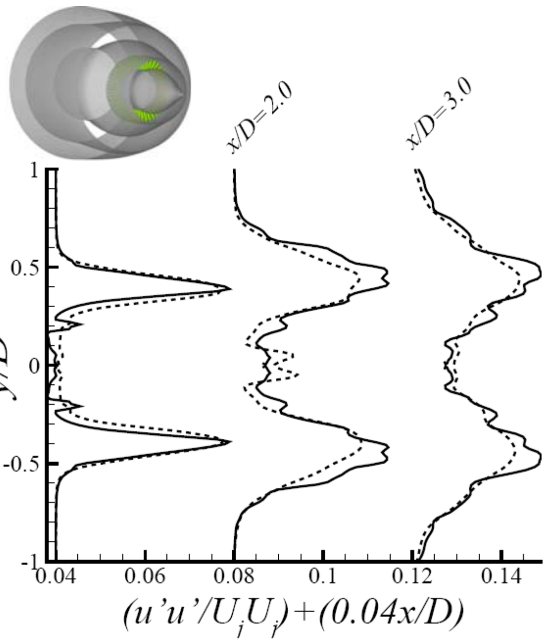


Pylon – circumferentially averaged

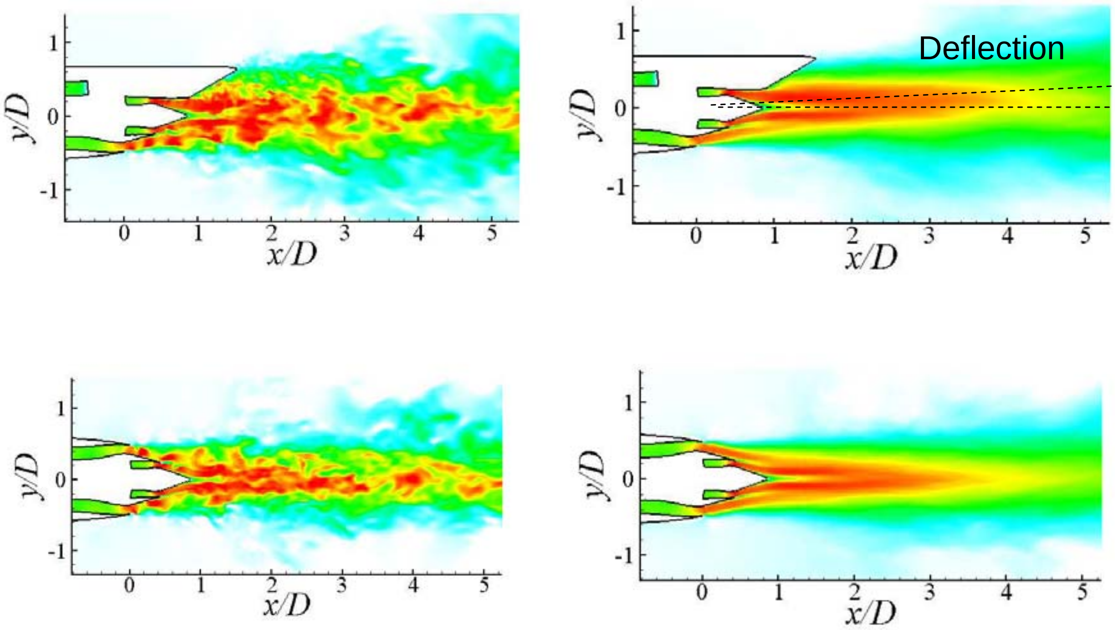


Internal geometry – on blade trailing edge

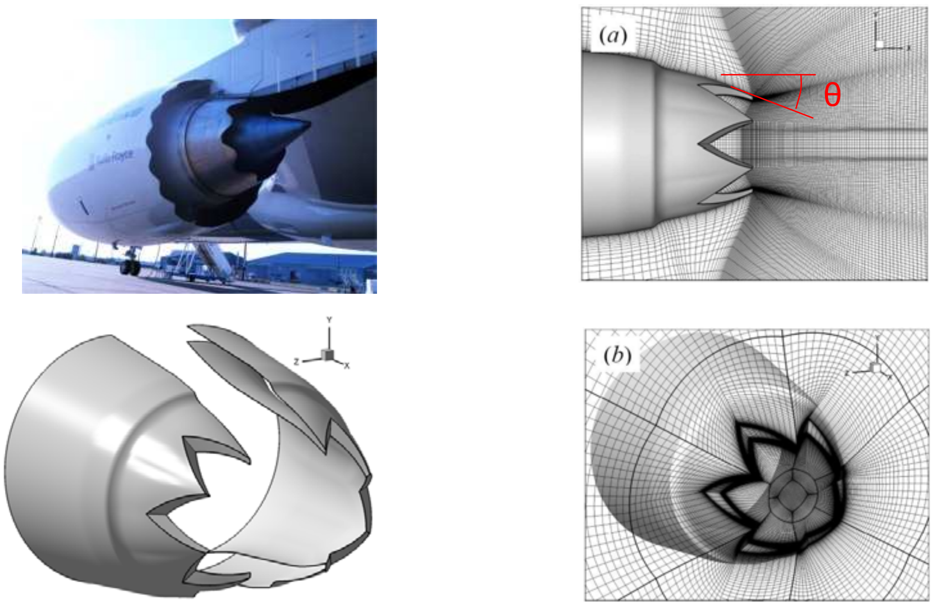
Pylon Geometry

Instantaneous Streamwise Velocity

Time Averaged Streamwise Velocity

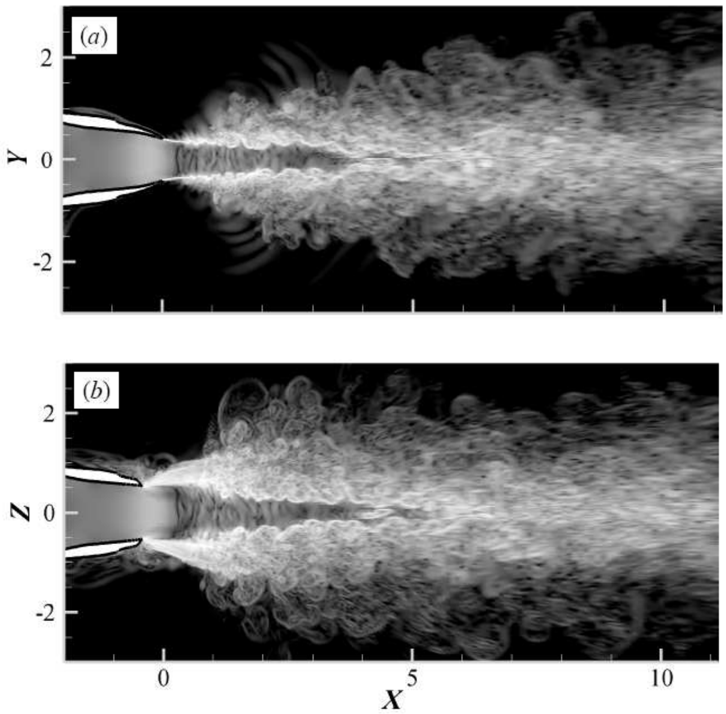


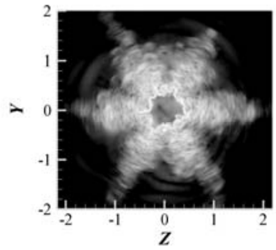
Chevron Nozzle



$12 \times 10^6 < N < 60 \times 10^6$, $Re = 1 \times 10^6$

‘Numerical Schlieren’





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Flow Visualisation

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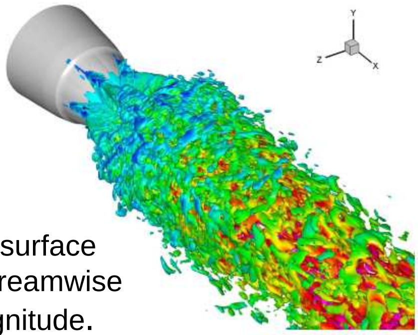
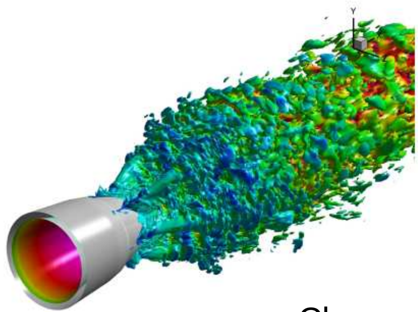
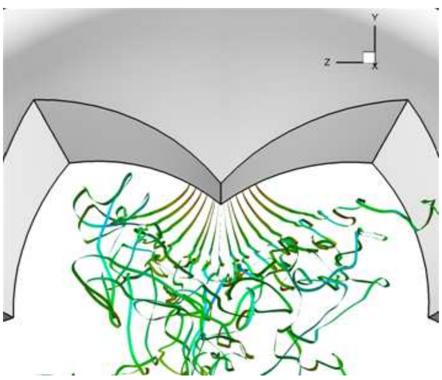
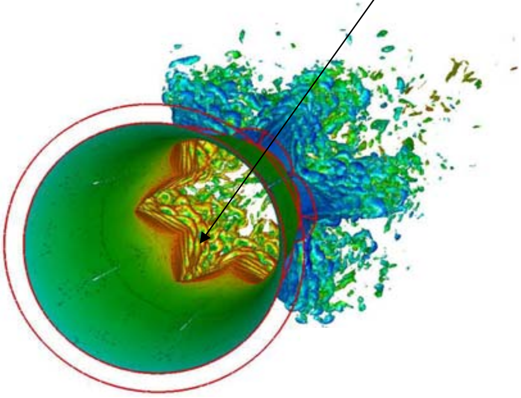




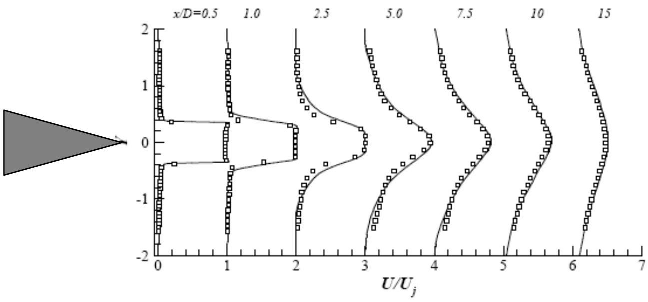
Vorticity iso-surface coloured by streamwise velocity magnitude.

Chevron K-H rollers

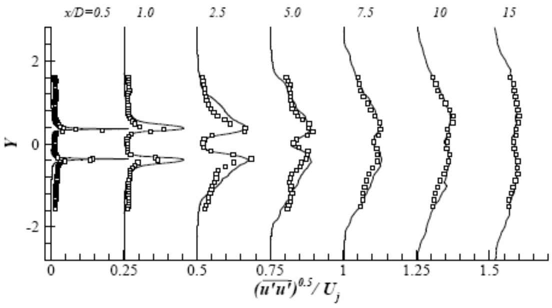


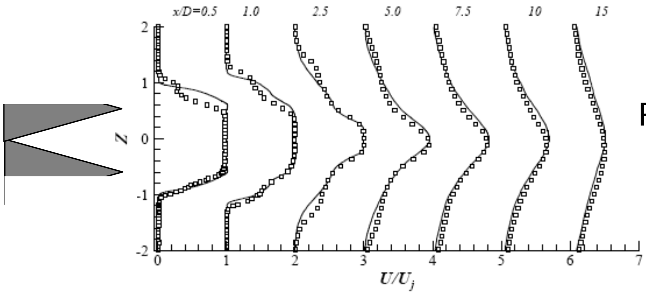


Statistics

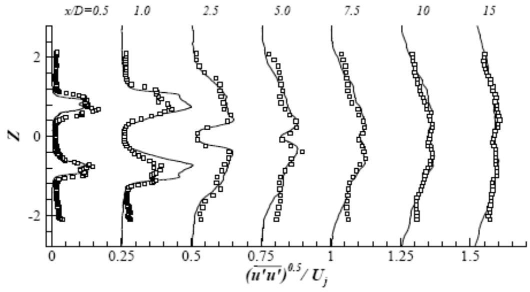


Tip

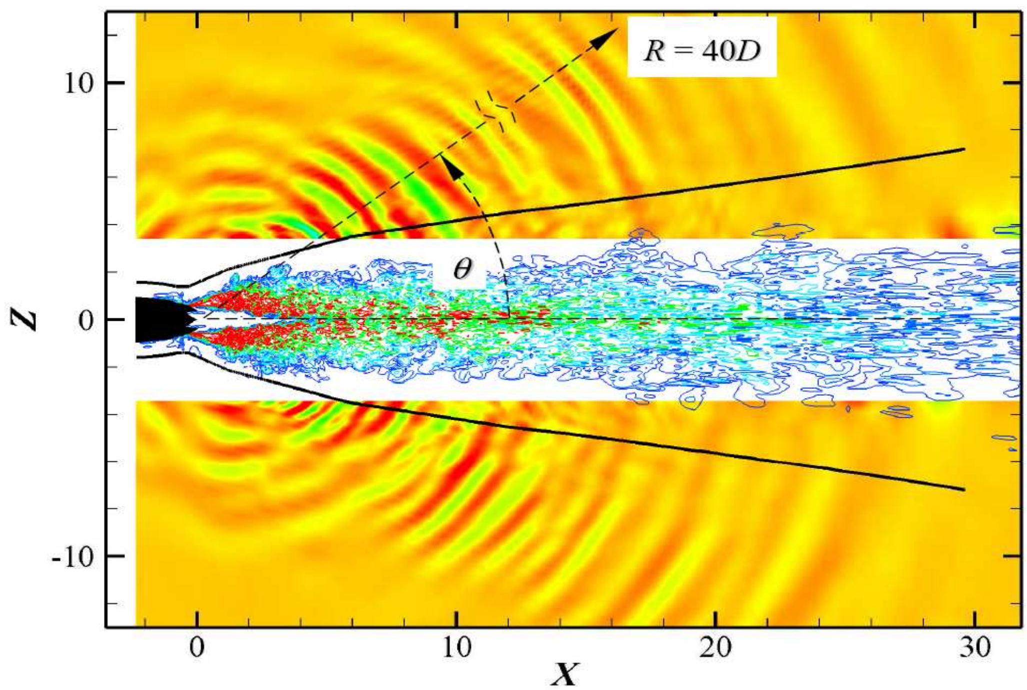




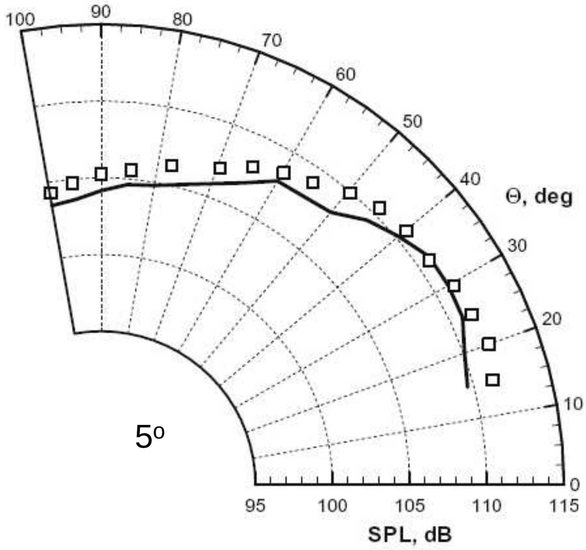
Root

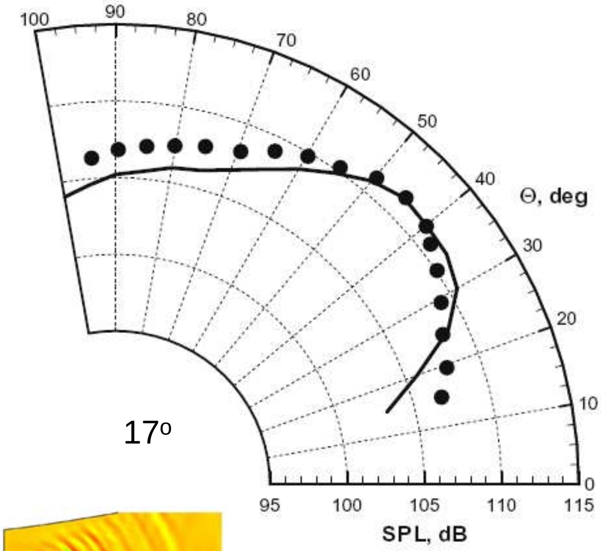


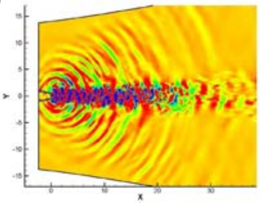
RANS-LES + FWH

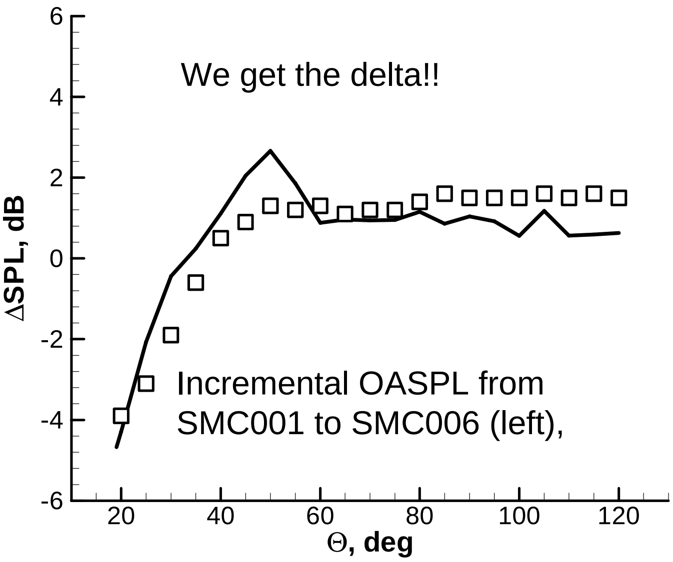


Chevron Far-field Sound (SPL)

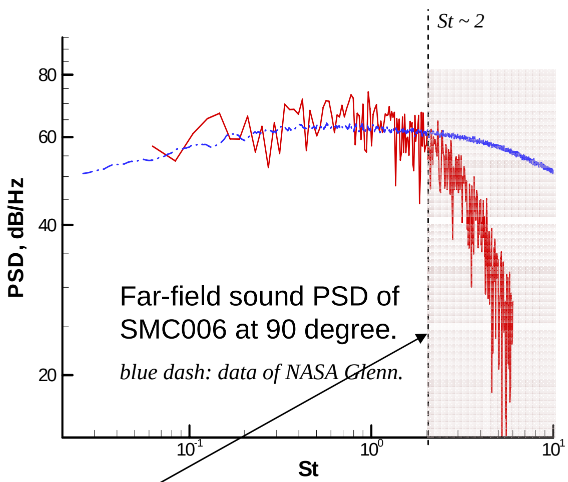








Power spectral density



$St_{max} < a_\infty / 4\Delta$

Assume 4 nodes can resolve a wave accurately

Fan Blade Section (Re = 3 x 10^6)

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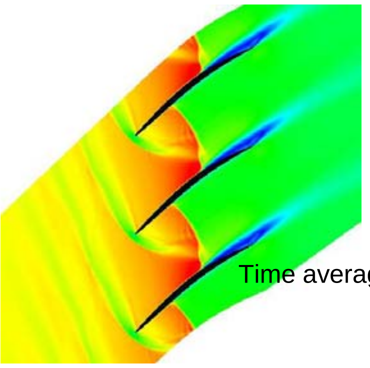
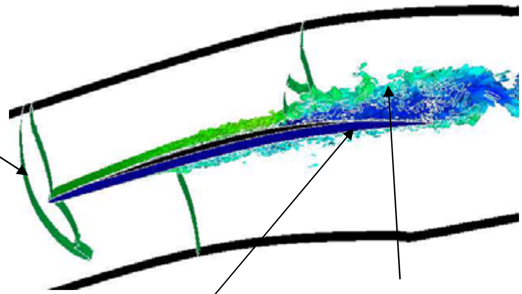
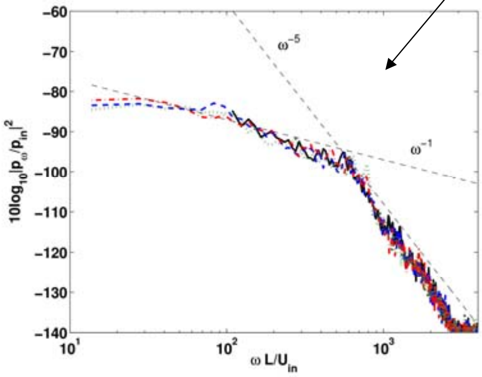




Blade surface pressure spectra



Goody (2004) AIAA J.

N = 8 million

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Cut back trailing edge

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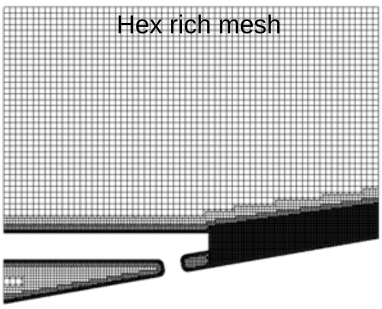
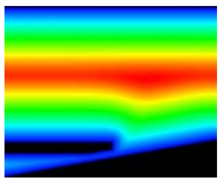
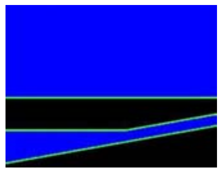
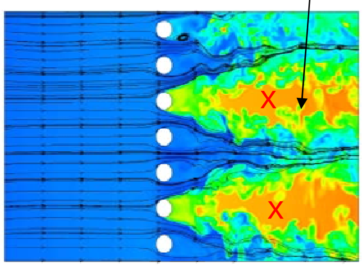
'Martini & Schultz' (2004) type case, Kacker and Whitelaw (1969)

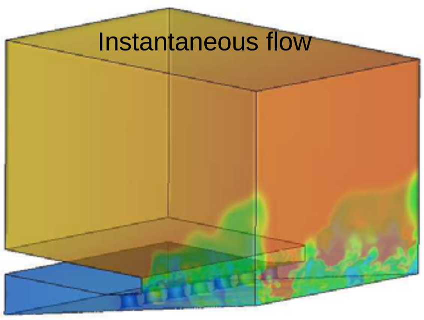


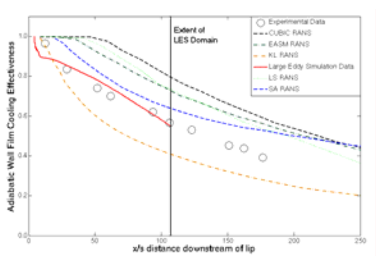


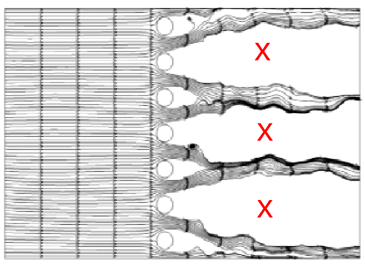




Instantaneous flow – vacillates – periodicity issues







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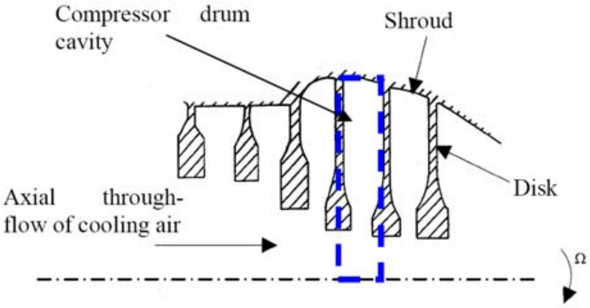
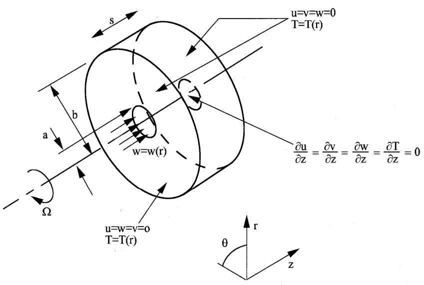
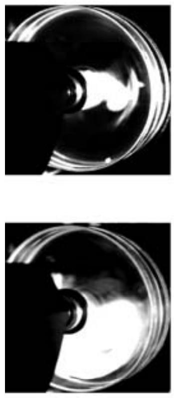
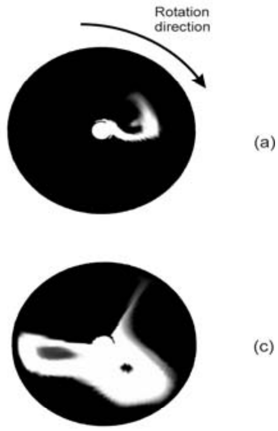
High pressure compressor drum





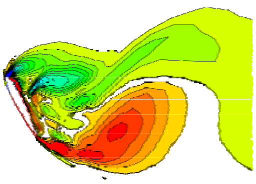


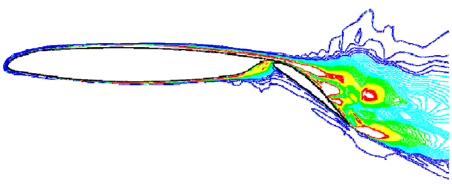
(I)

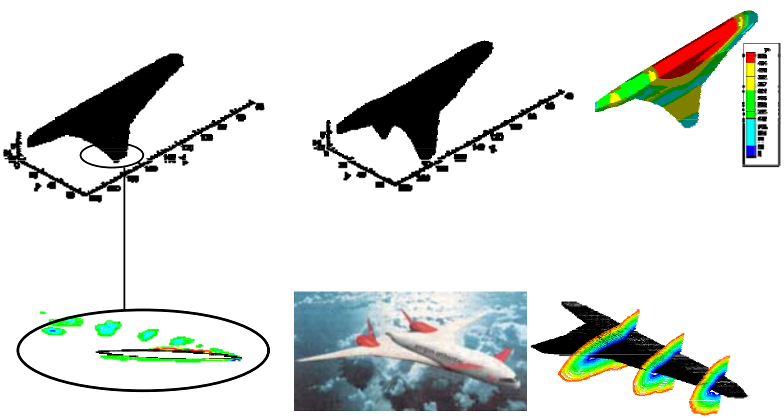


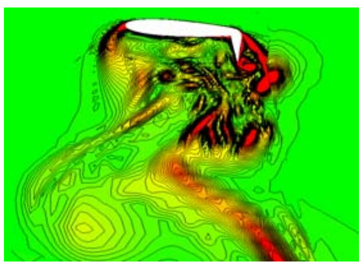
(II)

PROBLEM AEROSPACE FLOWS









Open rotor engines

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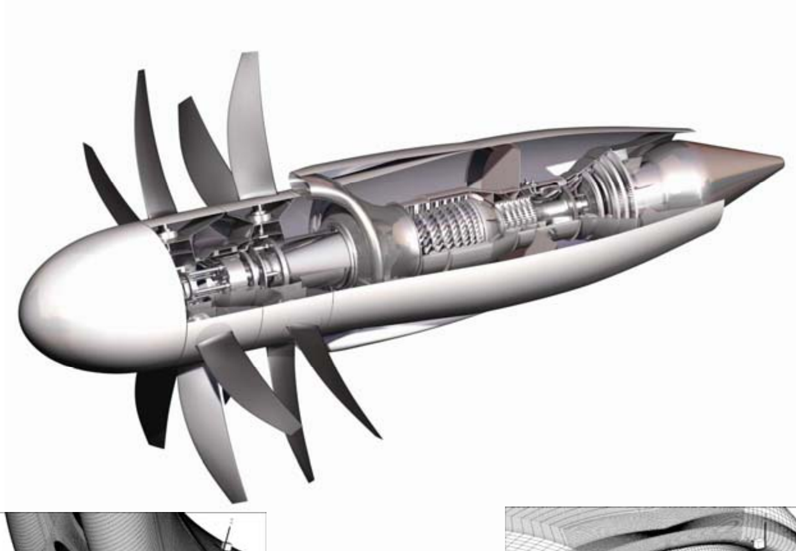

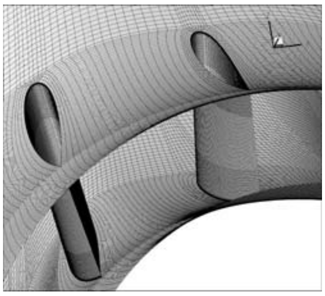

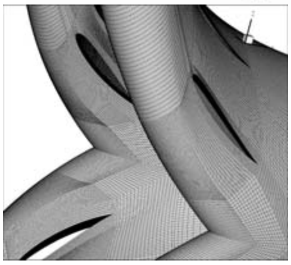

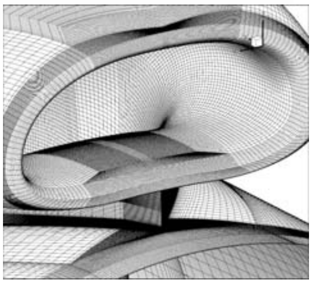

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Y0 PLANE

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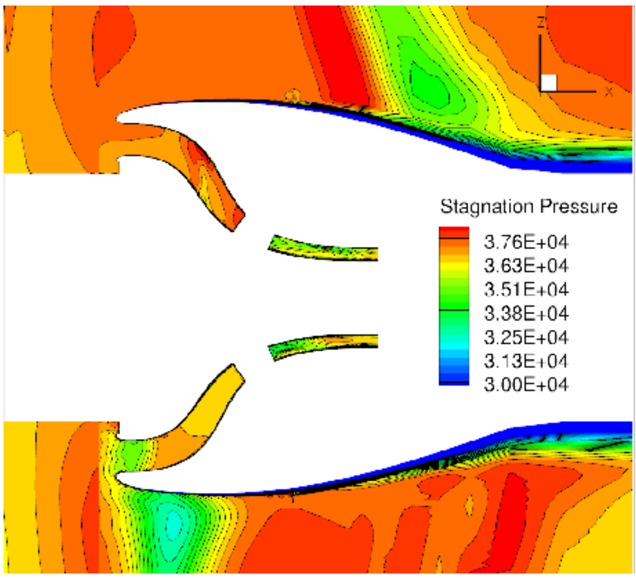

Total Pressure Contours

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Experimental data & Best Practices

- To correctly validate/exploit detailed comparisons with u'u' and E(k) data is desirable
- Lacking in many turbomachinery studies
- More importantly LES can need inflow (*U*, *l* & *Ti*) and careful definition of general BCs
- Frequently missing from experimental studies
- To advance LES, both numerical practitioners and experimentalists need to move forward together
- Formal framework for recording simulations and what to record

Conclusions

- High cost of testing and low fidelity of RANS makes the development of LES attractive
- Considered field of 'practical LES', where dissipative RANS based solvers are frequently used
- LES model omission is an attractive option with near wall RANS model – hybrid RANS-NLES
- Combined with suitable grid topologies (hexahedral meshes seem highly preferable) method gives useful results
- For industrial LES hierarchy is: problem definition, wall modeling and grid-solver compatibility with, last of all, the much debated LES model
- Better defined and more detailed validation data and best practice
- Caution must be exercised – still needs user expertise and best practices should be developed