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LES OF TURBOMACHINERY FLOWS

Paul Tucker

Cambridge University

Summary

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- Variety of flows studied
- LES benefits and uses outlined
- Zonalized LES strategy outlined
- Taxonomy of flows, cost, BCs, turnaround given
- Industrial setup process proposed

Engine zones where (N)LES performed

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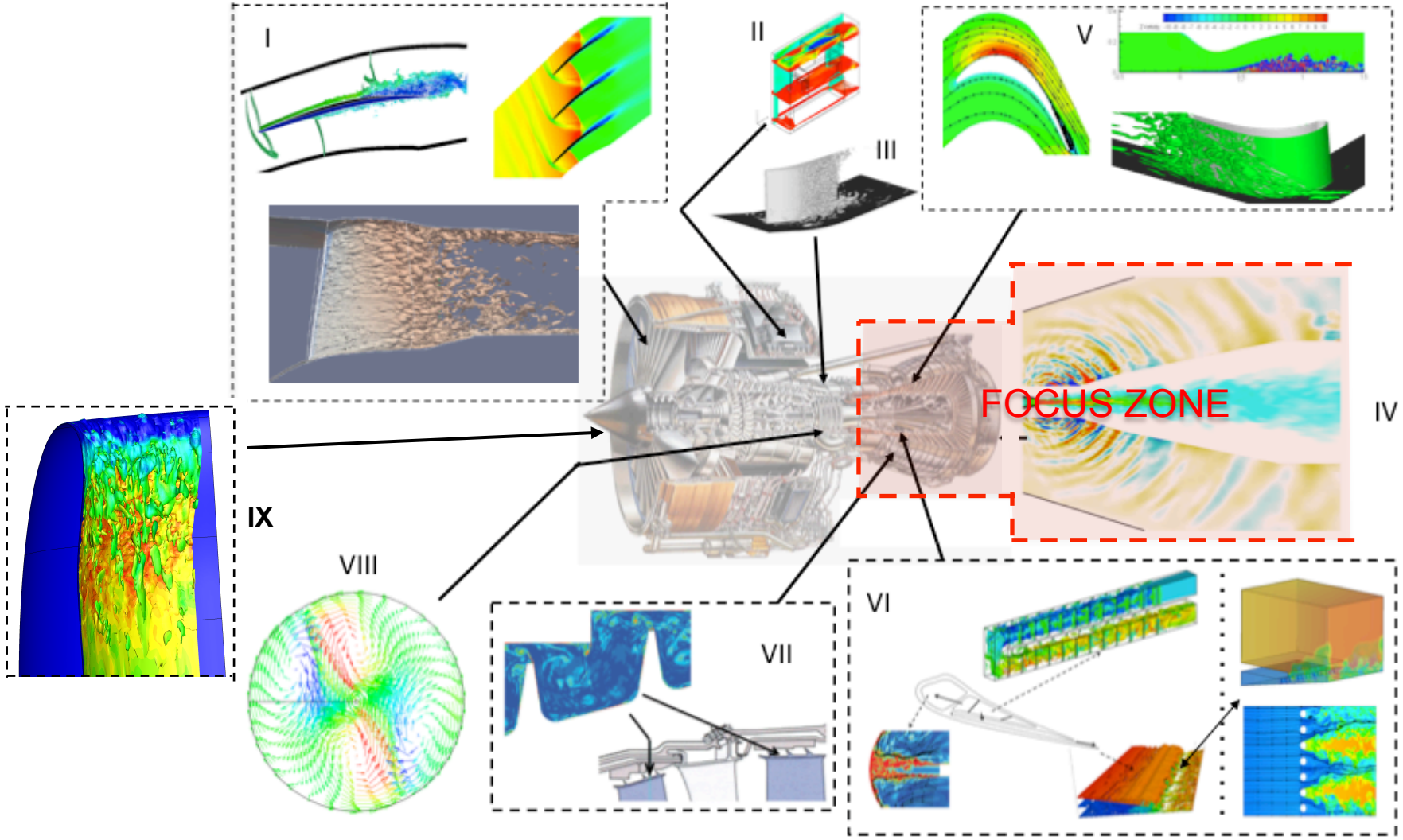

Chapman's vision (1975)

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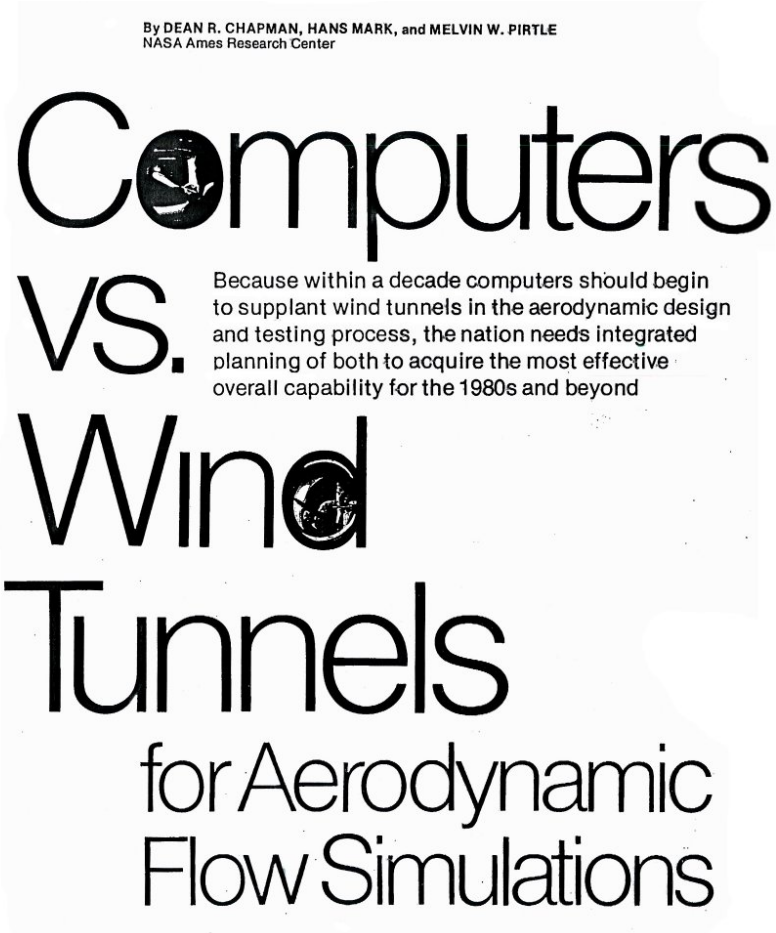

By DEAN R. CHAPMAN, HANS MARK, and MELVIN W. PIRTLE
NASA Ames Research Center

Computers vs. Wind Tunnels

for Aerodynamic Flow Simulations

Because within a decade computers should begin to supplant wind tunnels in the aerodynamic design and testing process, the nation needs integrated planning of both to acquire the most effective overall capability for the 1980s and beyond

- 10^{14} flops N = 10^{9} → Road Runner (2008) 10^{15} flops
- Computer speed grown by 1 million in past 25 years
- Exascale due 2018
- Choi and Moin (2012) confirmed Chapman's wall resolved estimates
- GPUs provide cheap computing

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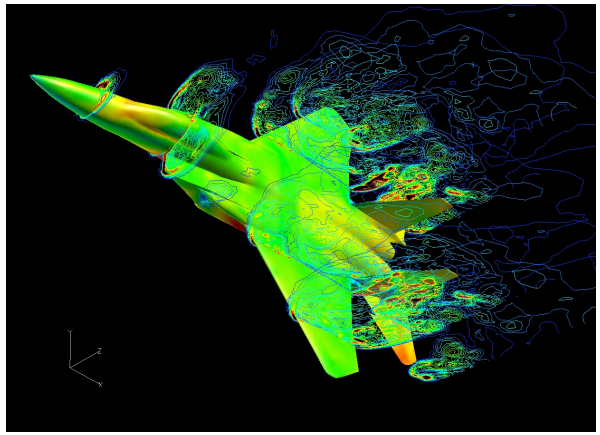
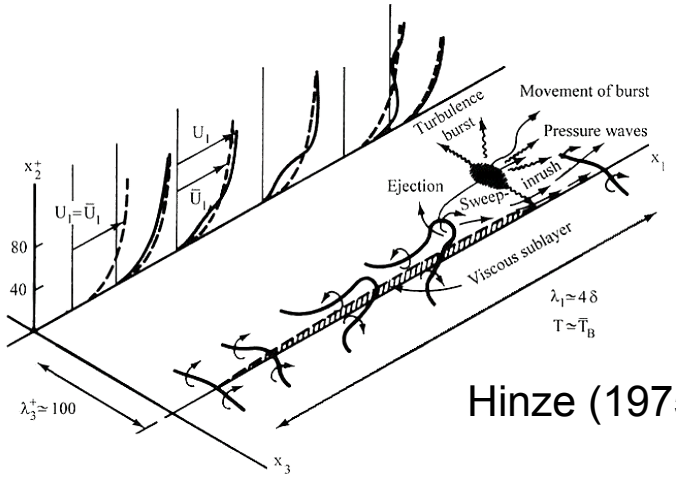
Key LES problem

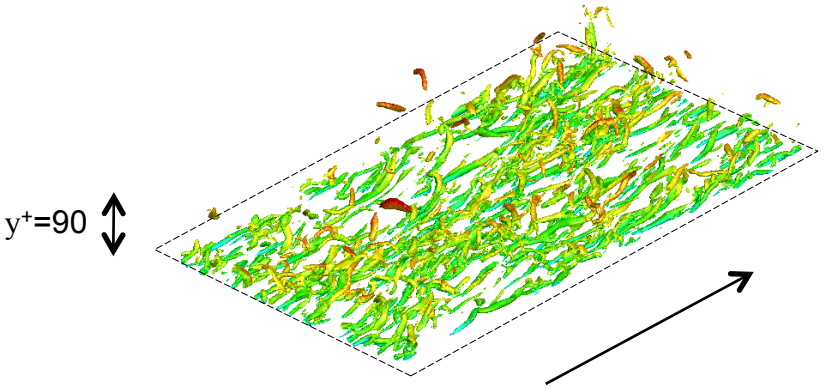
- Resolving streaks
- Trent 1000 fan at cruise 10^7
- LES Cost α $Re^{2.5*}$
- Hybrid LES-RANS Cost α $Re^{0.5\text{-}1}$



DES type problem
By Forsythe, Wurtzler, Squires, Cobalt
Early 2000s



Hinze (1975)



*Piomelli, AIAA-2008-396

Flow taxonomy

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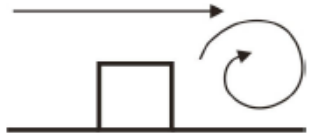
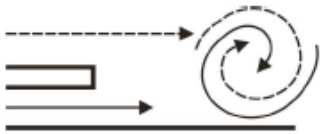
Impact / Ease = HIGH → **MODERATE**

A: Wake (*Re* independent)

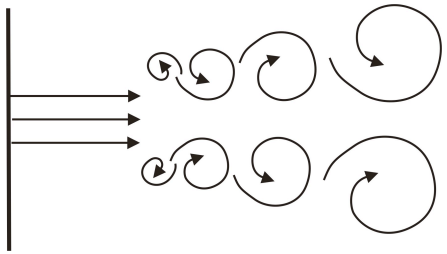
Ribbed passages



CBTE



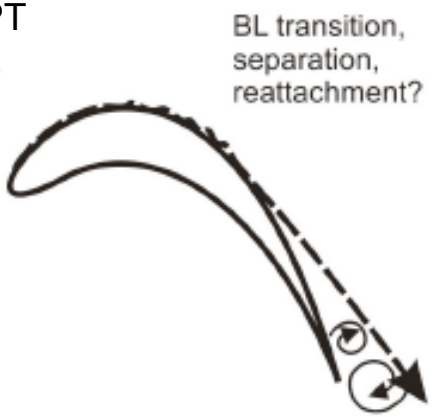
Propulsive jets / combustors



(I)LES

B: Low *Re*

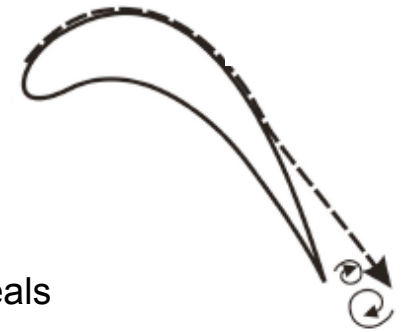
LPT



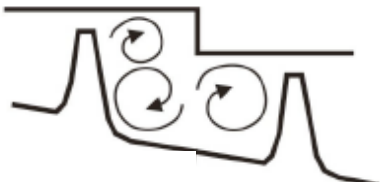
(I)LES

C: High *Re*

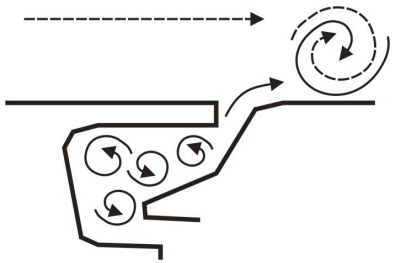
HPT



Lab seals



Rim seals



Mixed

RANS-(I)LES

Grid requirements and the need for Zonalization

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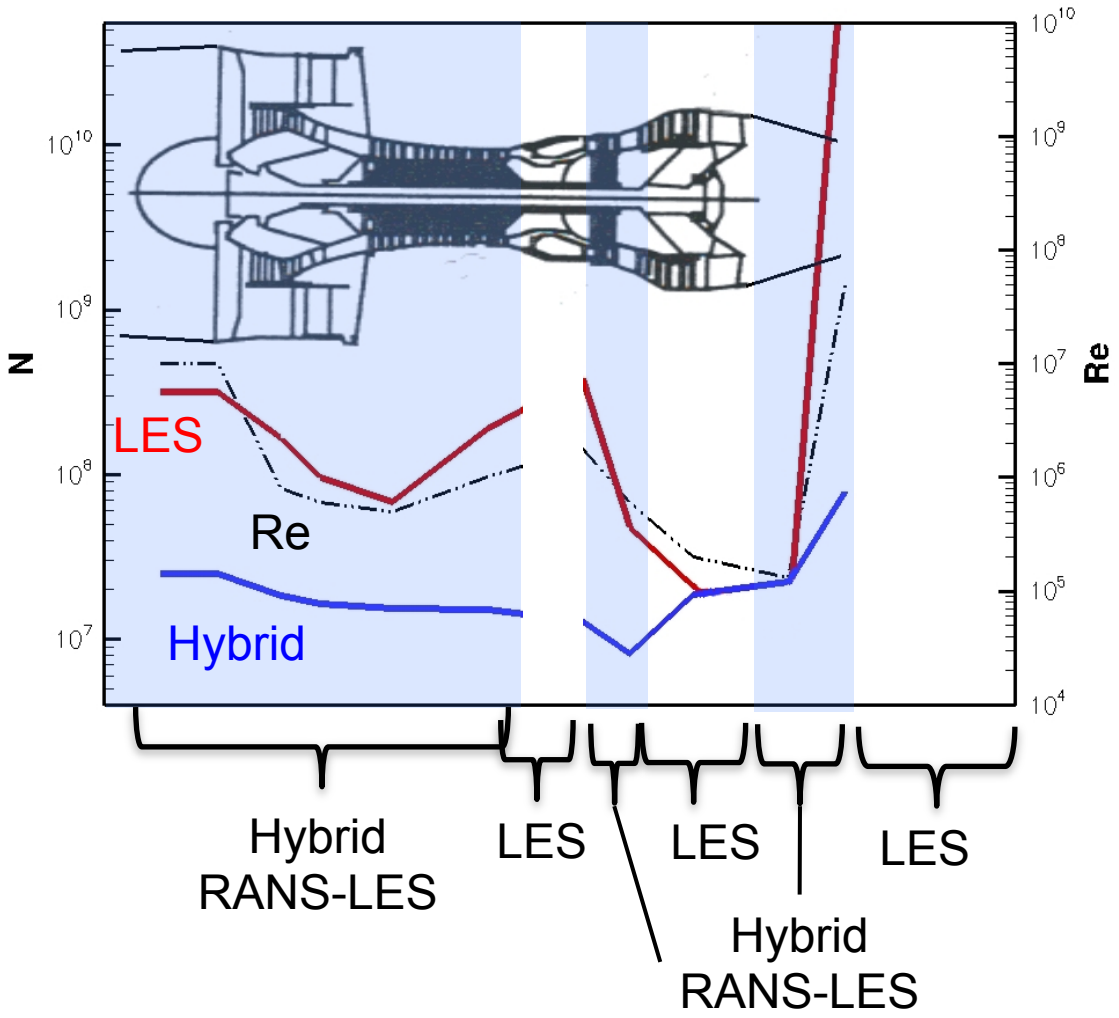
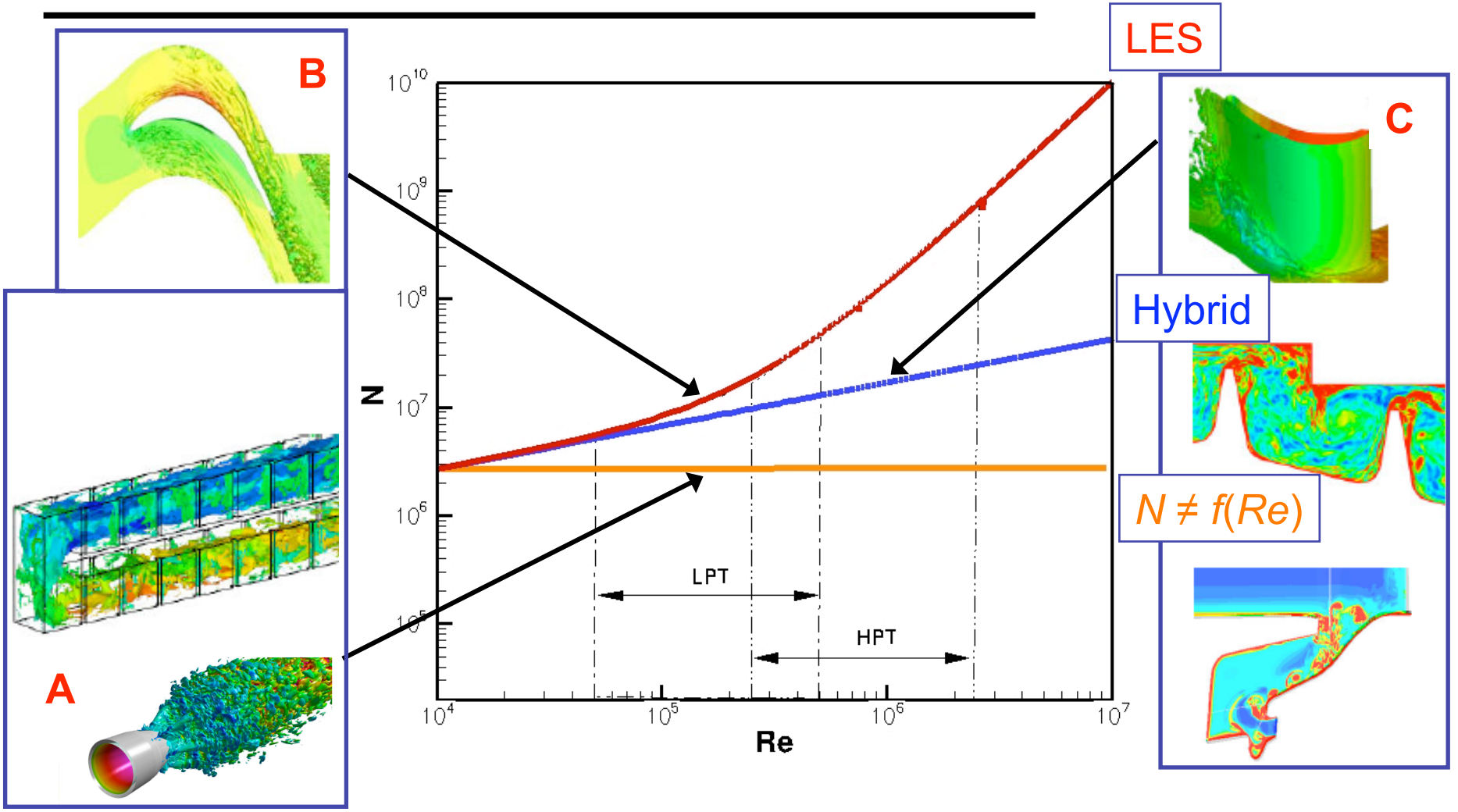


LES resolution requirements



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

LES Resolution Requirements

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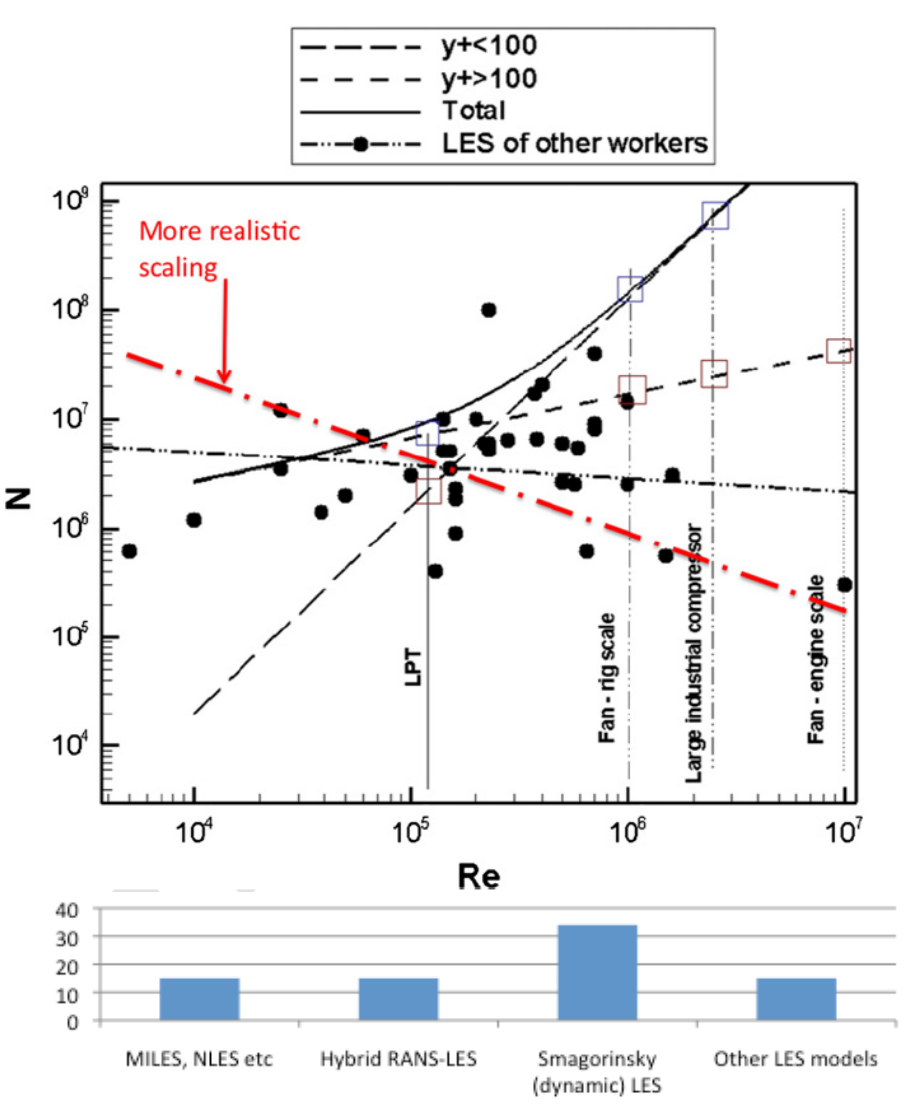

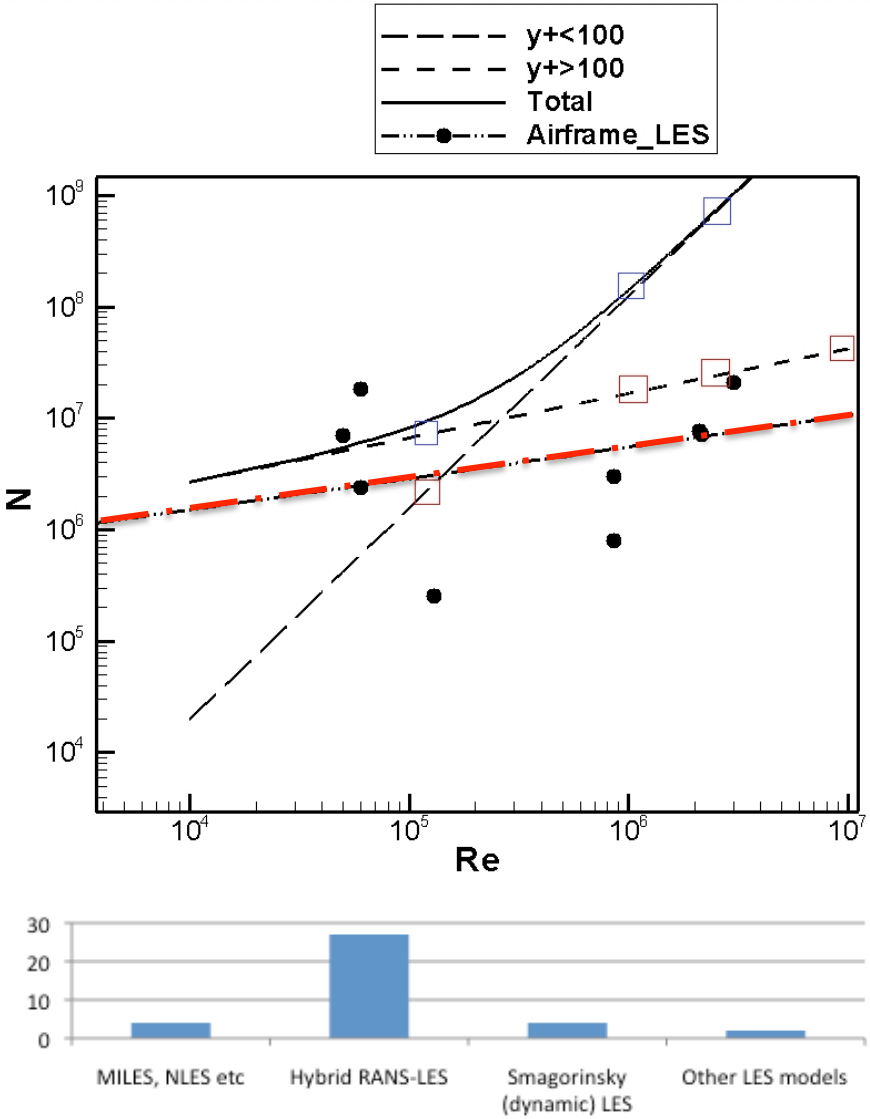

Inflow classification

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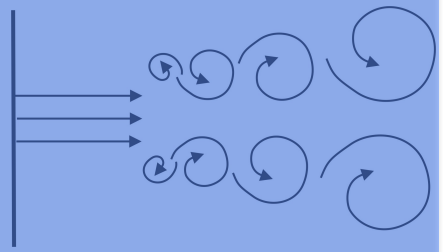
A: Wake (*Re* independent)

Ribbed passages

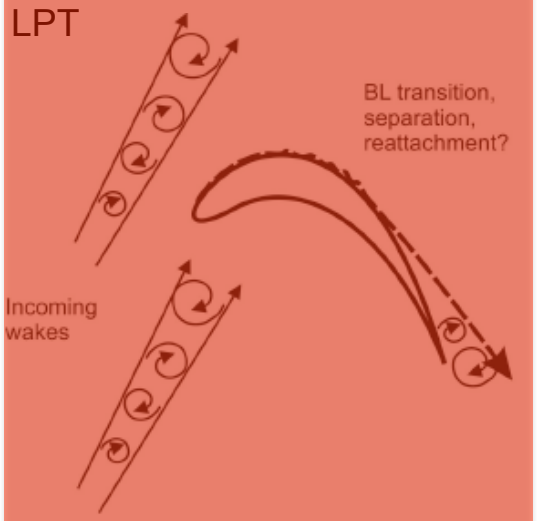
CBTE

Jets



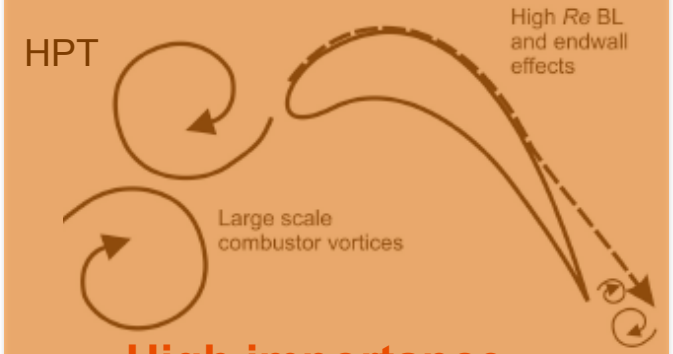
Low importance

B: Low *Re*



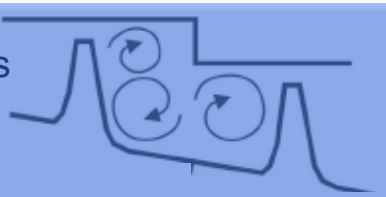
Crucial

C: High *Re*

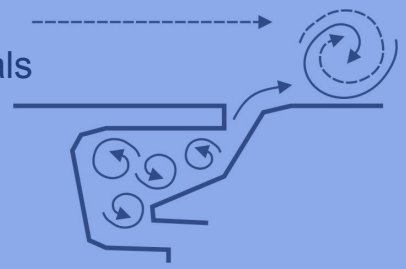


High importance

Lab seals



Rim seals



Low importance

LES model validity and modelling strategies

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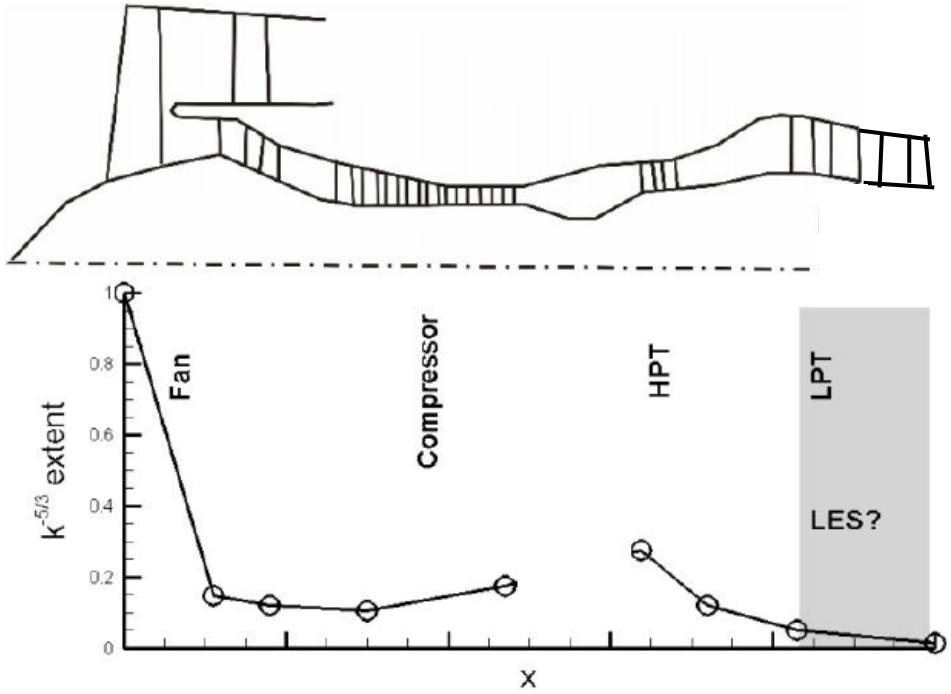

Wake + low *Re*

- Short $k^{-5/3}$ range
- LES validity?
- (I)LES / QDNS

High *Re*

- RANS layer required
- RANS-(I)LES

Case overview - HPT blade

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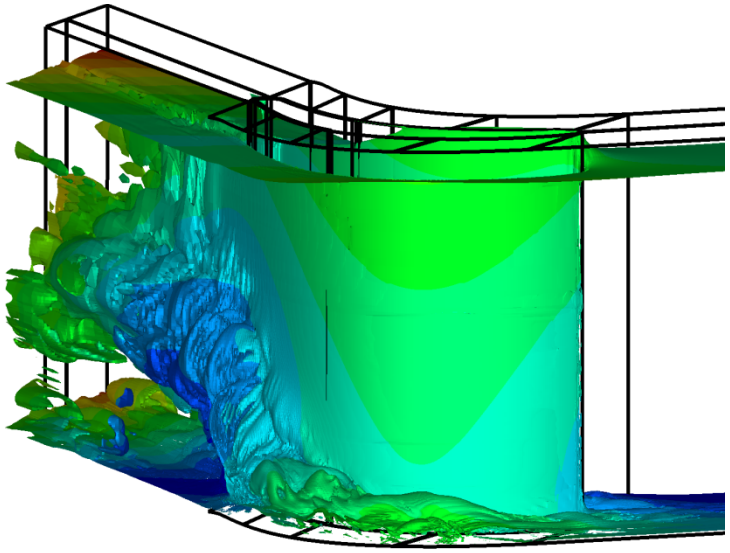

Re ≈ 0.6 million,
N = 5.5 million

Flow type	**C: High *Re***
Method	**RANS-(I)LES**
Inflow type	**Critical: Turbulent BL, combustor eddies**
Benefits	**Moderate: Modelling cooling holes challenging**
Disadvantages	**Doesn't naturally test stress/component failure**
Uses	**Understand flow physics, improvement of lower order modelling**

Validation - HPT blade

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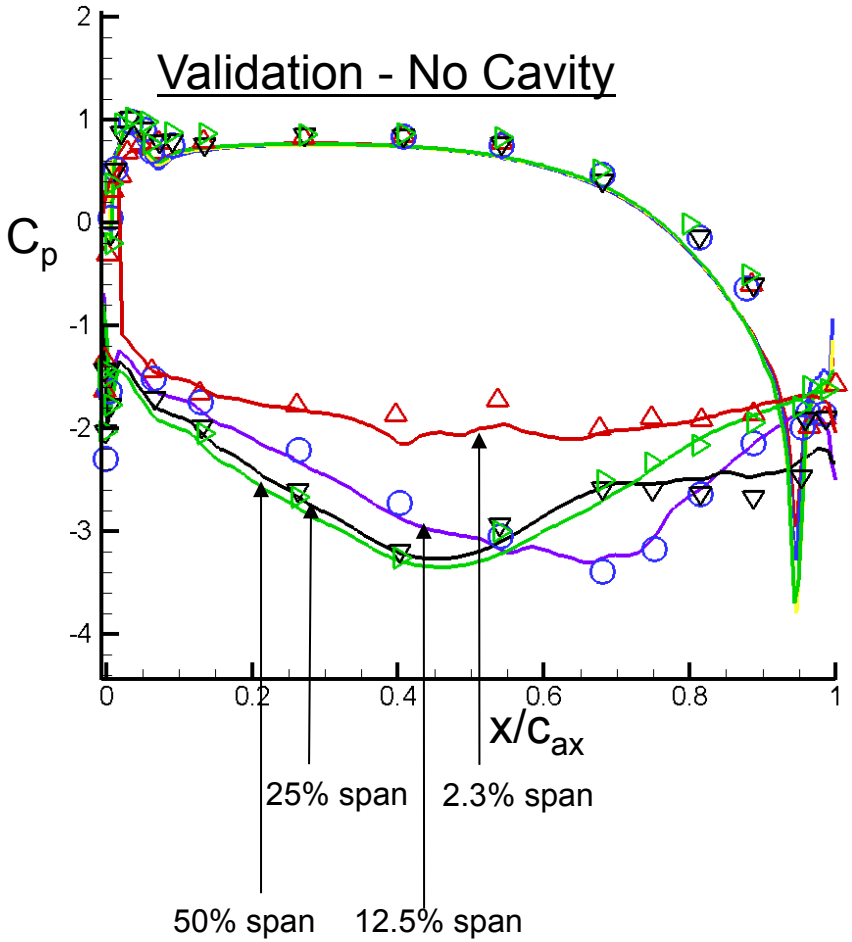
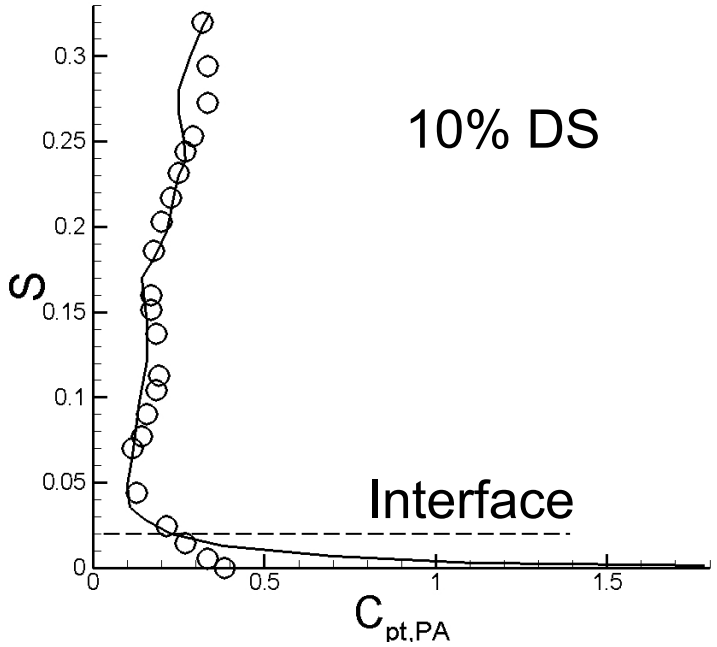
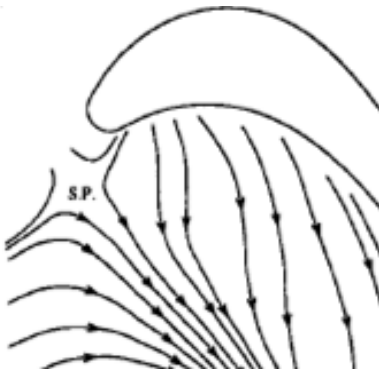
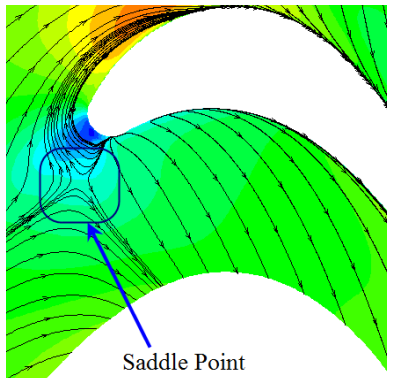
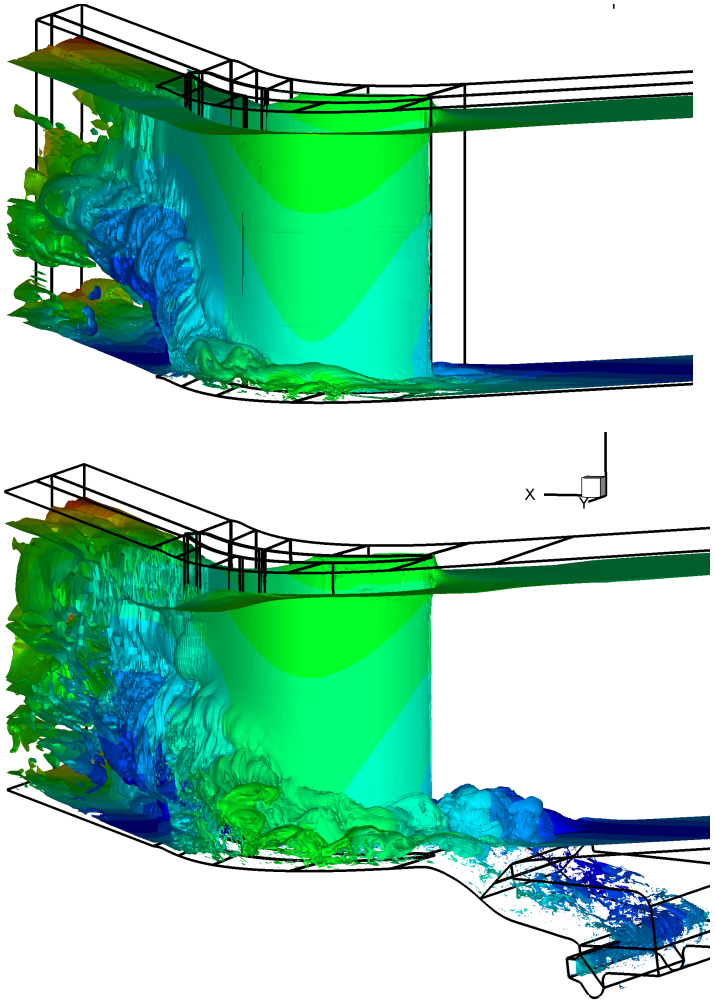




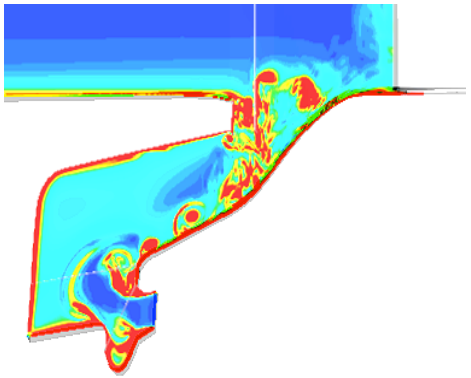


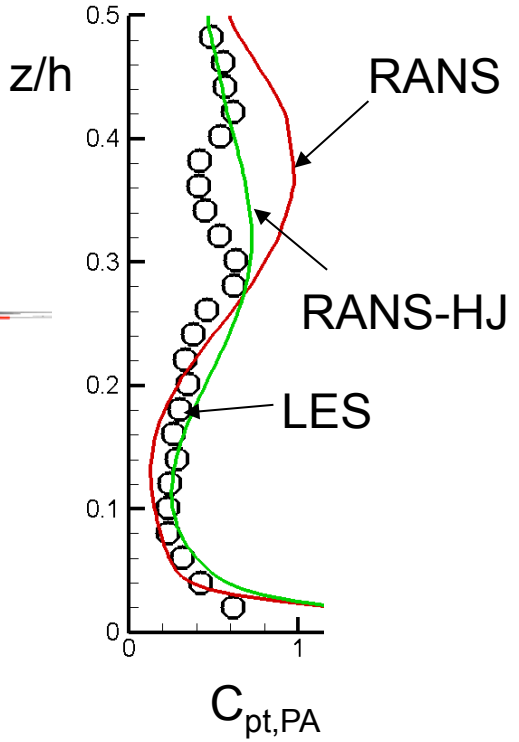


LES uses – HPT blade



Real inflow:





Jefferson-Loveday et al.
ASME J. Turbomach.

Uses – HPT real turbine surface roughness effects

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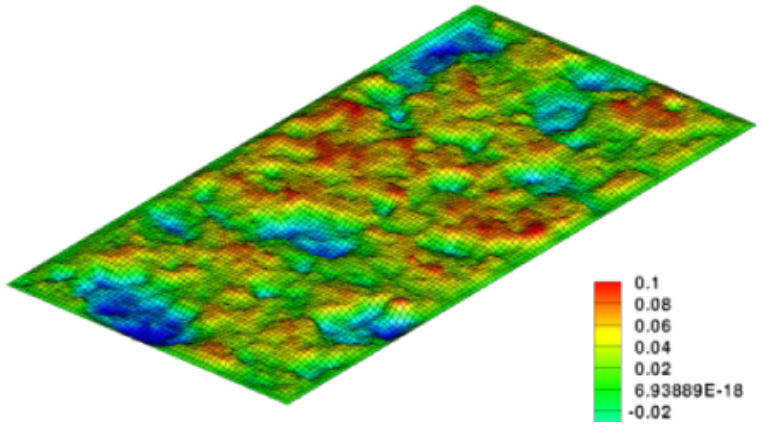
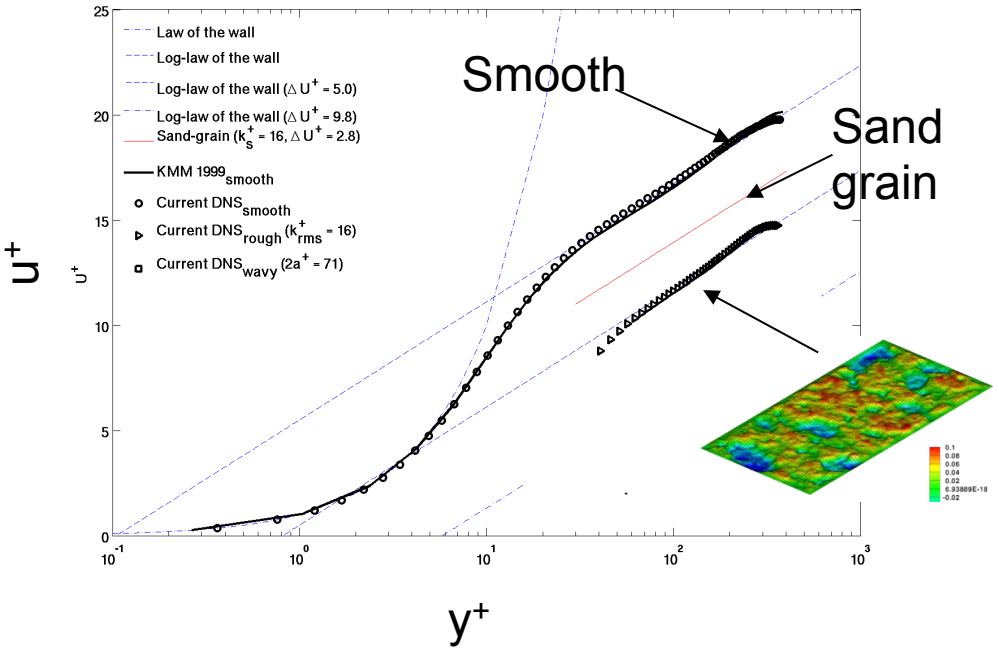
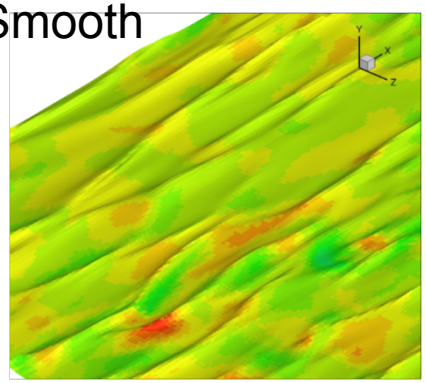
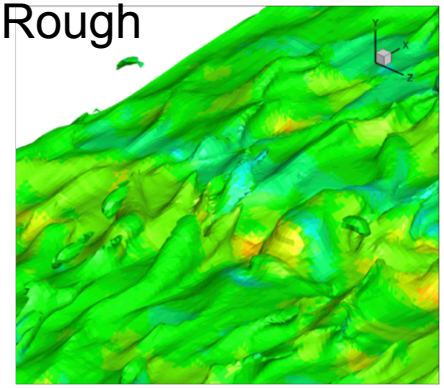




Smooth



Rough



- 80% higher C_f
- Energy budgets
- Improve RANS

Case overview – Labyrinth / Rim seals

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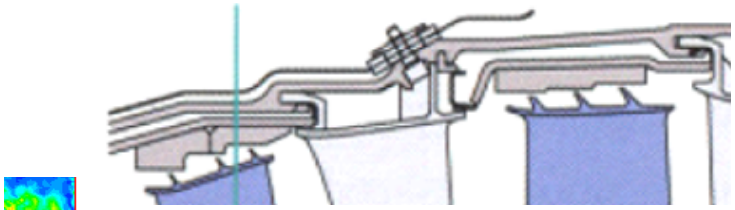
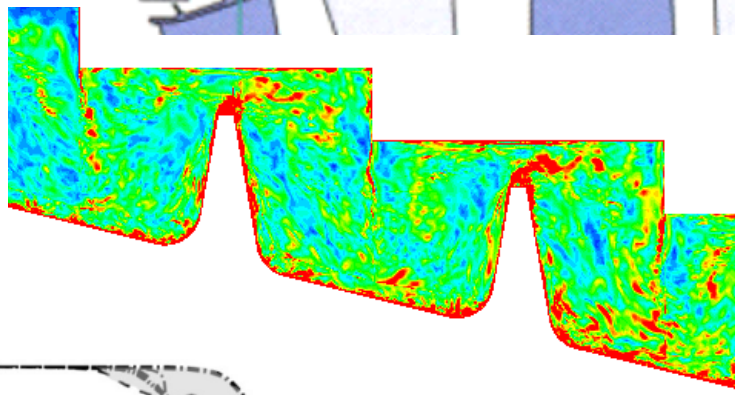
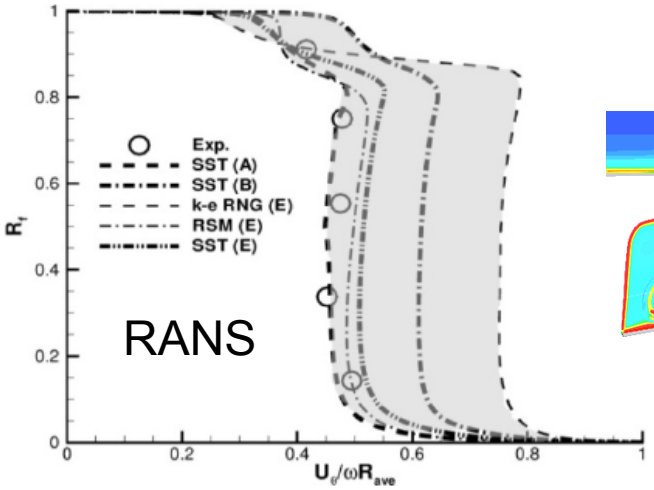
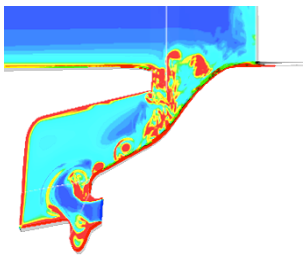


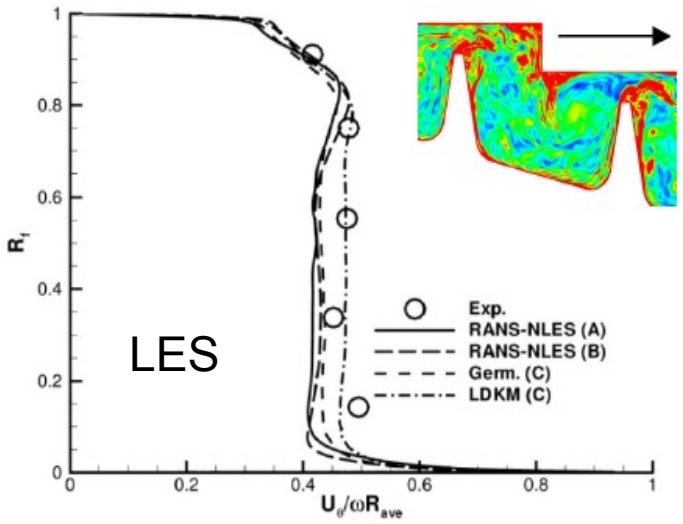


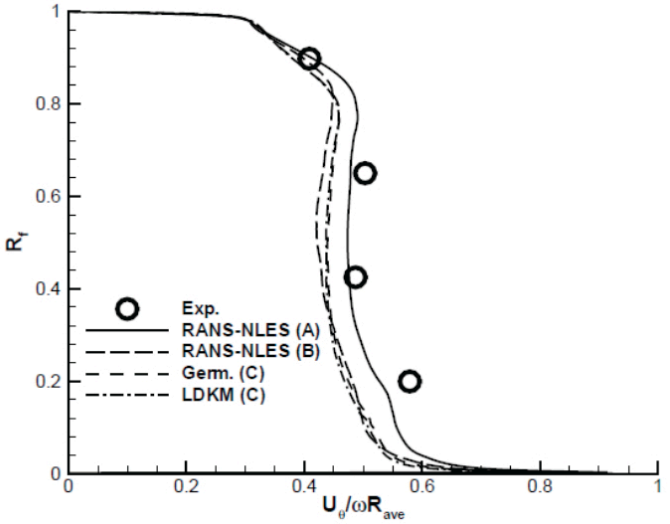


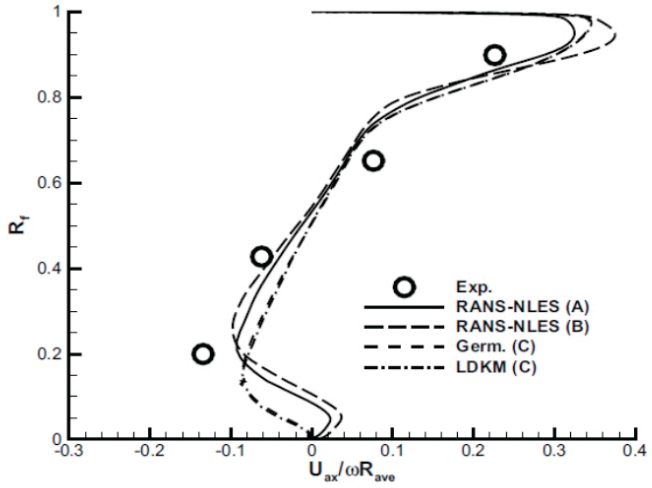


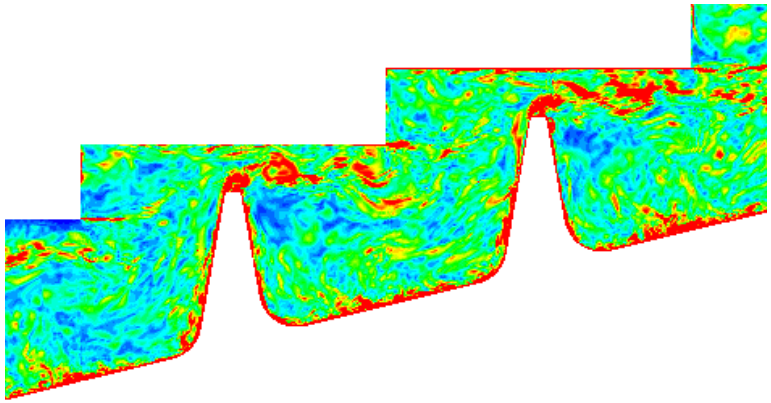
Flow type	C: High *Re* BL + Wake
Method	(I)LES/RANS
Inflow type	Simple: Large geometric scales form rapidly
Benefits	High: Accurate and consistent for all operating conditions. Lower cost.
Uses	Test new designs, add to and improve existing databases, improve low-order modelling (Correlations ~100% error in some cases)

Validation – Labyrinth / Rim seals

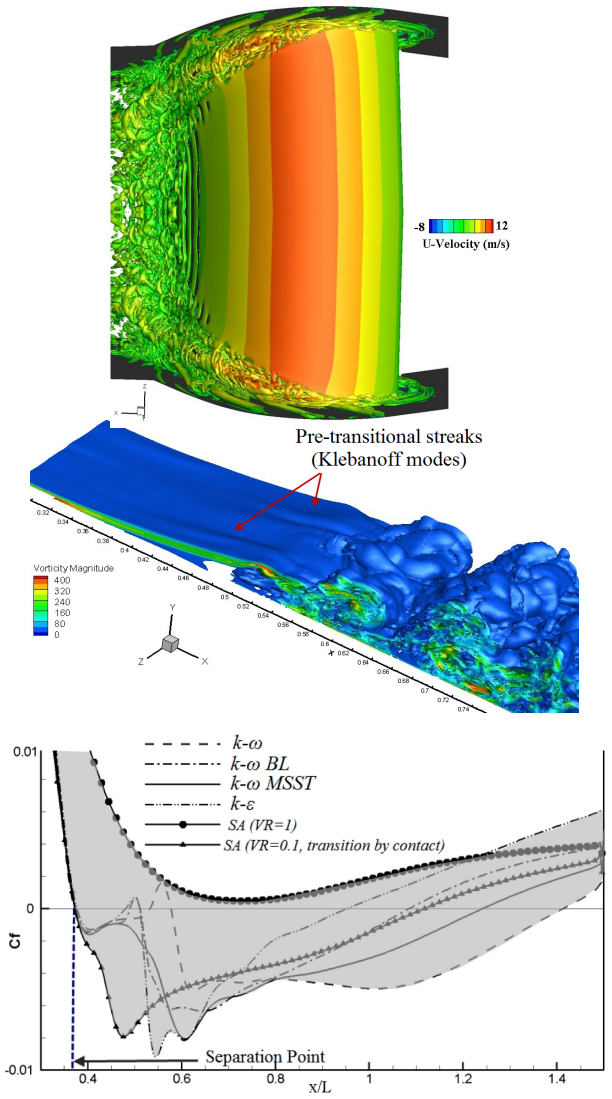








Case overview - LPT blade



Flow type	B: Low *Re*, transitional
Method	(I)LES
Inflow type	Critical: Wakes, FS turbulence, endwall turbulence
Benefits	High: LES crucial to capture and understand complex flow physics for future technologies, lower cost
Uses	Understand transition processes, real surface roughness effects, improve performance estimates.

Ultra and High Lift Cases

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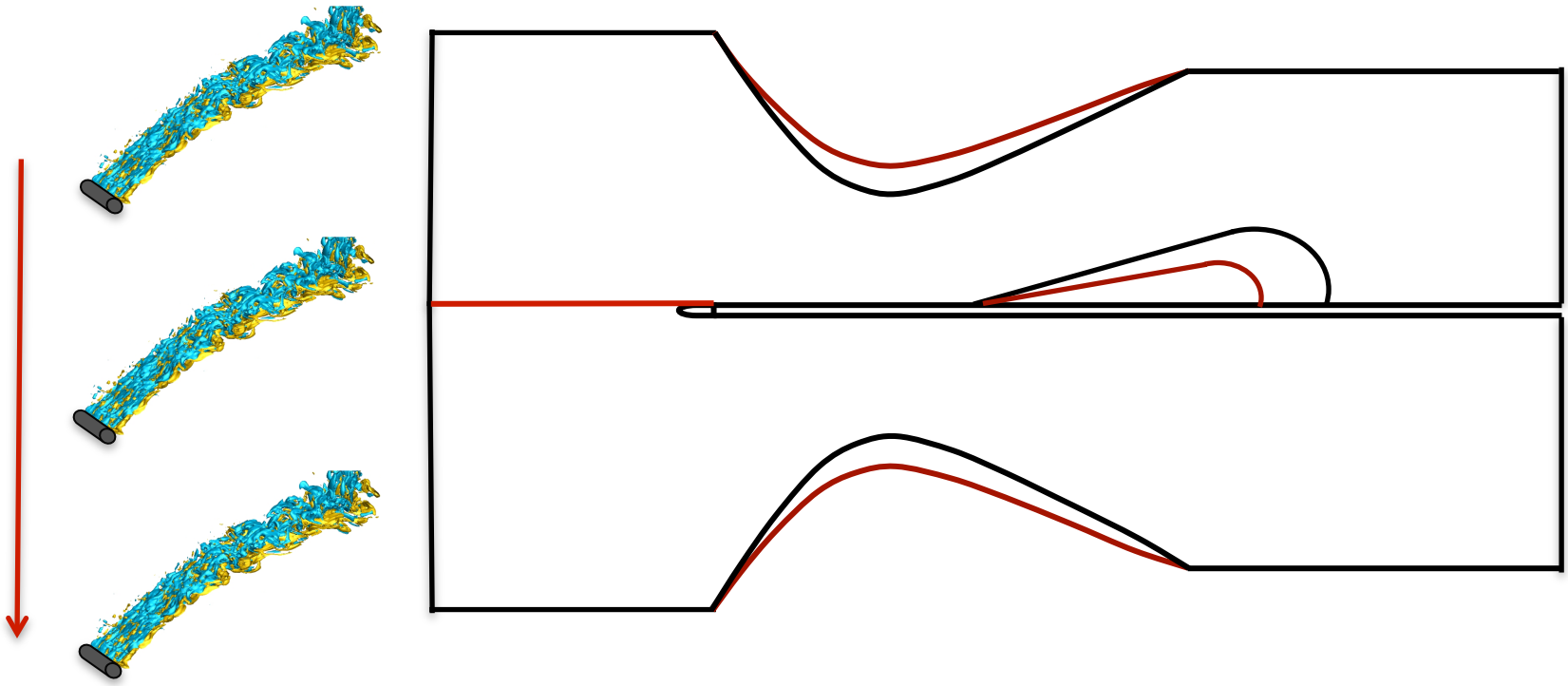

Ultra High Lift

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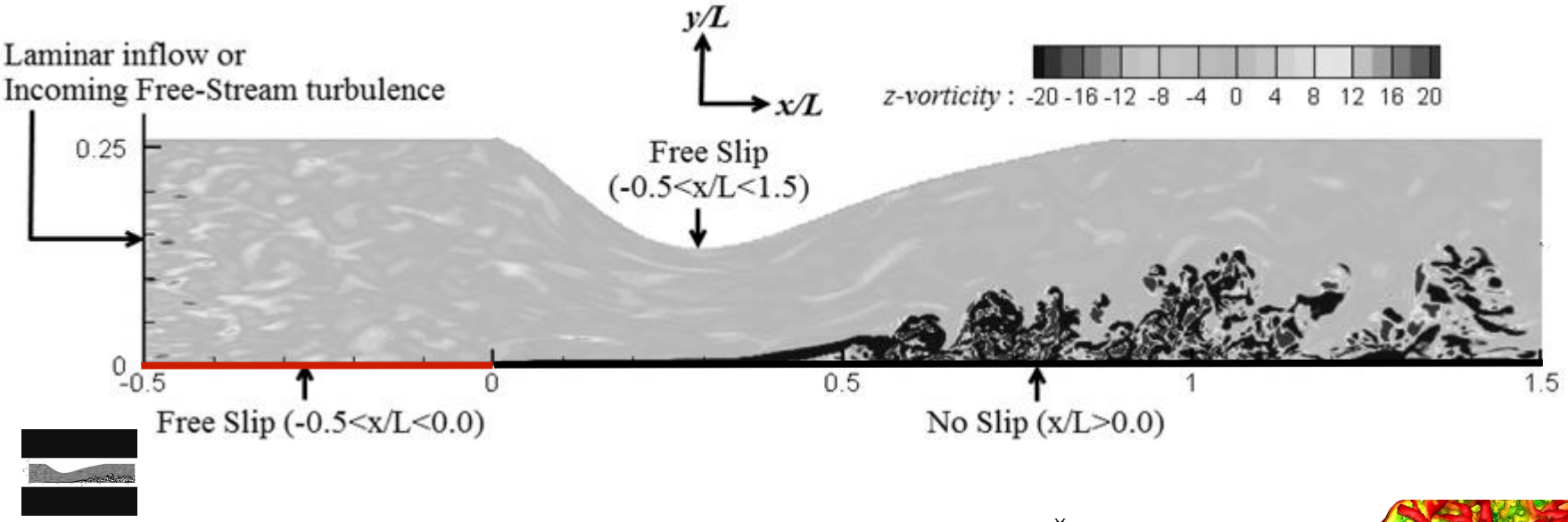
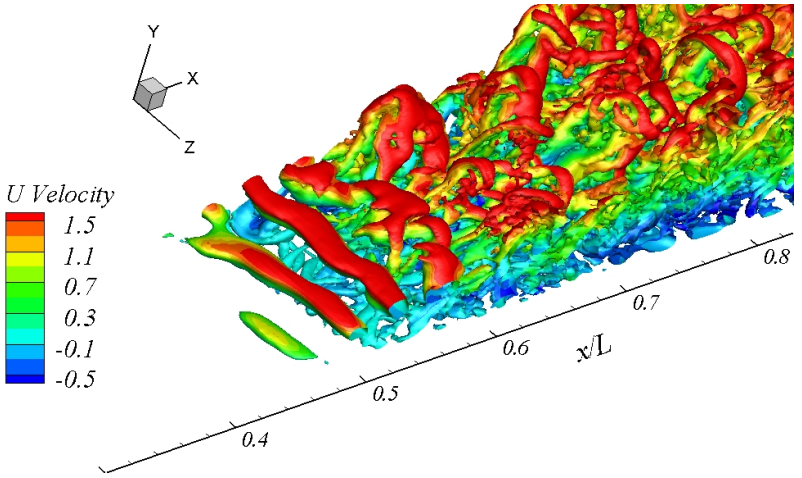


$Re_{(L,\ Uin)}$ = **60,000**
Mesh : **4.3 x 10^6**
SGS Model: **VMS**
Span: **0.12L**



Validation – Ultra high lift

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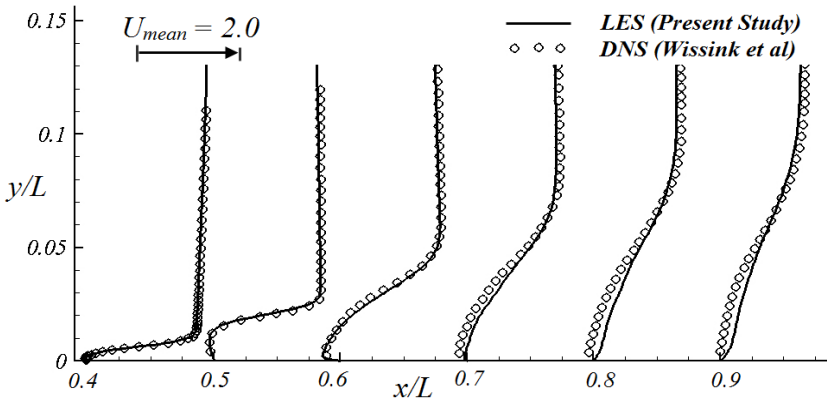
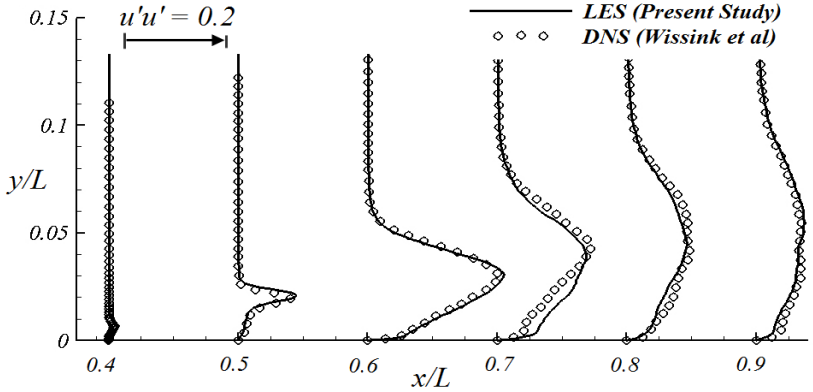
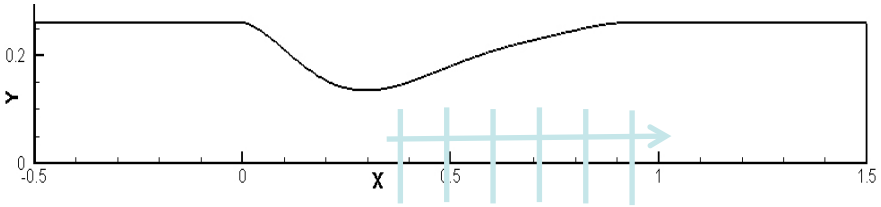
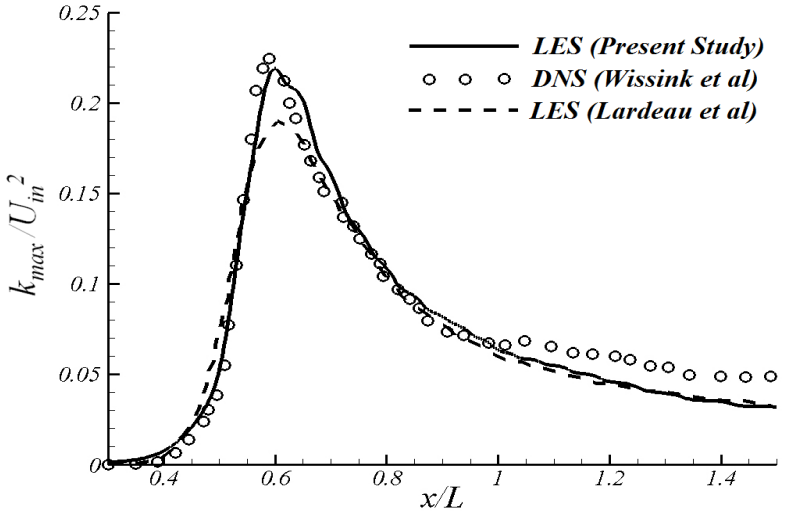


Mean velocity profiles (U_{mean})



Reynolds stress profiles ($u'u'$)





Streamwise variation of maximum turbulent kinetic energy

LES Uses – New Physics

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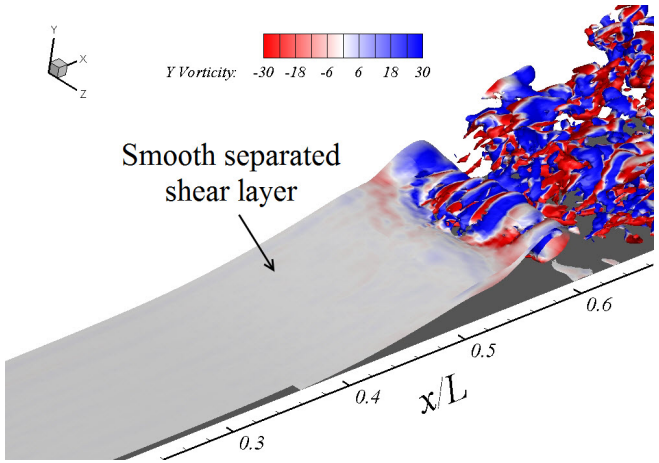

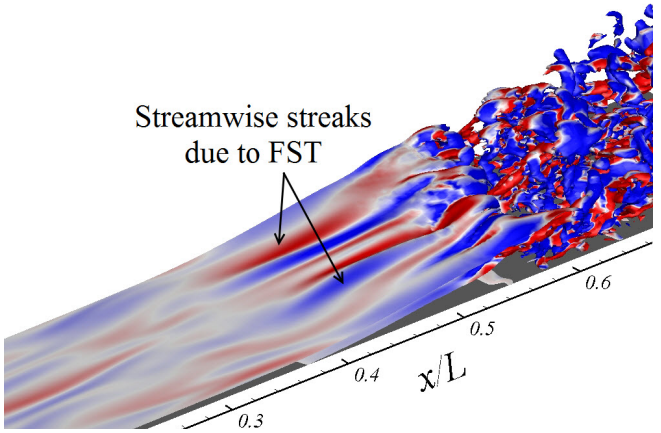

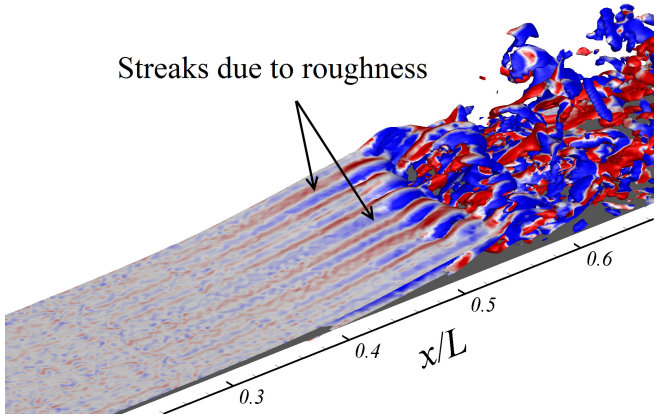

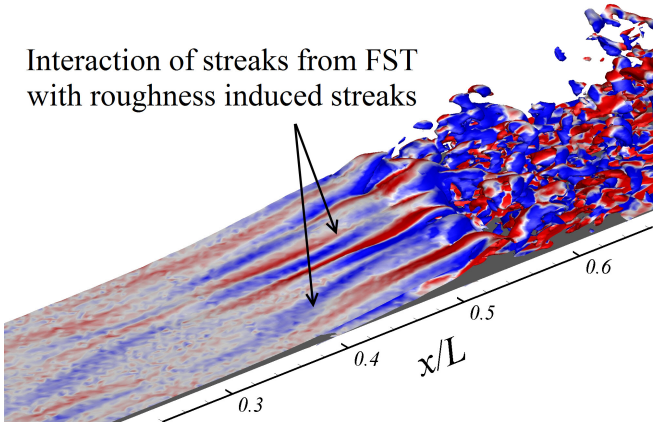

Streaks enhance mixing → promote early transition → yield smaller separation bubbles

Validation – High Lift

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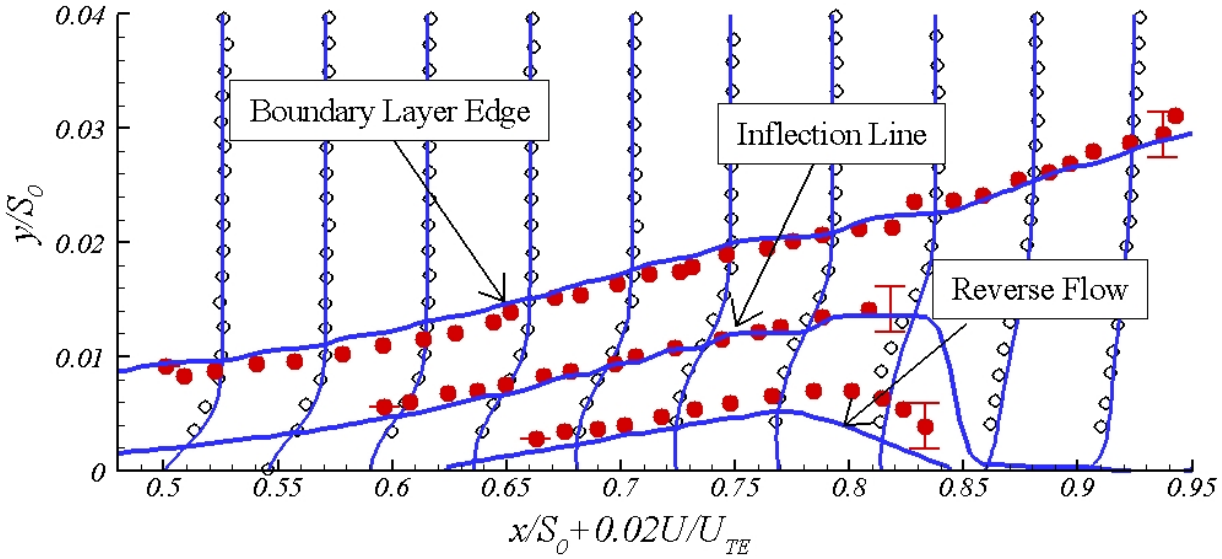
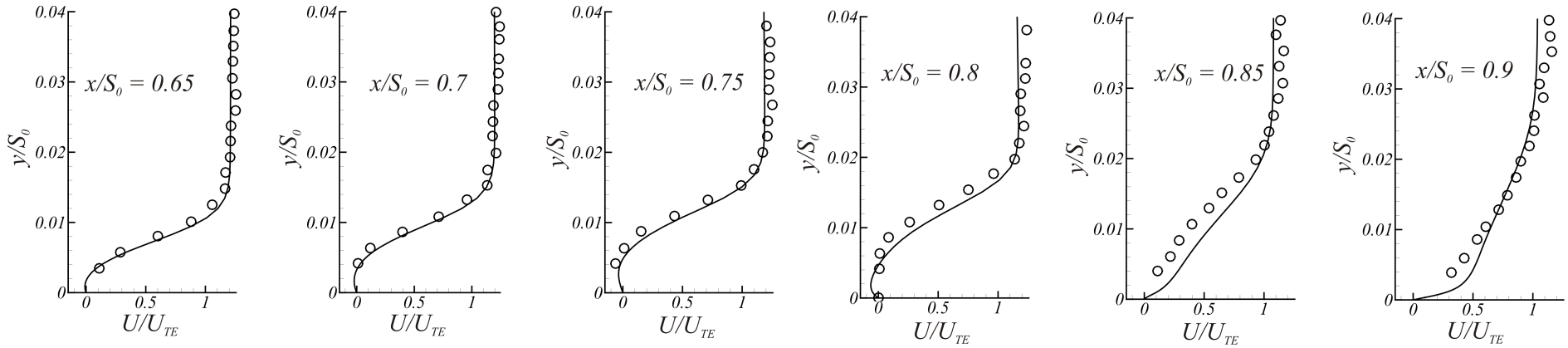


Experiments

LES

$Re_{(L, UTE)}$ = **84,000**
Mesh : **8 x 10^6**
SGS Model: **VMS**
Span: **0.2L**



Comparison of Streamwise velocity profiles

Validation – High Lift

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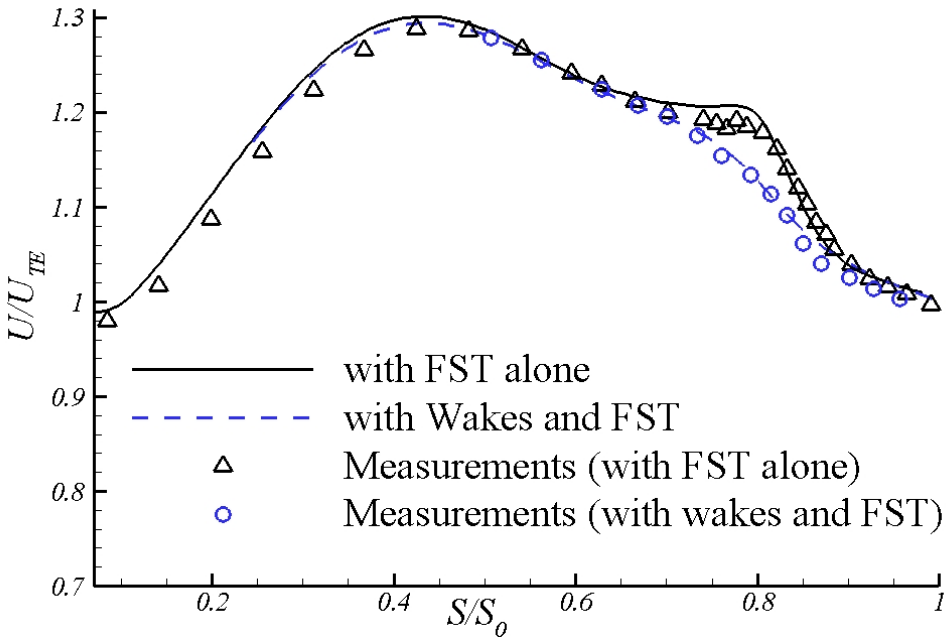

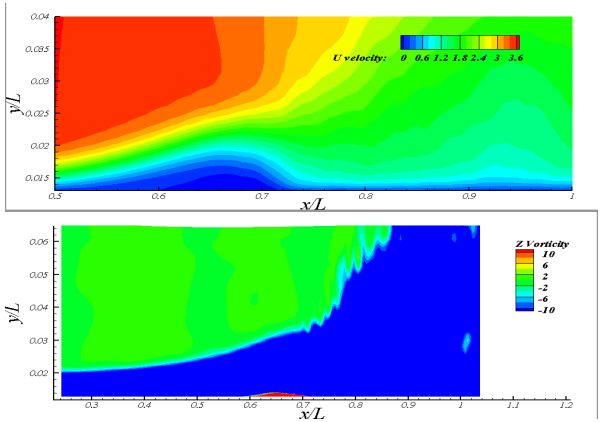

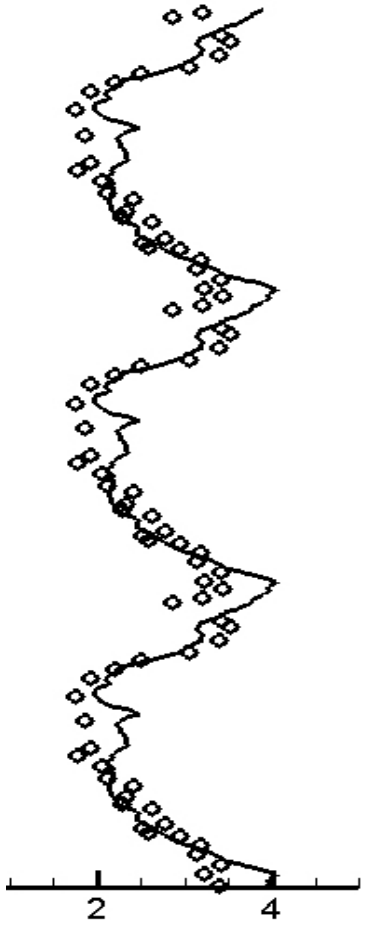

Comparison of θ_{TE} with experiments

LES Uses - New Physics

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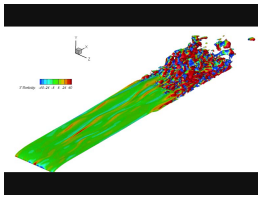
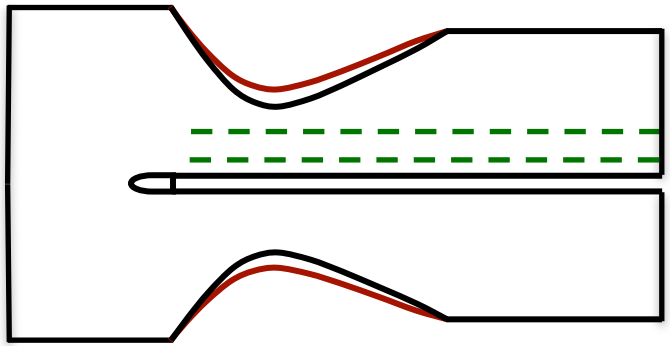
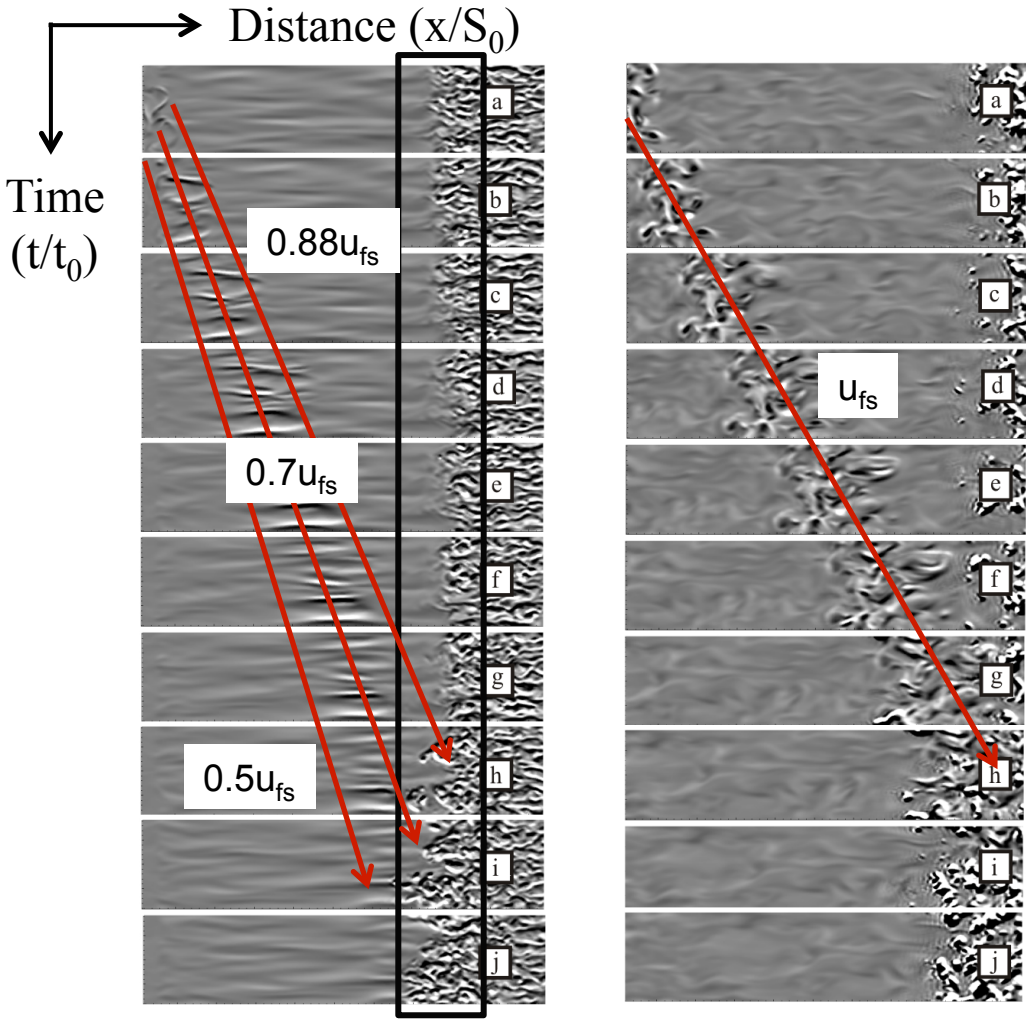


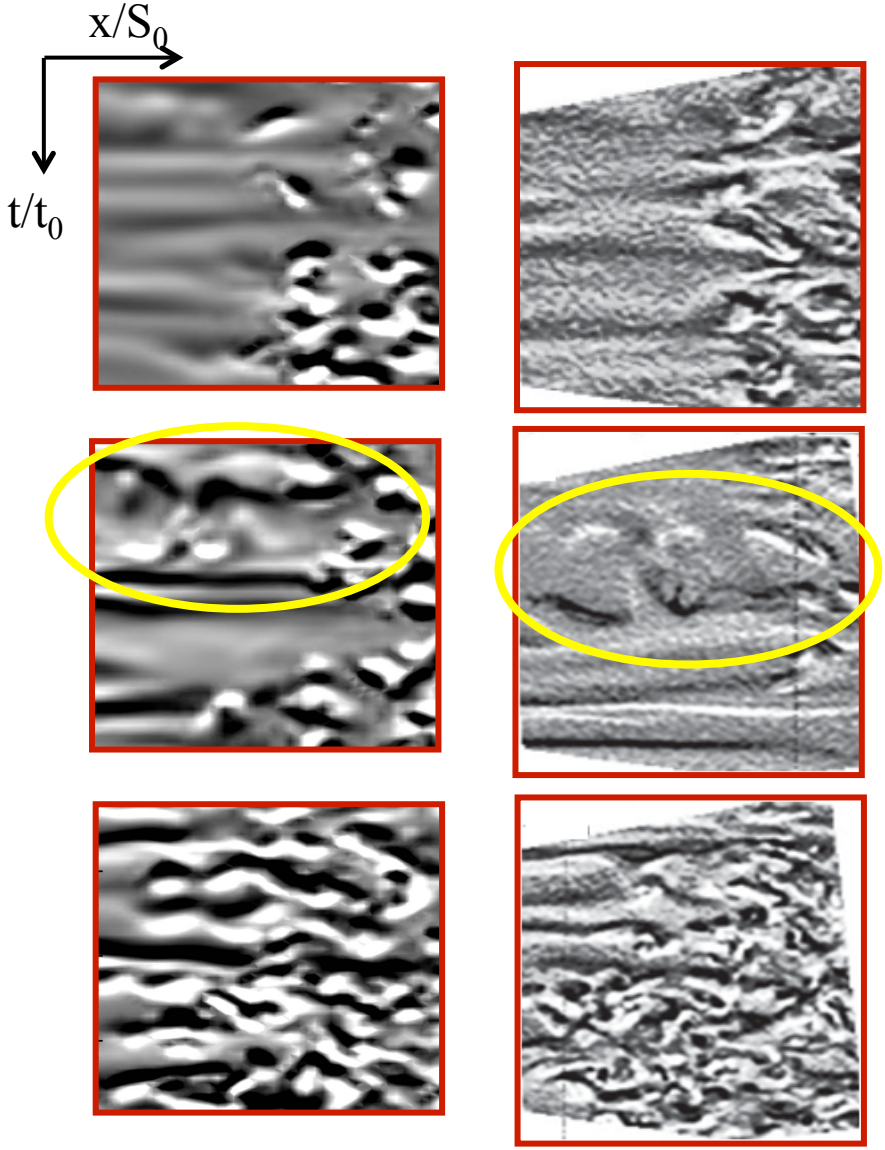
Wakes induce Stronger Streamwise Streaks than FST **(periodically in time)**



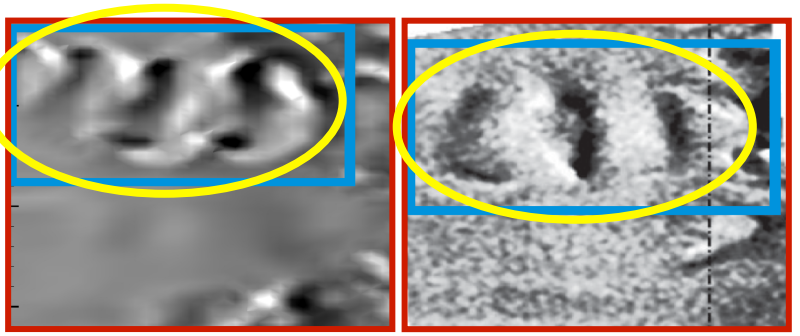


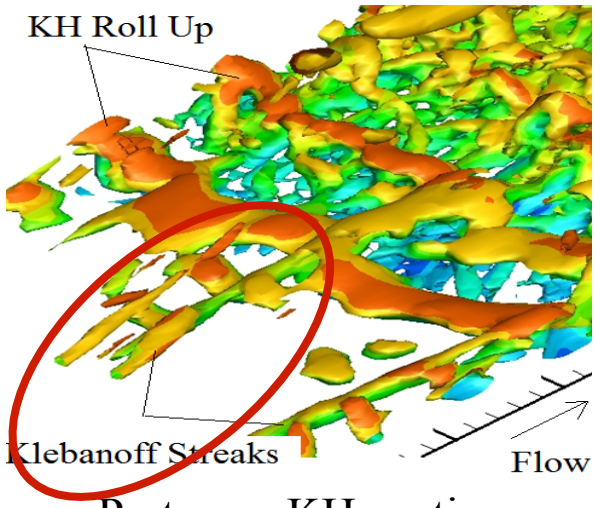
LES Uses – New Physics

UNIVERSITY OF CAMBRIDGE



Wall- normal velocity





Part span KH vortices

LES Uses – New Physics

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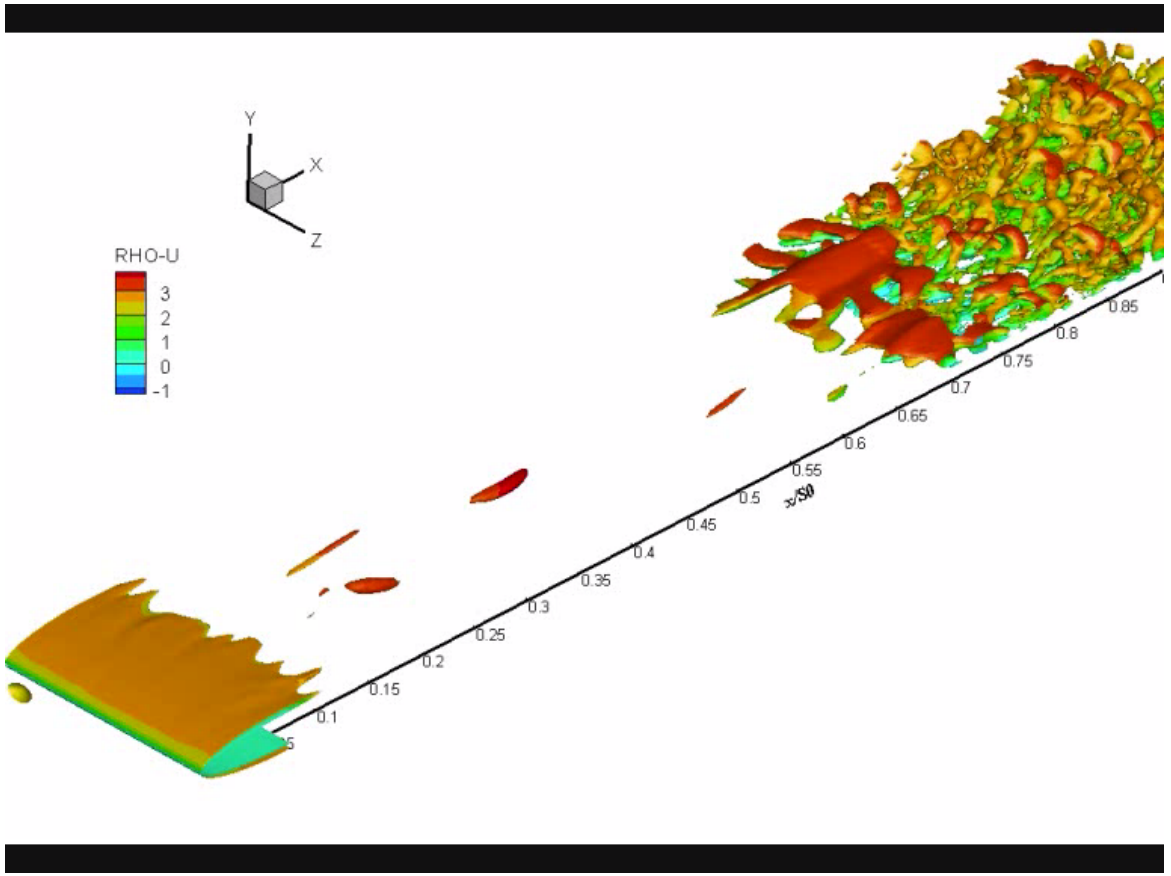
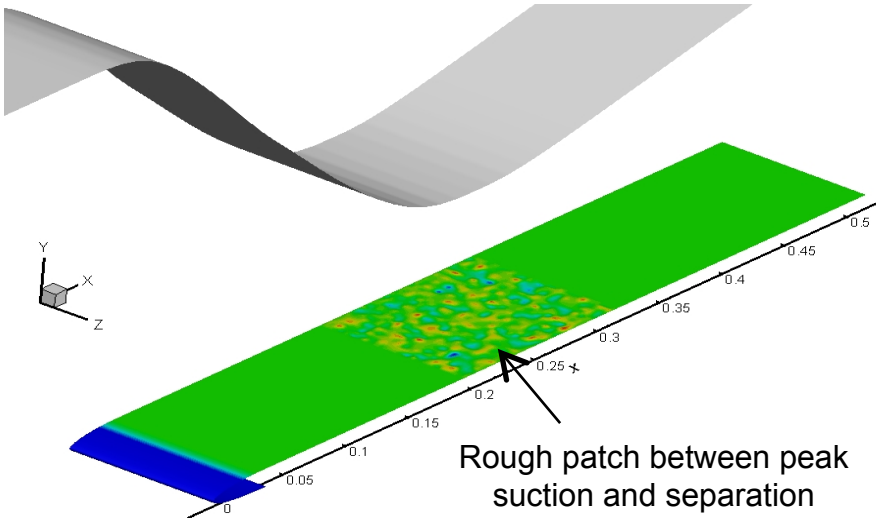
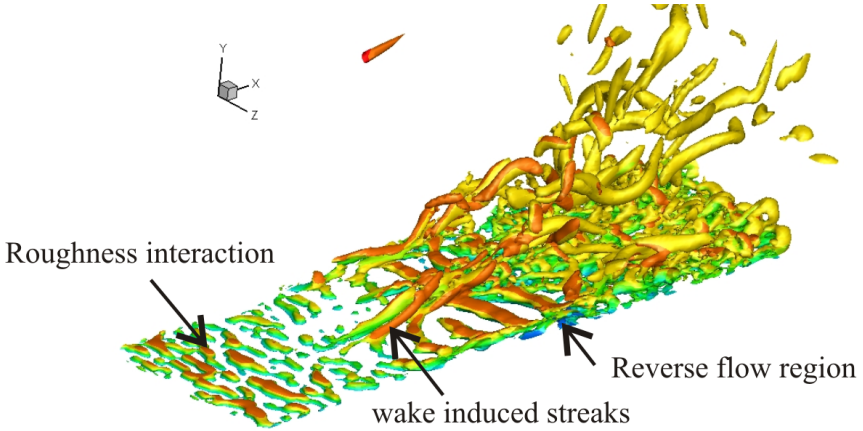


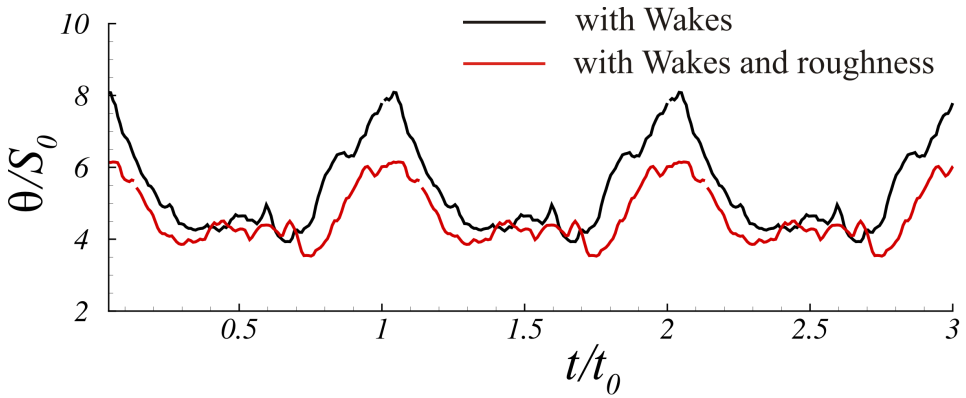
LES Uses – New Physics

UNIVERSITY OF CAMBRIDGE



Rough patch between peak suction and separation





Roughness benefit is still seen

(However benefit is more pronounced in Ultra high-lift case)

Type of Work in Progress

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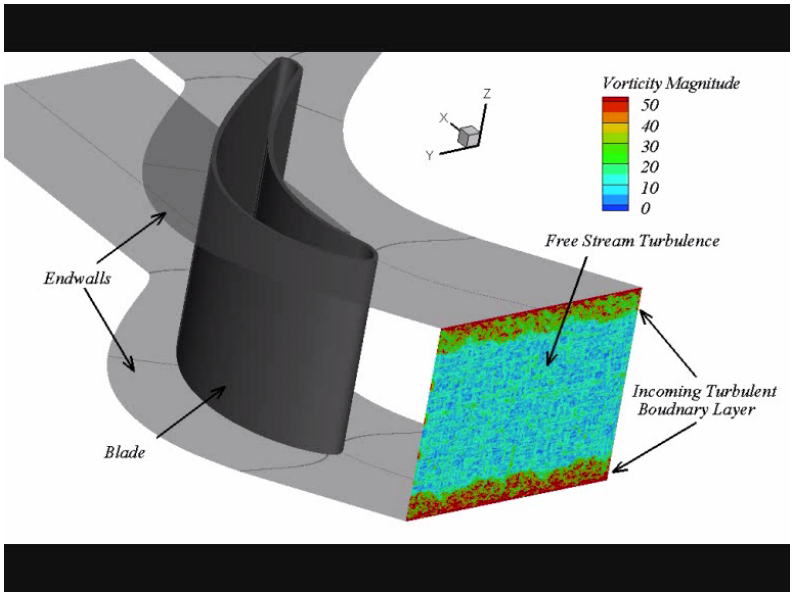
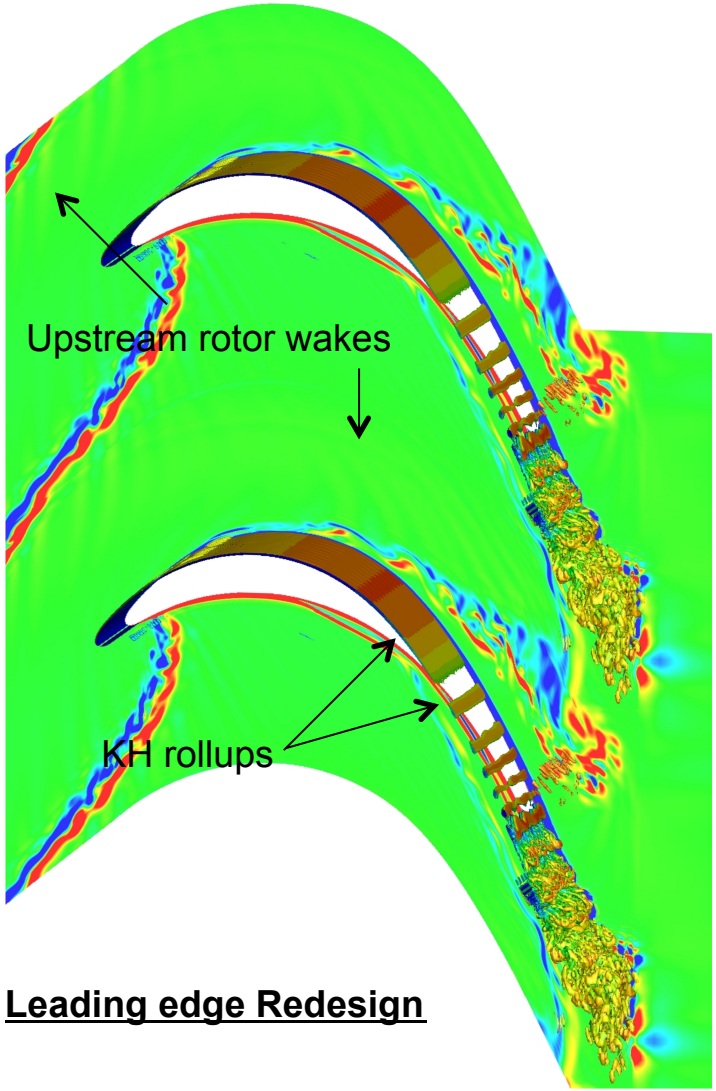


Endwall Effects



Leading edge Redesign

Low Pressure Turbine (T106A)

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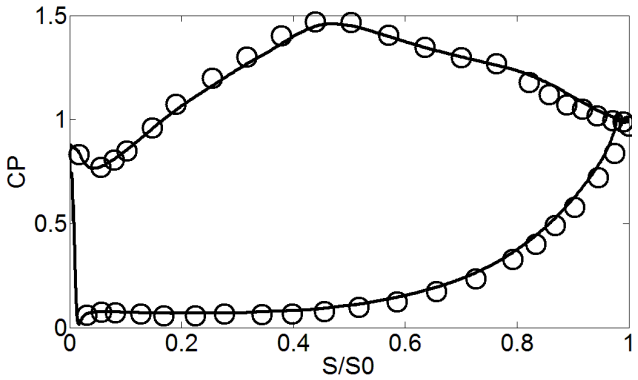
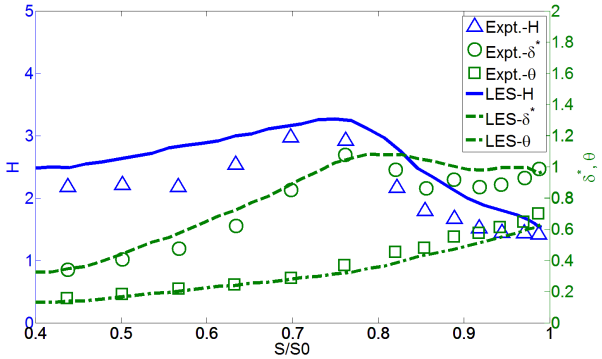
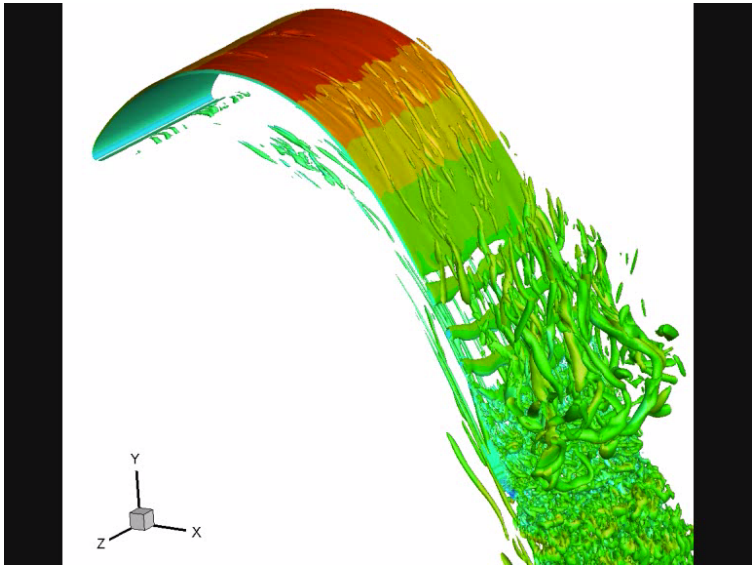
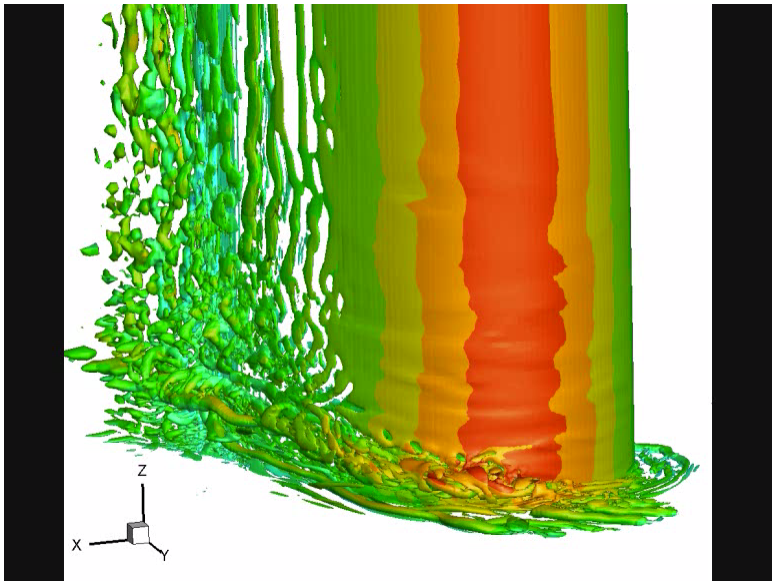


Pressure coefficient



Boundary layer parameters





Case overview - Internal cooling passages

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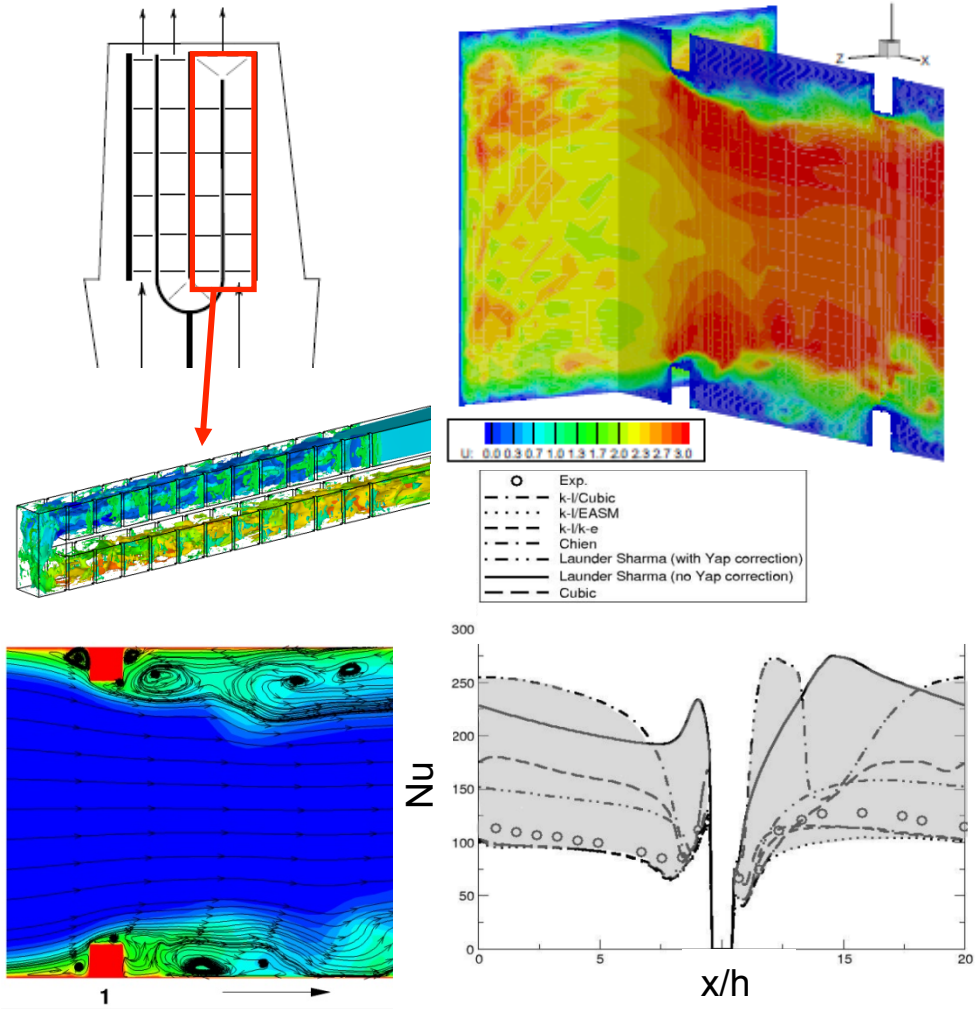
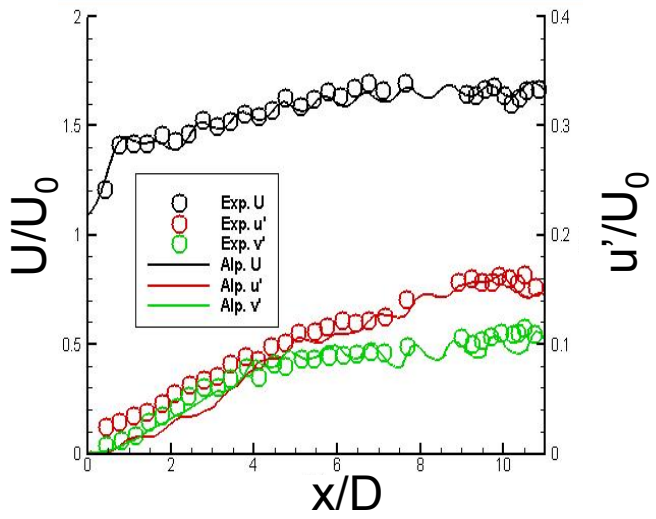
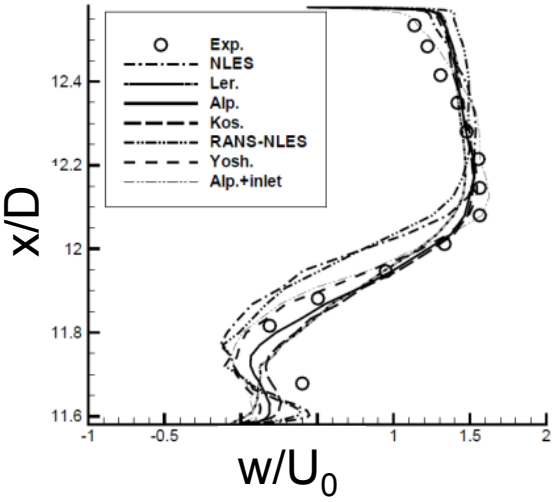
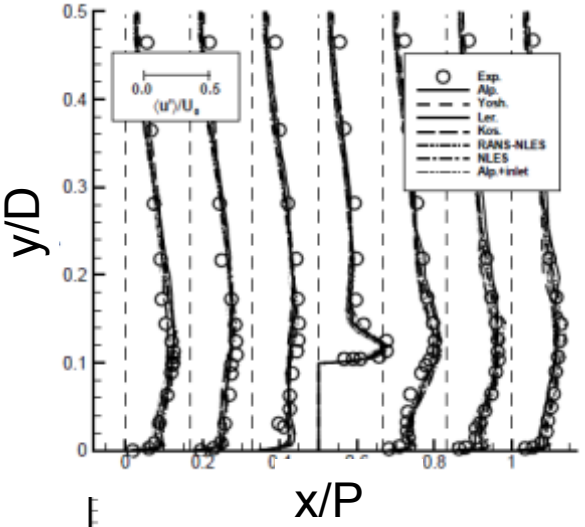


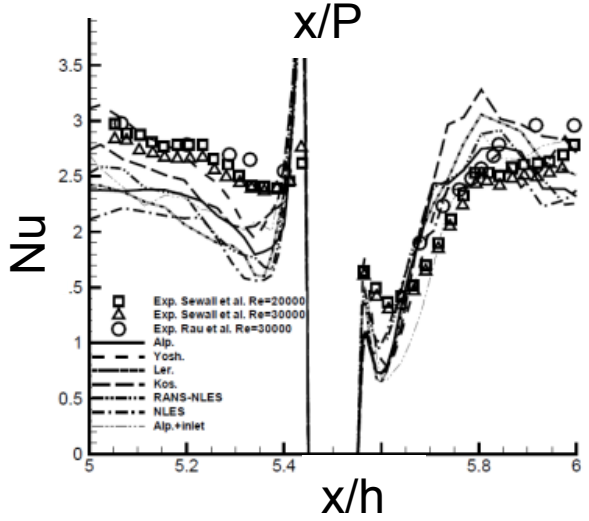
Flow type	**A: Wake**
Method	**(I)LES**
Inflow type	**Simple: Large geometric scales form rapidly**
Benefits	**High: Accurate and consistent HT prediction for complex geometries. Low cost.**
Uses	**Study flow/local hot spots. Improve designs directly - fast turnaround. Optimisation of existing designs. Refine lower order models**

Validation - Internal cooling passages



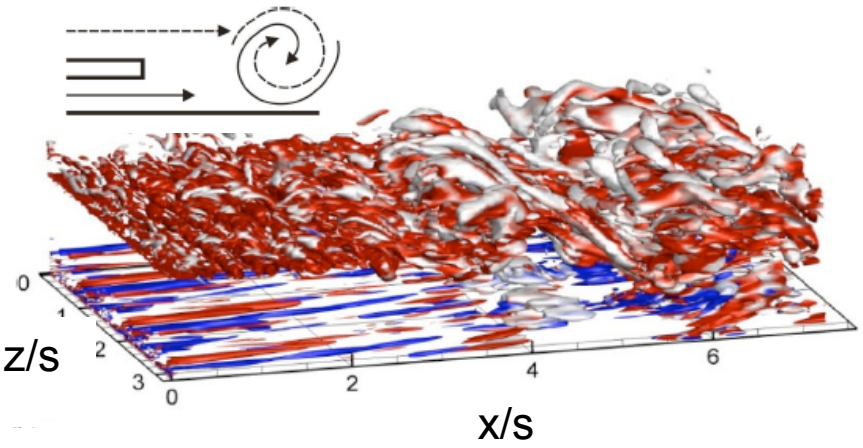


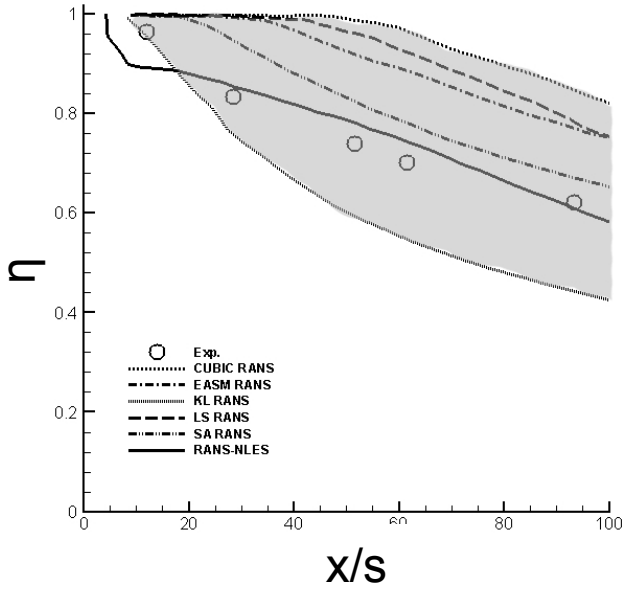




Case overview - CBTE

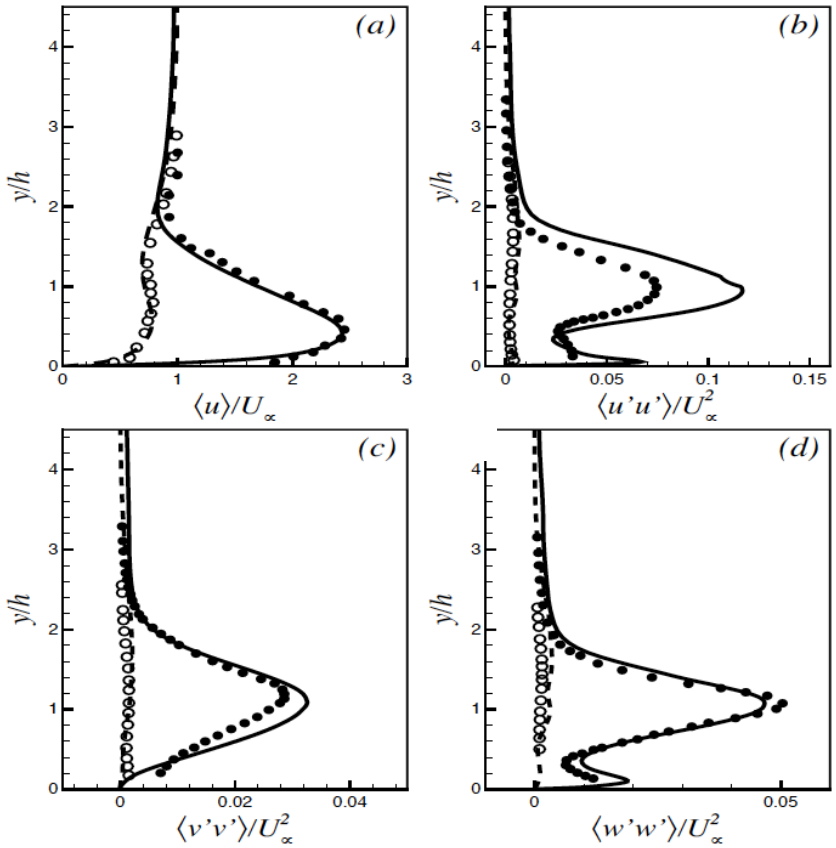
UNIVERSITY OF CAMBRIDGE

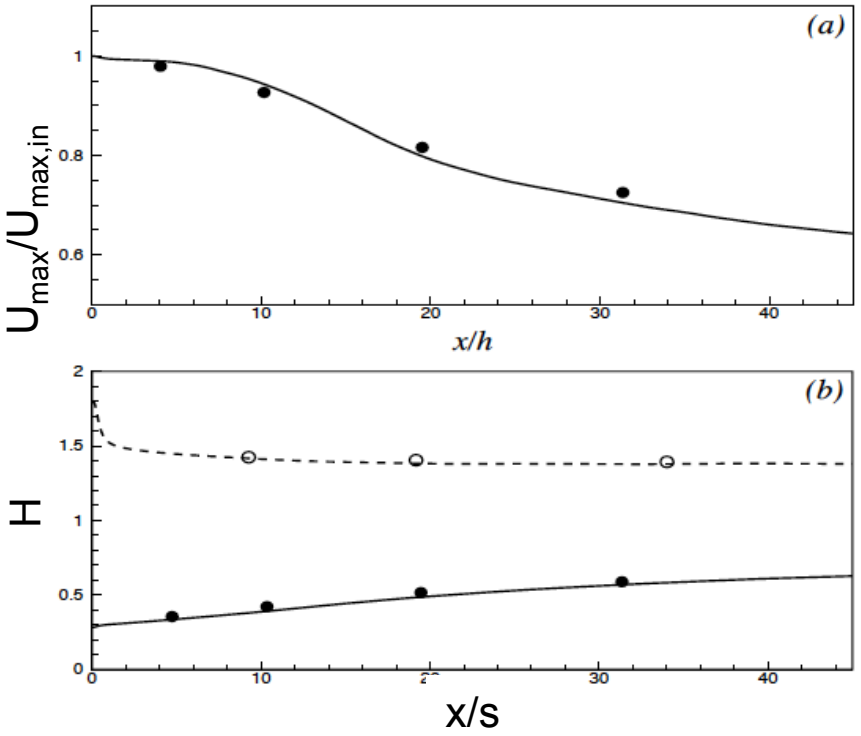




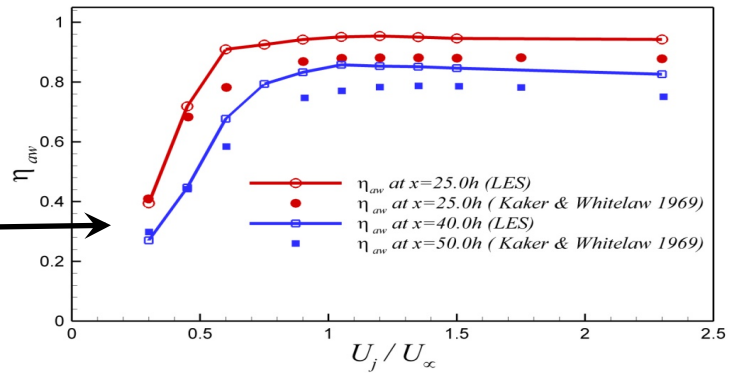
Flow type	A: Wake
Method	(I)LES
Inflow type	Simple: Large geometric scales form rapidly from turbulators +pedastals
Benefits	High: Accurate and consistent HT prediction for complex geometries and a variety of BR. Low cost
Uses	Improve designs directly - fast turnaround. Refine lower order models.

Validation - CBTE





Variation of effectiveness against various blowing ratios at two locations x=25h and x=40h.



LES of Trailing Edge Cutbacks

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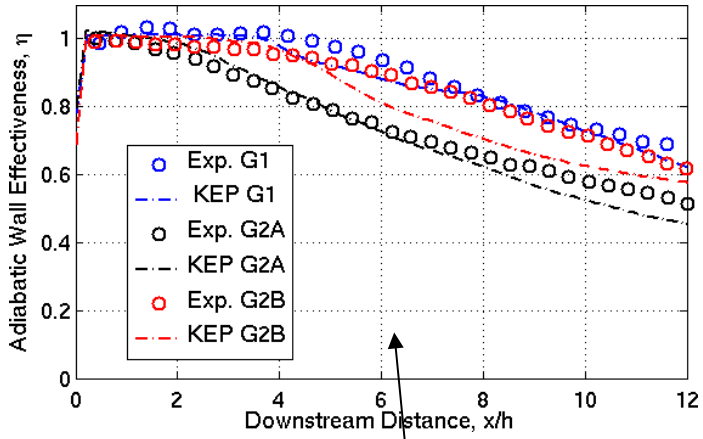
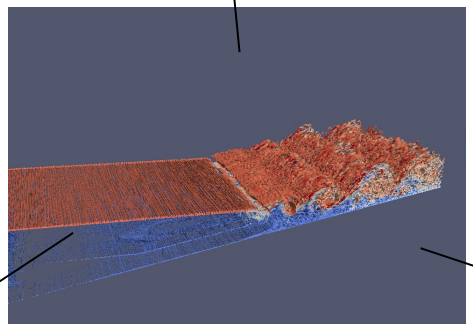
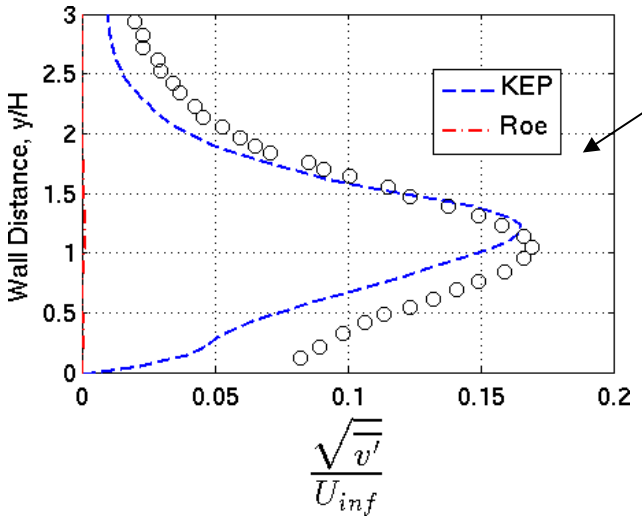
LES can predict the film cooling behaviour of a range of turbulator geometries

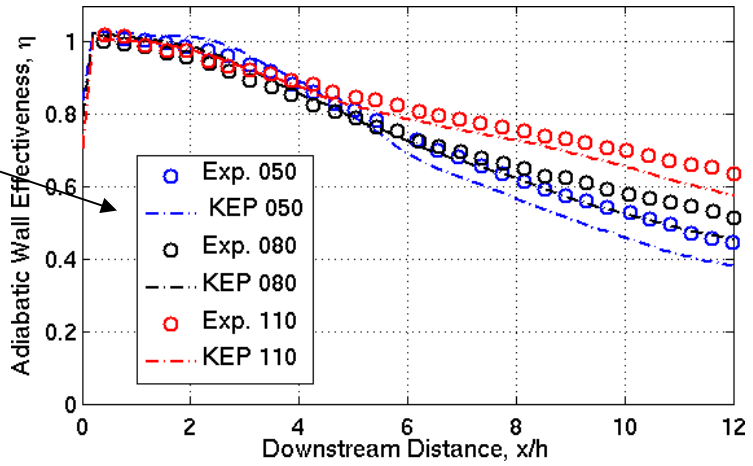


LES is well able to capture the changing behaviour of cutbacks as the blowing ratio is varied





LES can produce good estimates of experimental turbulent statistics



Design Optimization – 600 simulations

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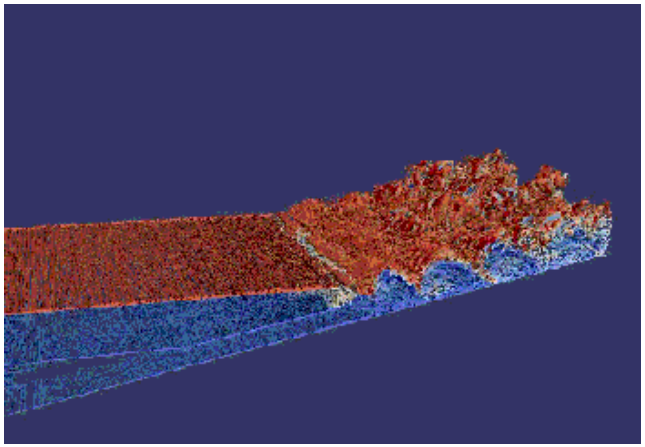
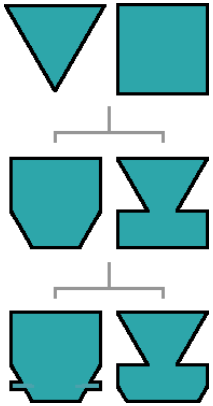
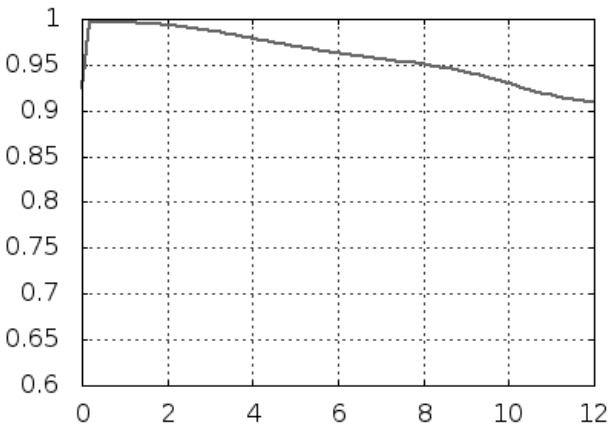


Vortex shedding from cutback trailing edge is inherently unsteady – requires unsteady solution

Evolutionary algorithms search the design space by mimicing Darwinian natural selection (in parallel!)





These can be best explored in parallel: independent cases tested sided by side

Final Design

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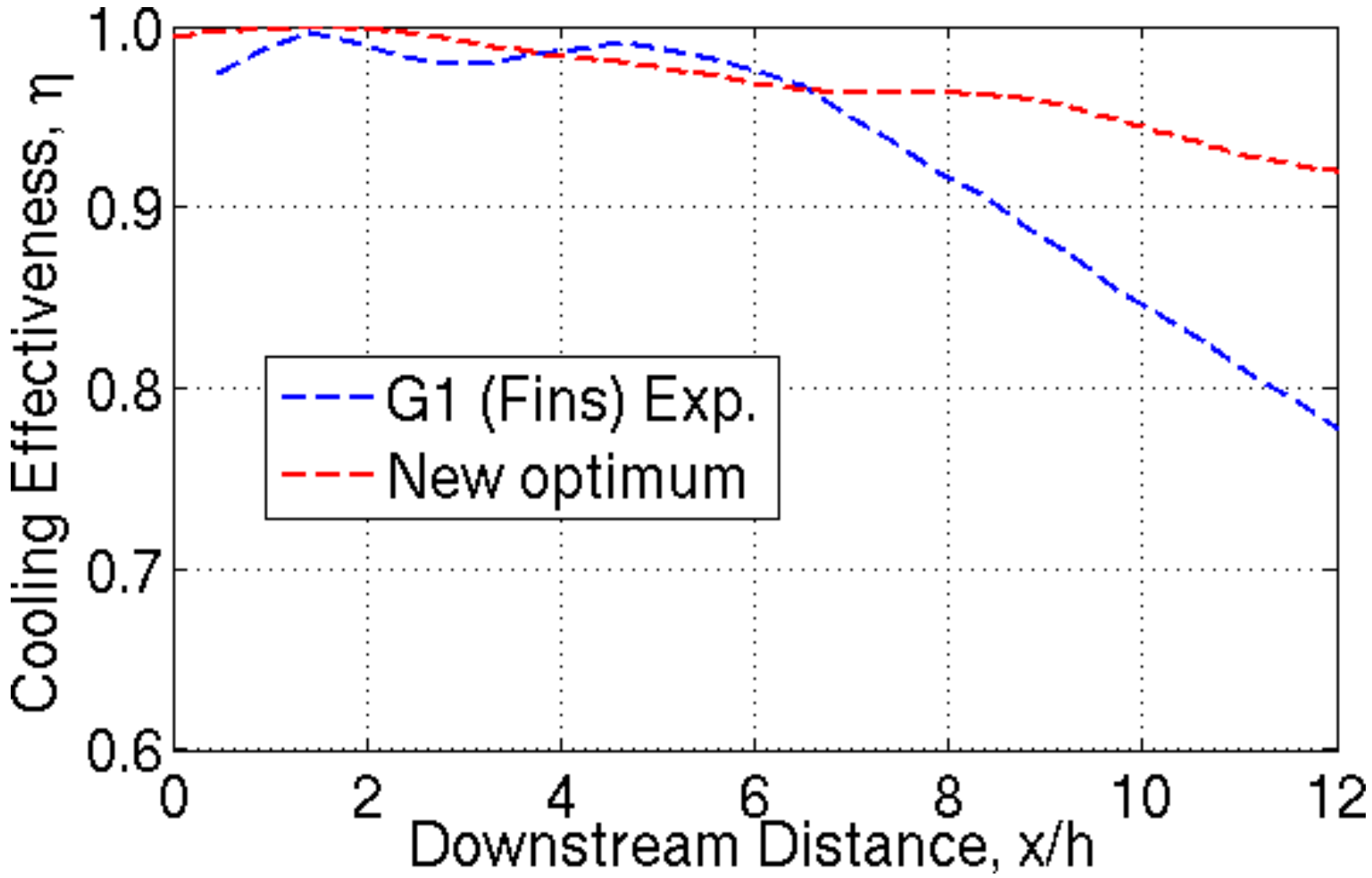

Overview - LES for real geometry jets

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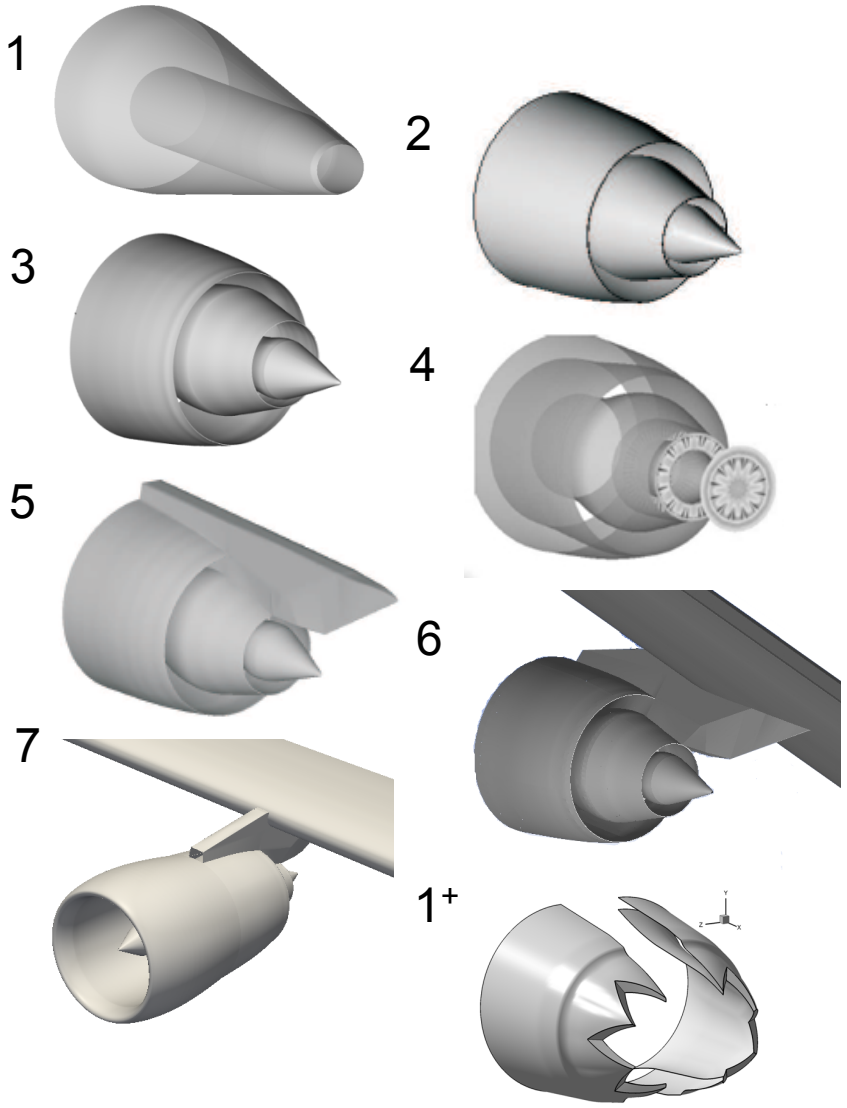
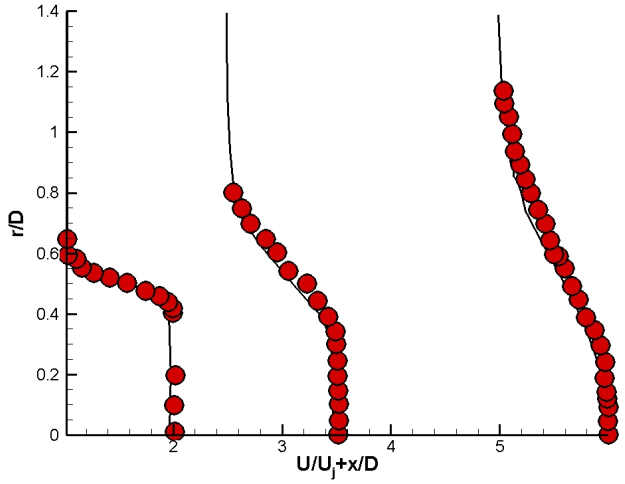
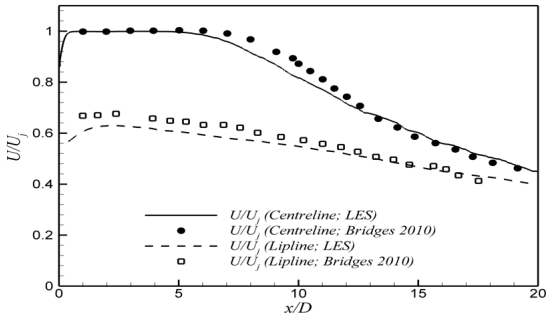
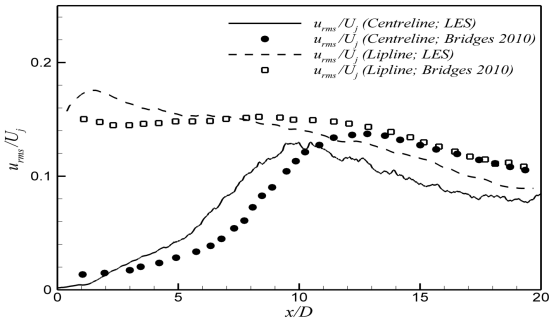


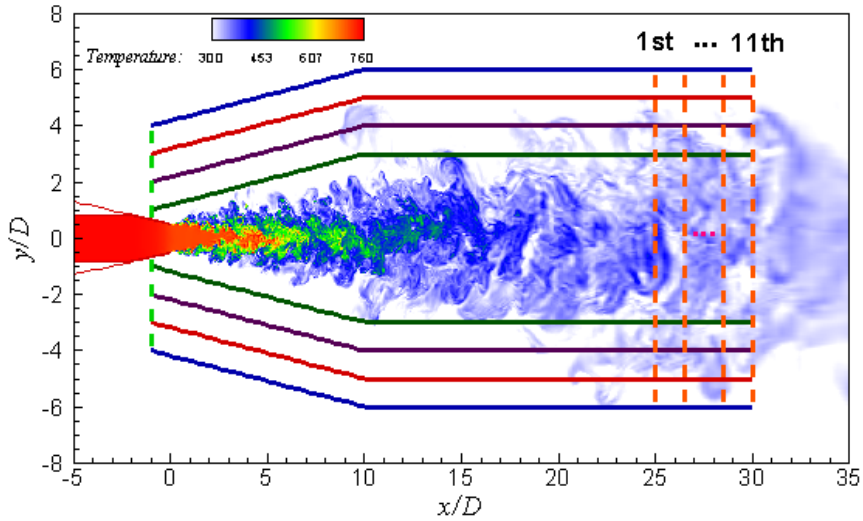
Flow type	A: Wake
Method	RANS-(I)LES
Inflow type	Simple: Need geometric details (pylon, internal struts)
Benefits	High: Remove experimental errors, test geometrical influences, lower cost
Uses	Impact of geometry, improve lower order acoustic predictions (Dowling et al.)

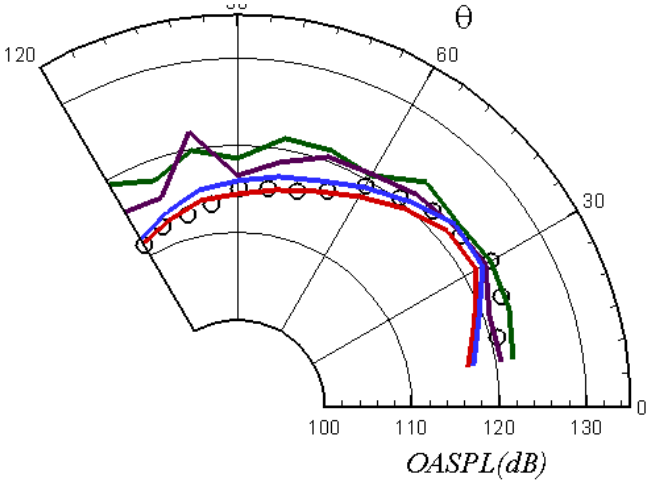
Validation - LES for real geometry jets - Cold











Validation - LES for real geometry jets – Hot (2.7) & Flight Stream (0.3)

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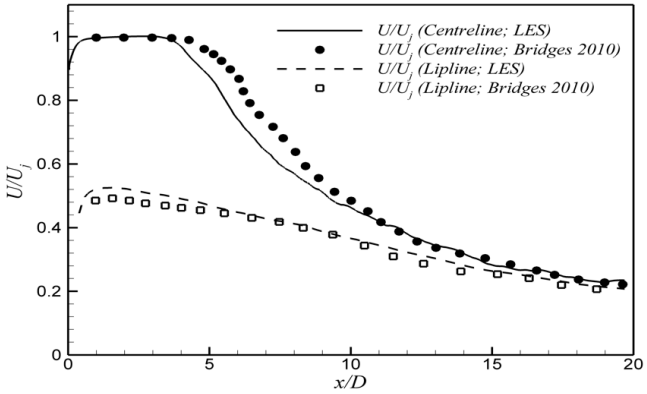

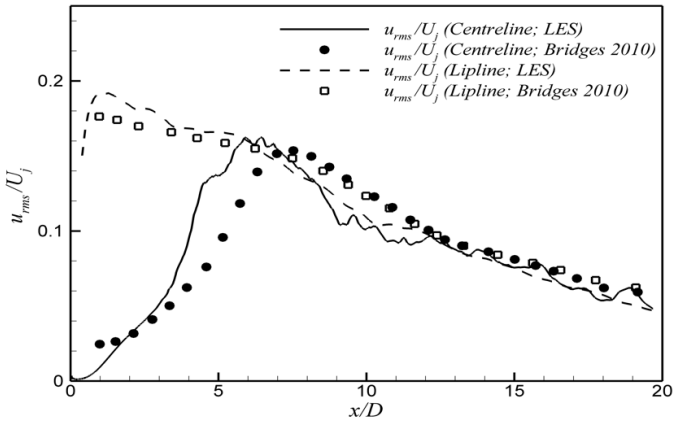

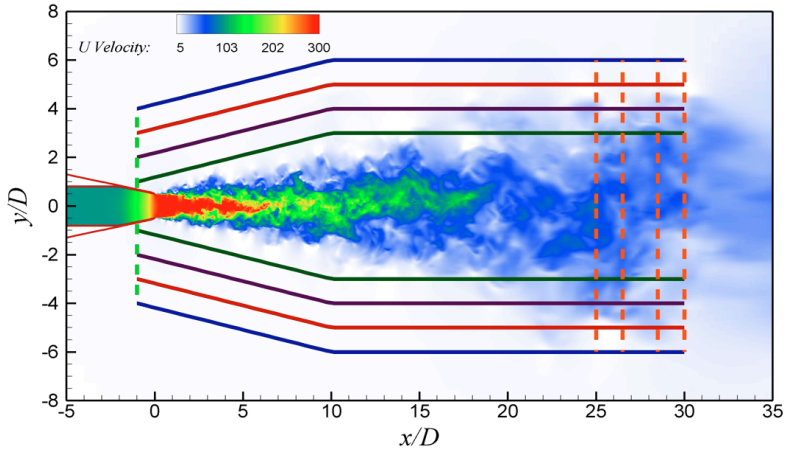

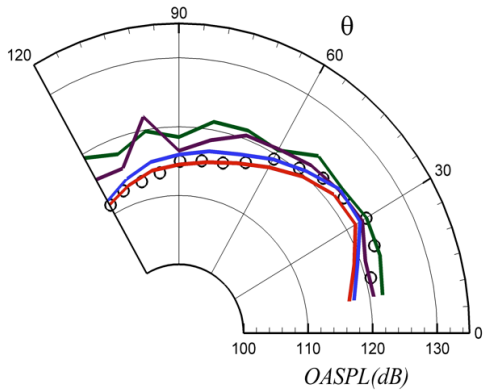

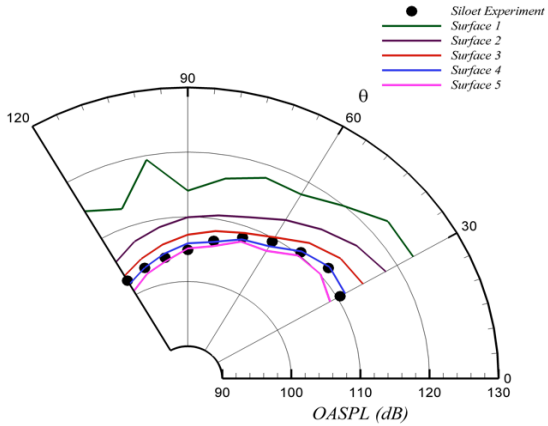

LES of Cold WARJEN Nozzle - Re = 3 x 10^5

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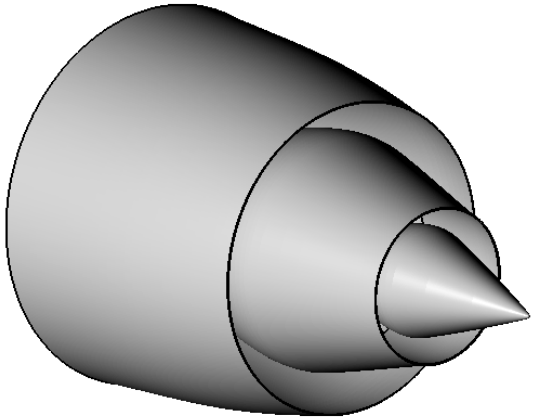

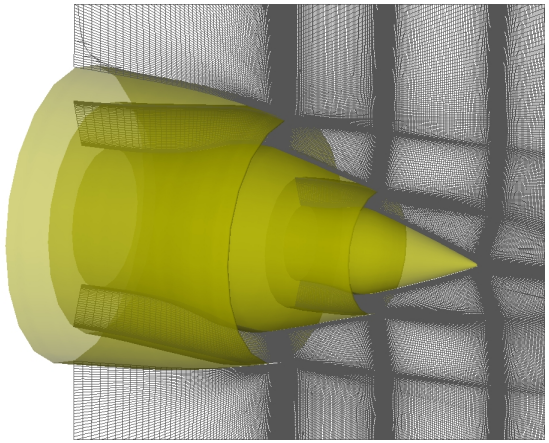

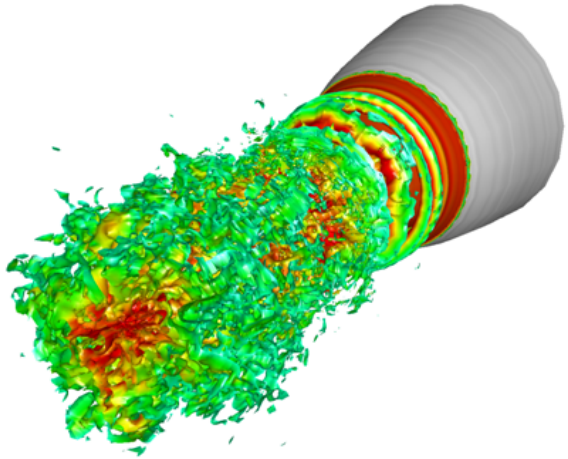

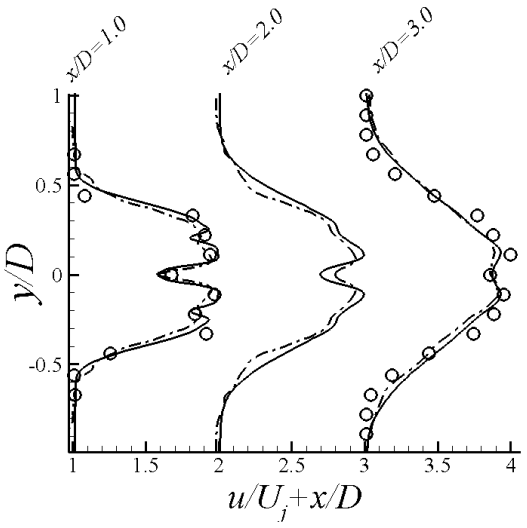

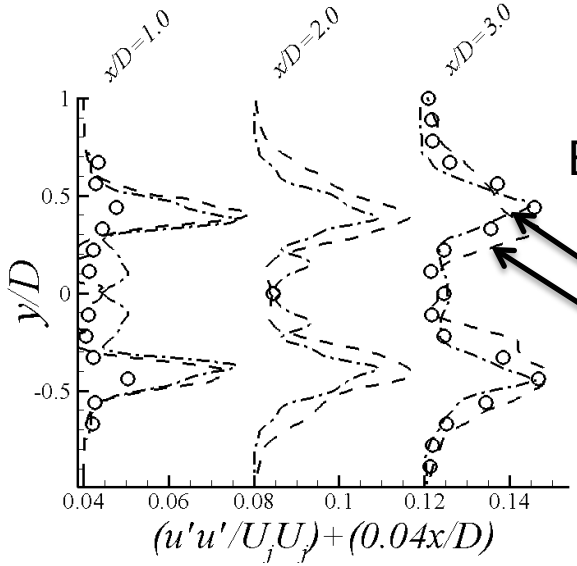

Eastwood et al. 2010 AIAA J.

5 million cells
50 million cells

HOT COJEN/JET LES

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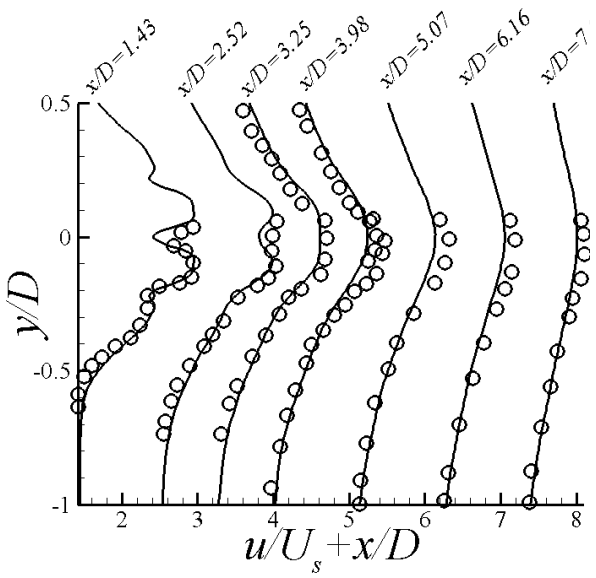
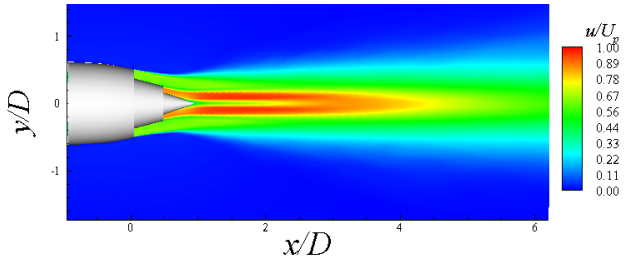
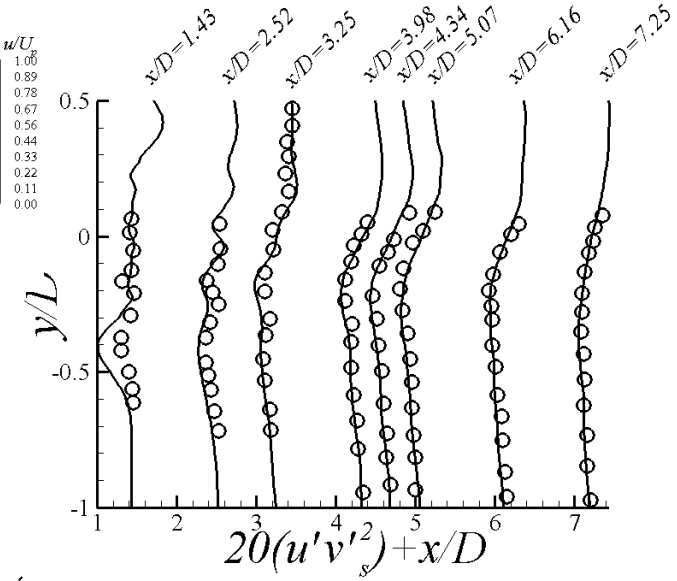
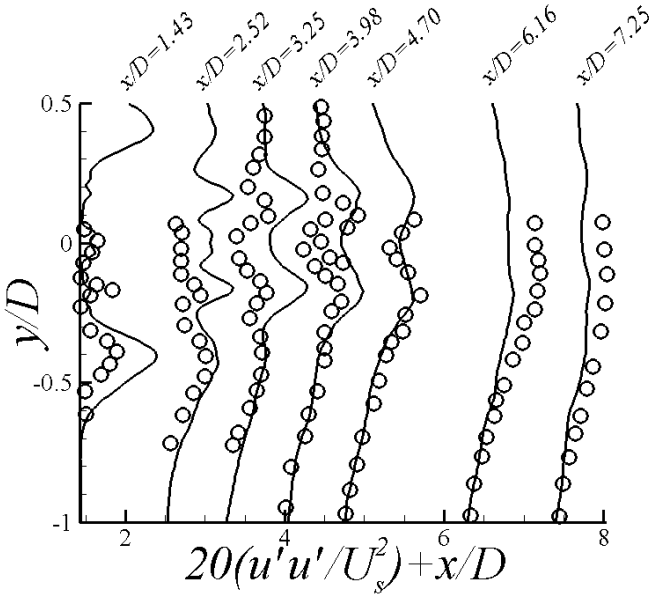




Eastwood et al.
AIAA J. of Propulsion and Power
2012 - Invited





Chevron Nozzle

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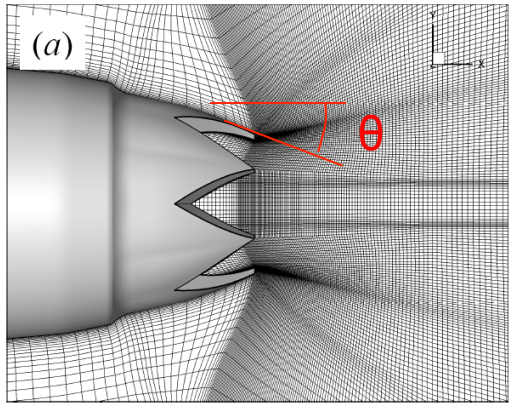

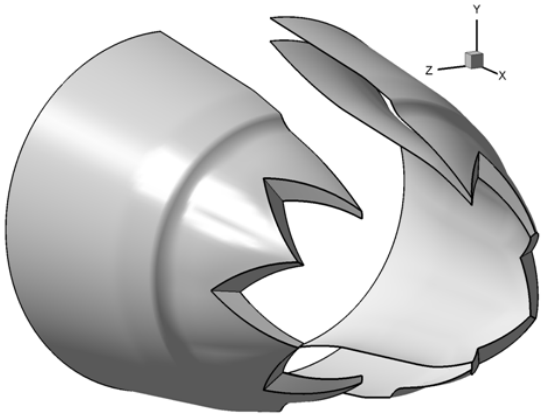

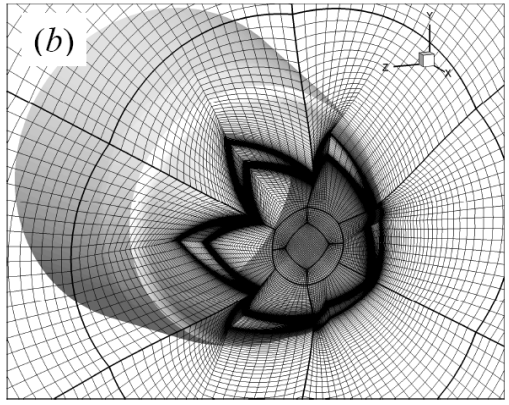

N = 12-20 x 10^6 , Re = 1 x 10^6

Validation

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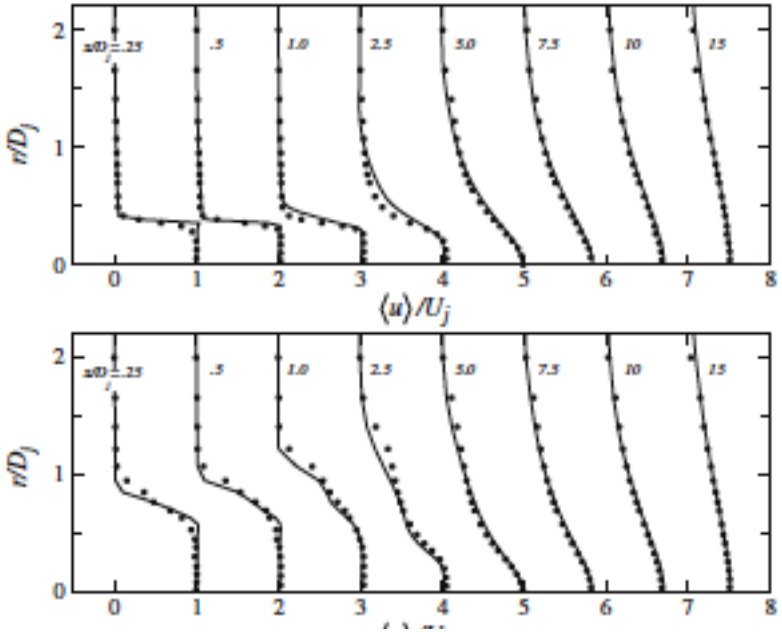

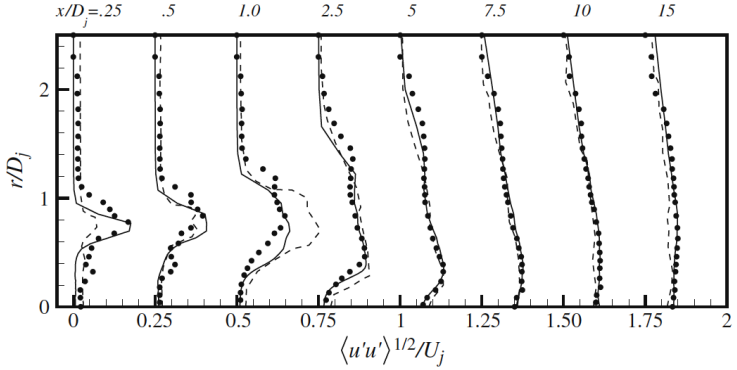

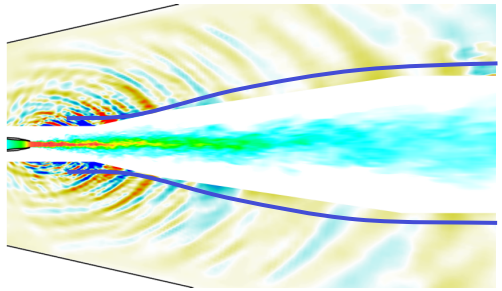

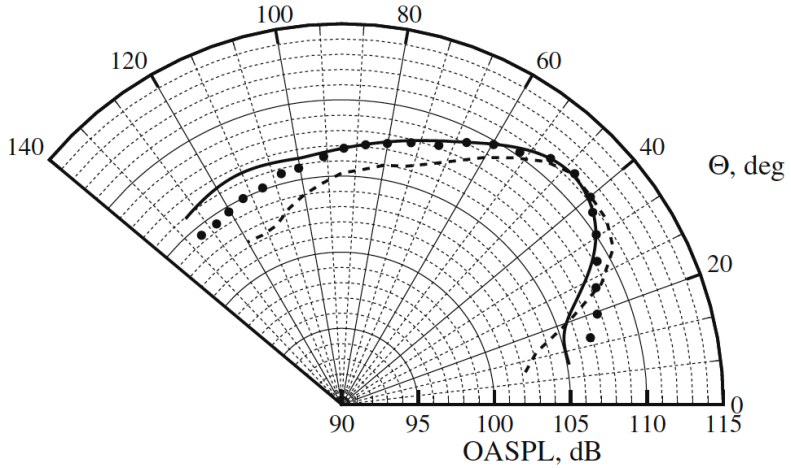

Validation

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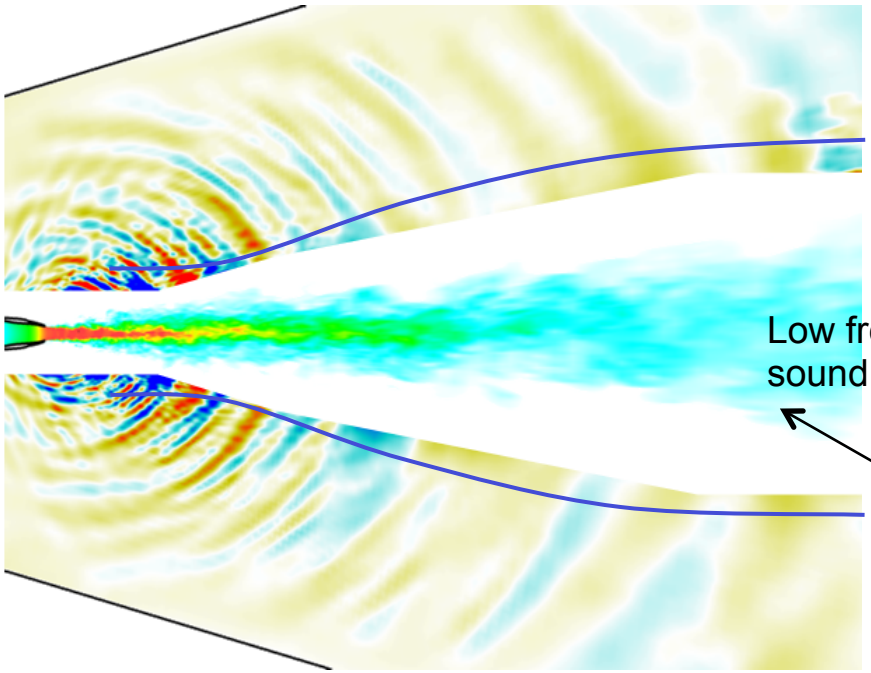
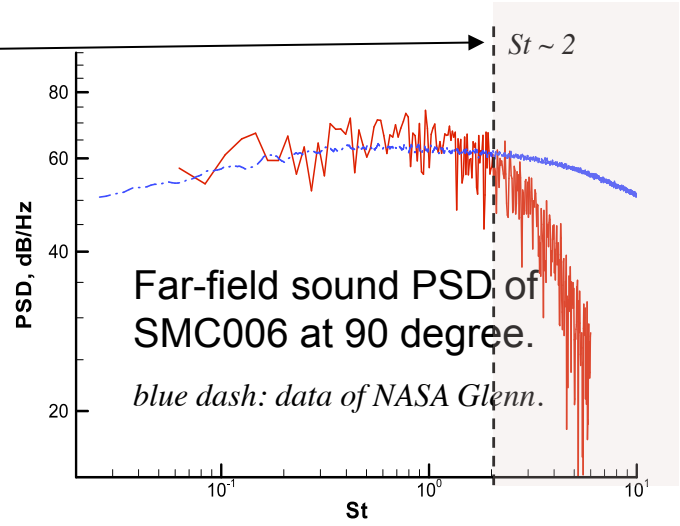
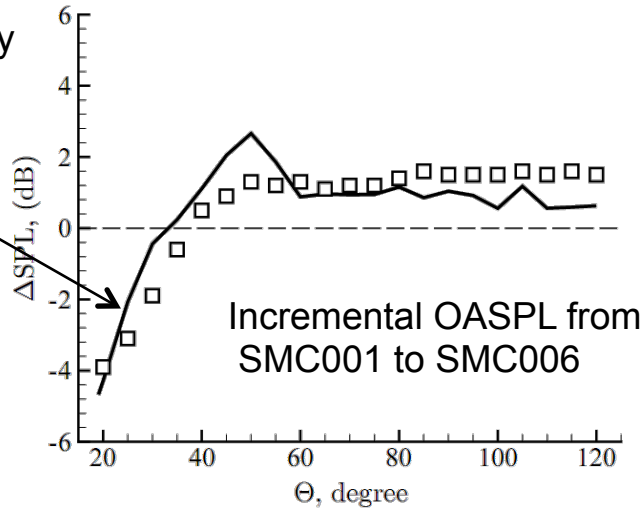
Assume 4 nodes can resolve a wave accurately



Near field sound pressure dilatation, p'



Low frequency sound drop



Flow Physics

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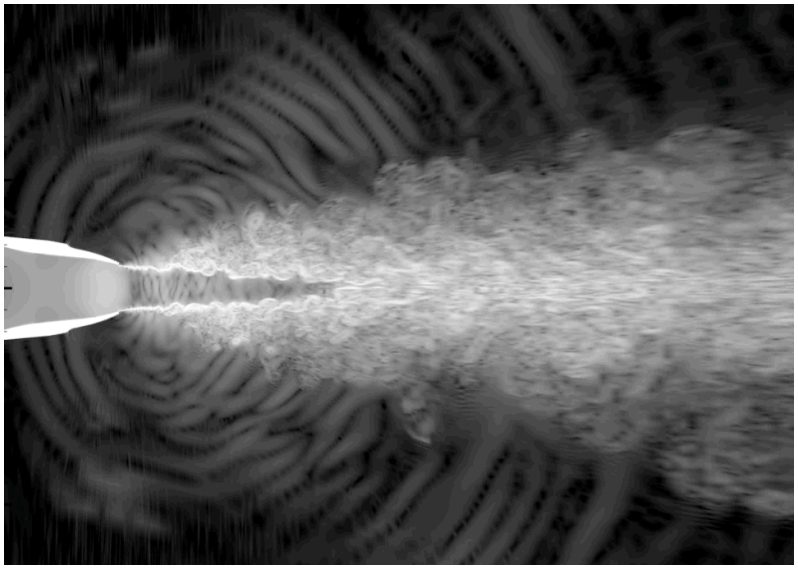

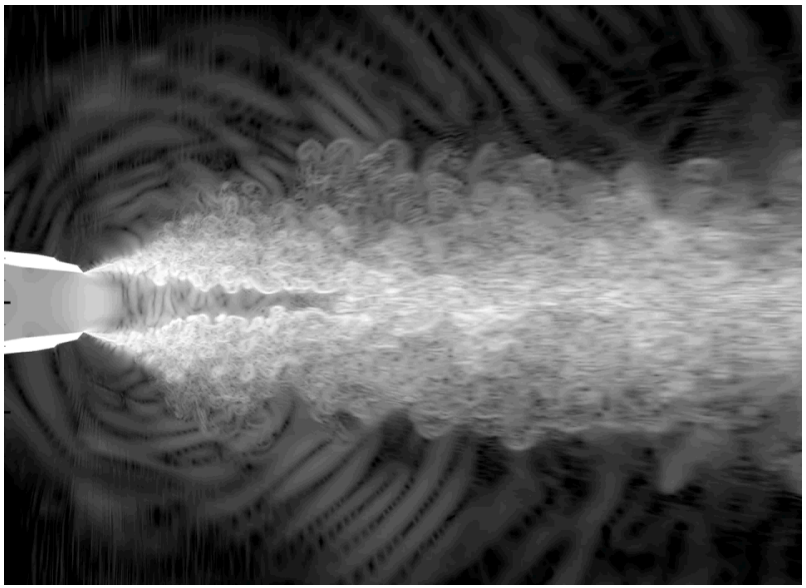

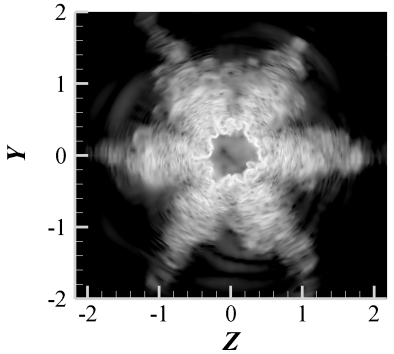

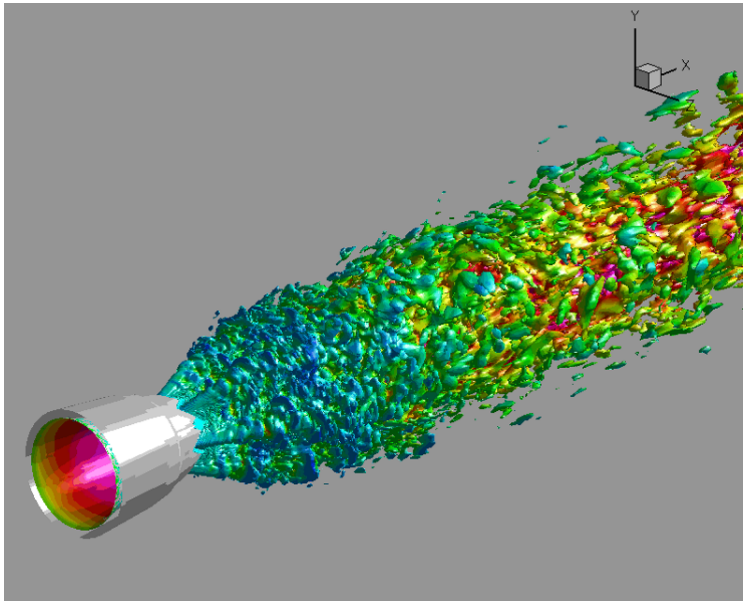

Vorticity iso-surface coloured by streamwise velocity magnitude.

LES Uses

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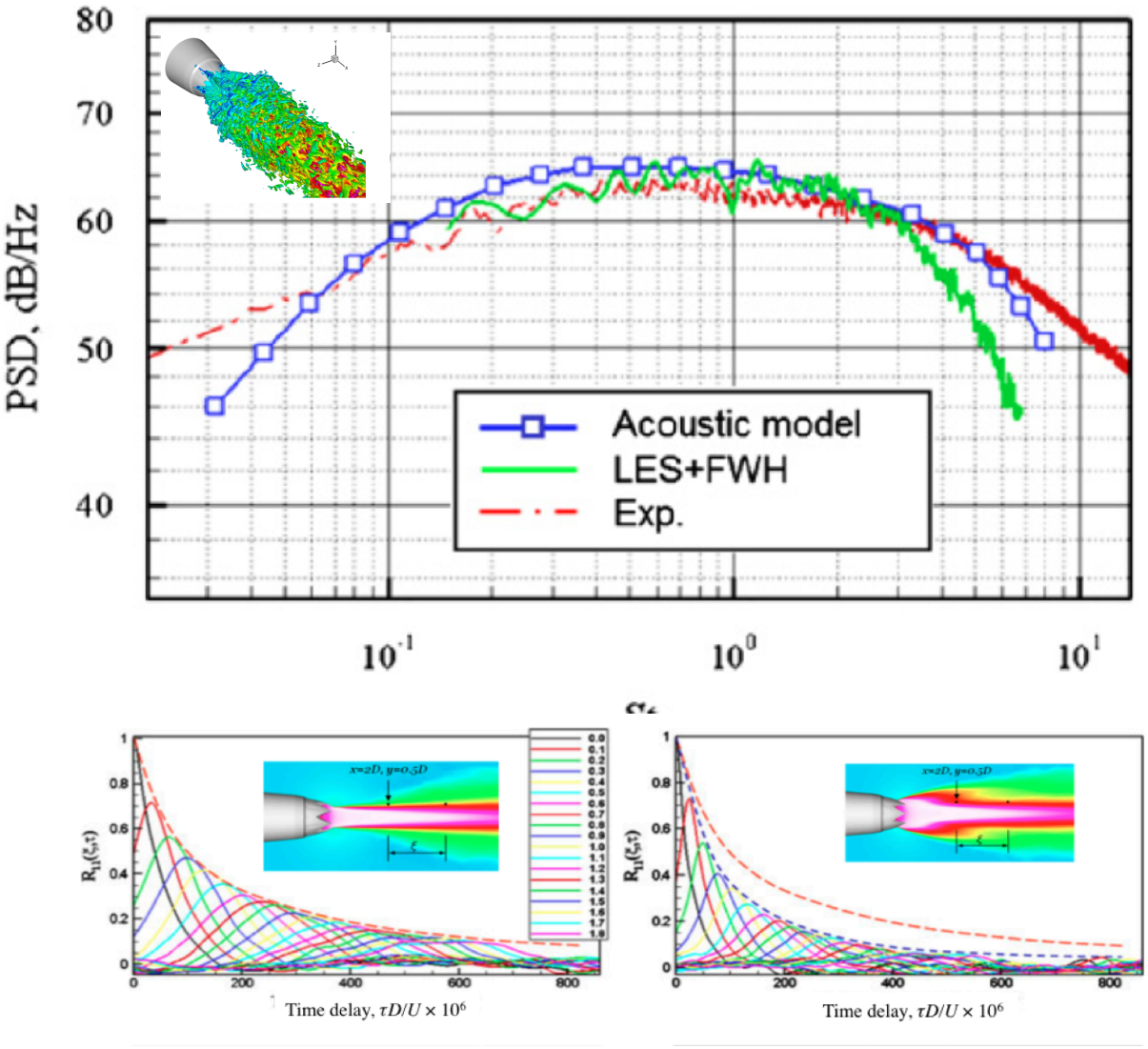
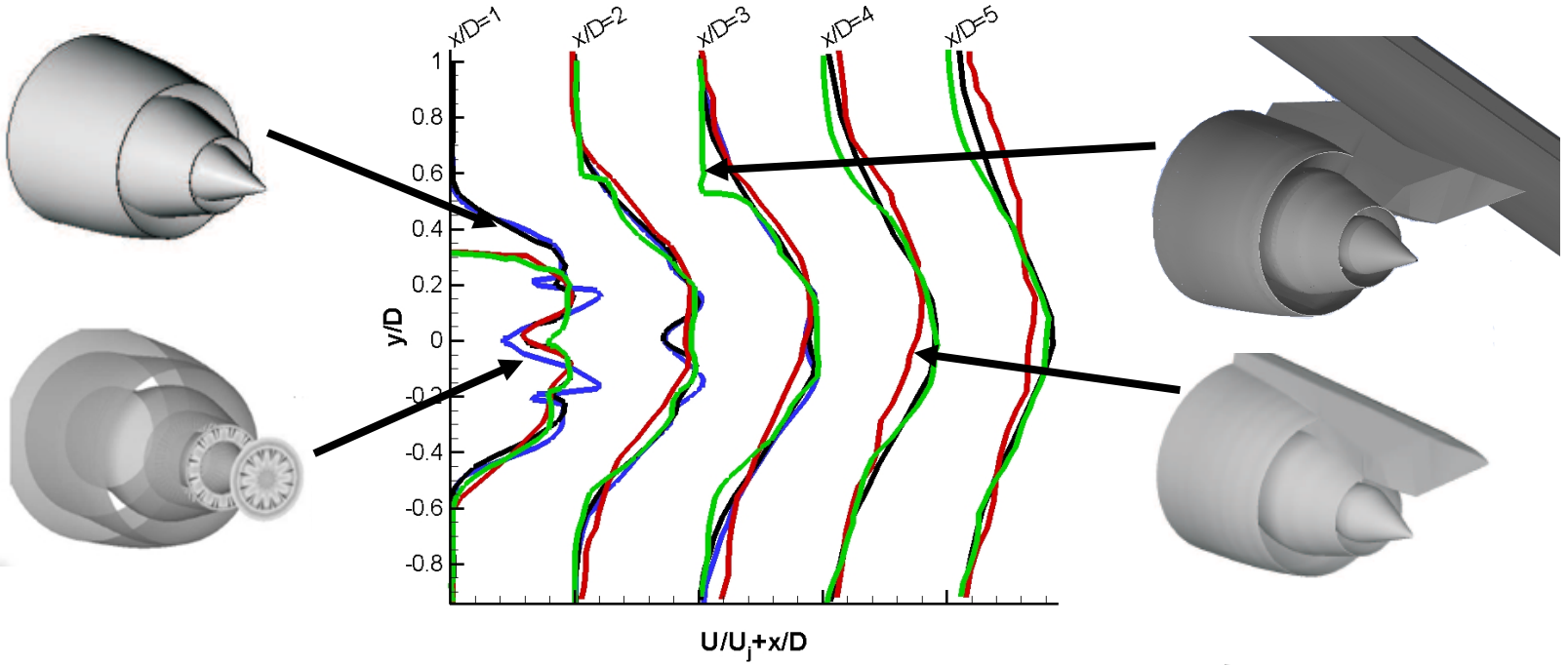
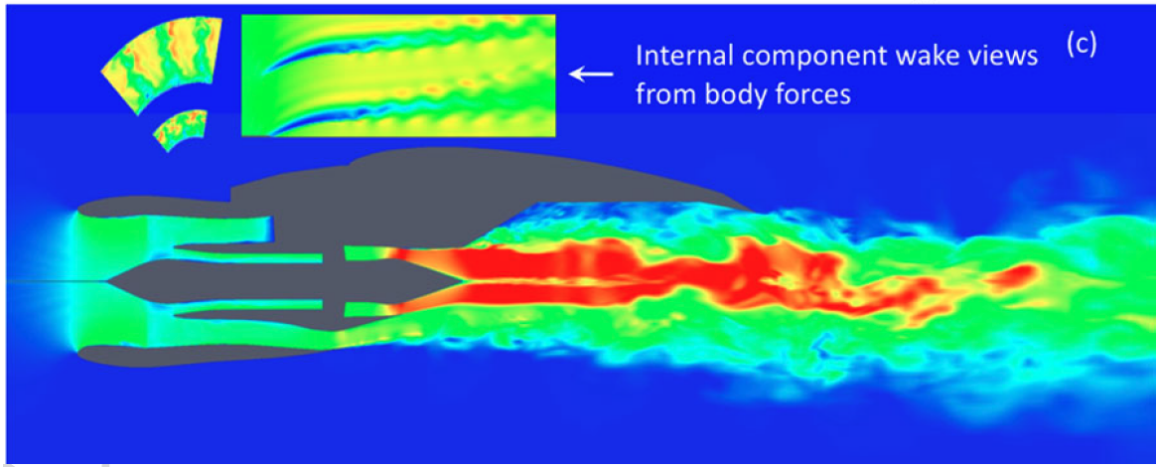
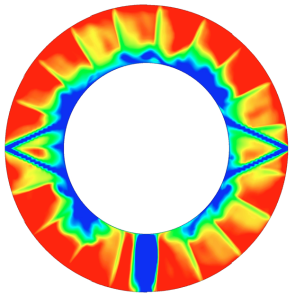


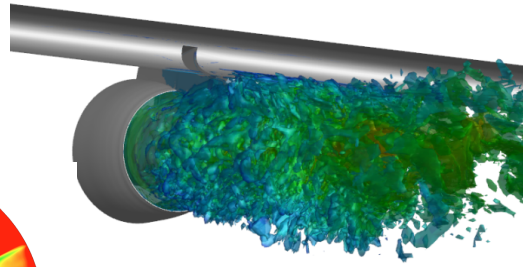
Depuru Mohan et al.
18th AIAA/CEAS Aeroacoustics Conference

Uses - LES for real geometry jets









LES costs

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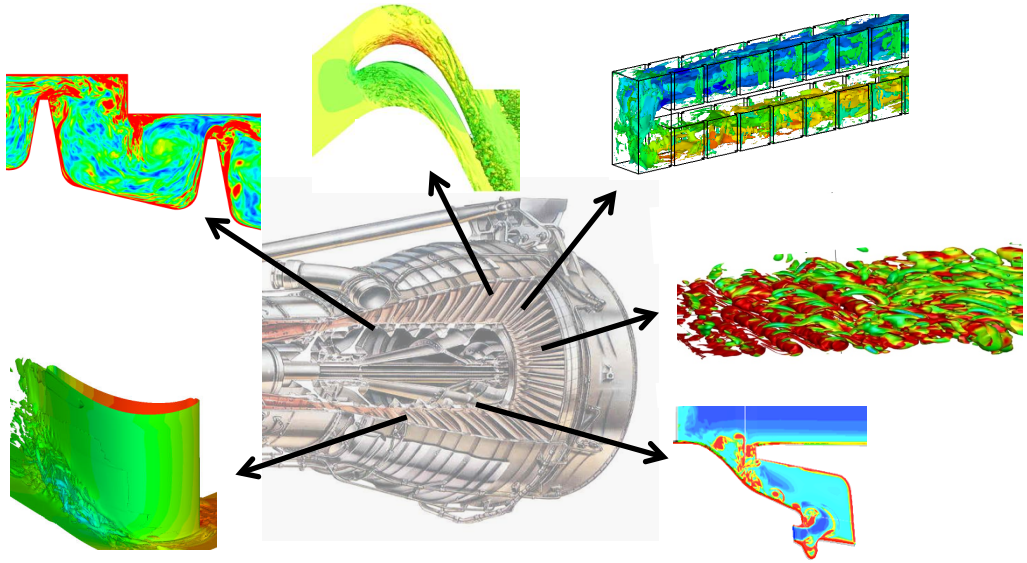


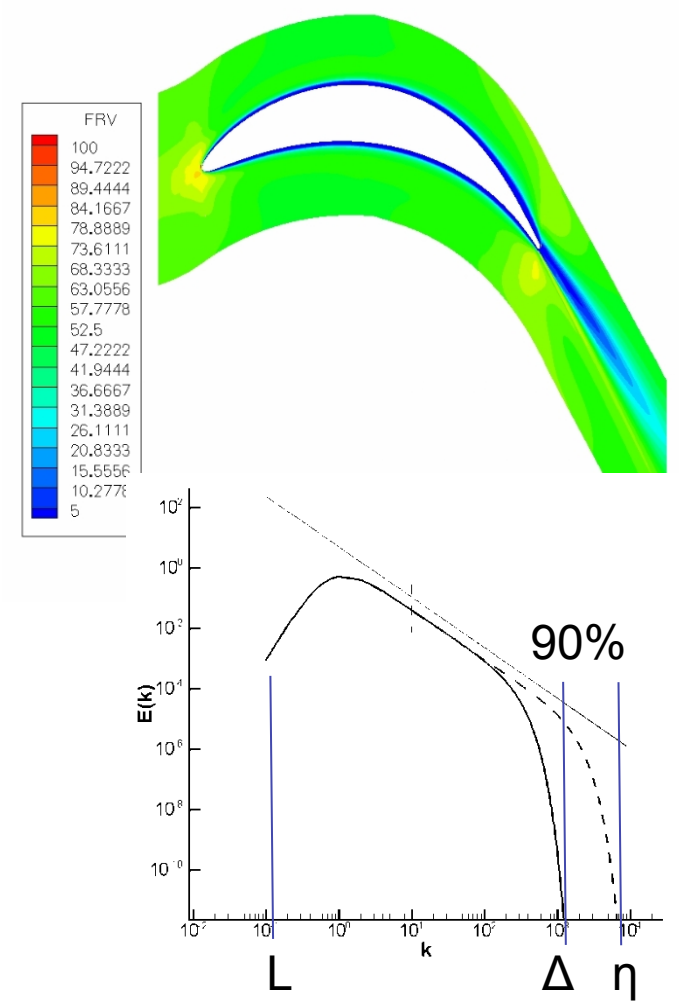
- 500 CPU cores

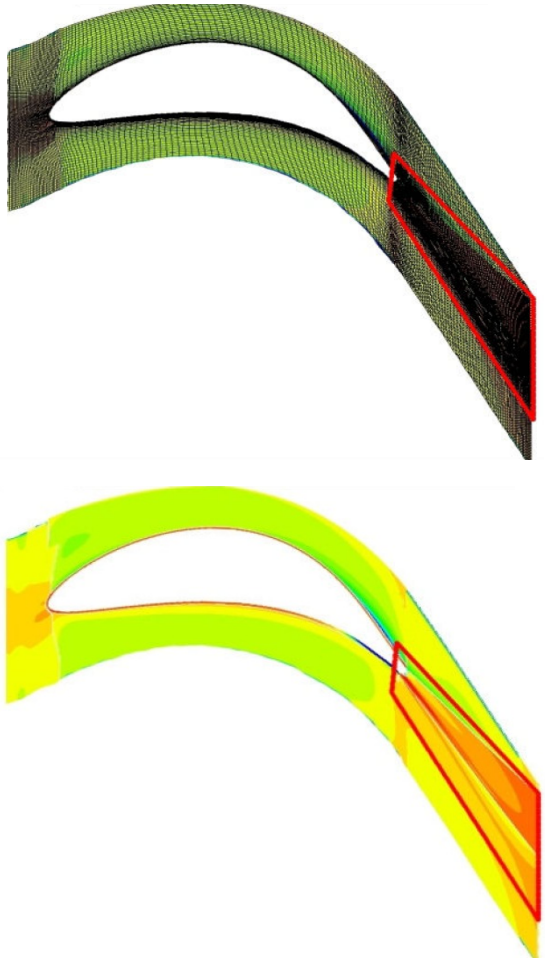
  (Modest cluster)

- Mean quantities ~ half runtime
- GPU 1/10th cost CPU
- Lab seal rotor cost >15-20k

	Flow type	LES cost using CPUs for turbulence and HT data
Ribbed ducts, CBTEs	A: Wake	<1.25k (<1 week)
Jets	A/C: Wake+high *Re* BL	<3k (<1.3 weeks)
LPT	B: Low *Re*, Highly complex, incoming wakes	<4.25k (2 weeks)
Lab seals, cavities	A/C: Wake+high *Re* BL	<3.75k (1 week)

Using RANS to inform grid generation





Process Elements – Tentative Ideas

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Import geometry

Classify flow (A/B/C)

Select approach (LES/Hybrid)

Estimate grid size

Identify inlet conditions + method

Estimate impact / ease

Run RANS (grid guidance)

Develop flow using coarse LES

Refine grid

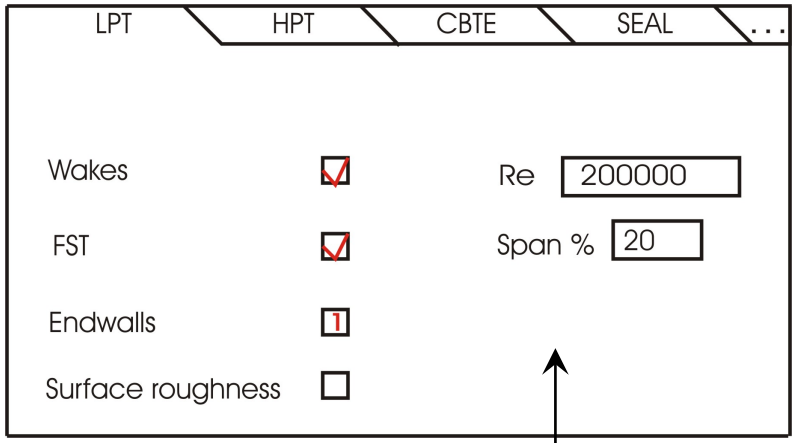
Interpolate to fine grid

Analyse solution

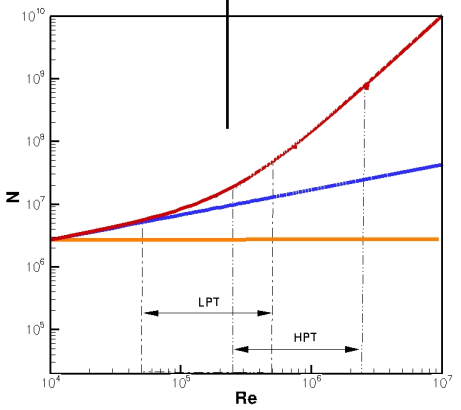
Is LES feasible ?

No

Stop



Integrated mesh generation by templates + semi-automated refinement



Numerical Scheme/Grid Impact

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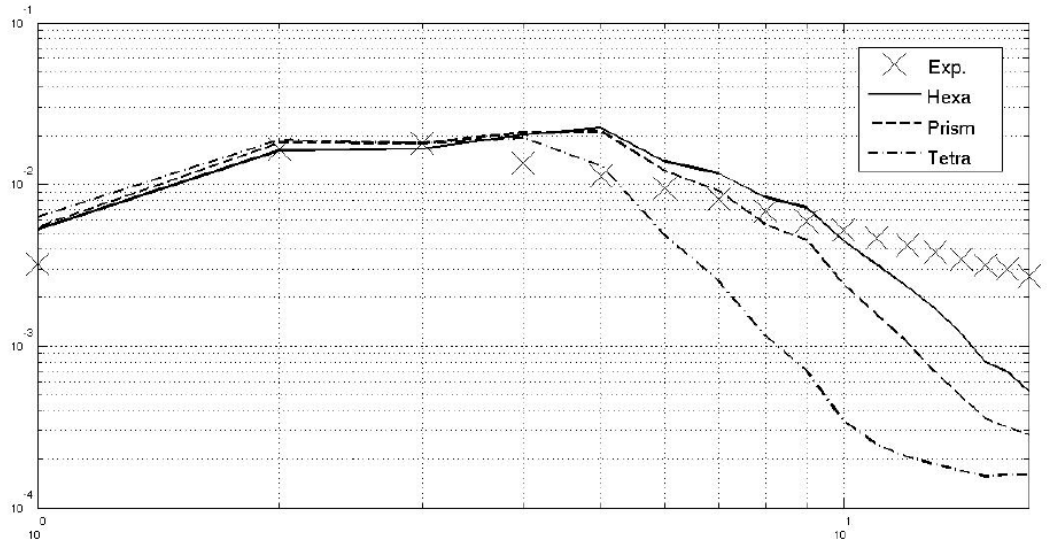

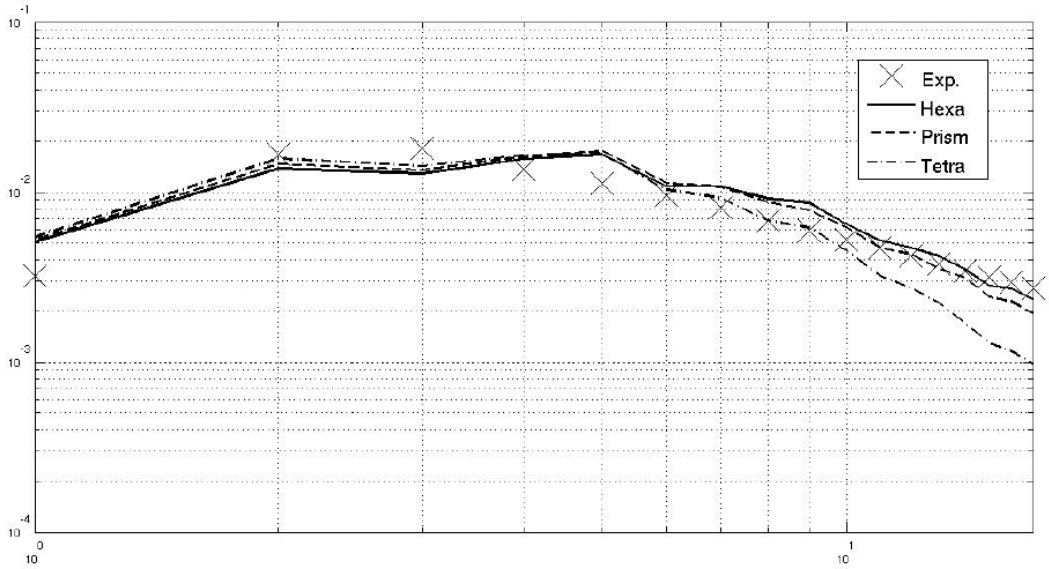

Real Inflow

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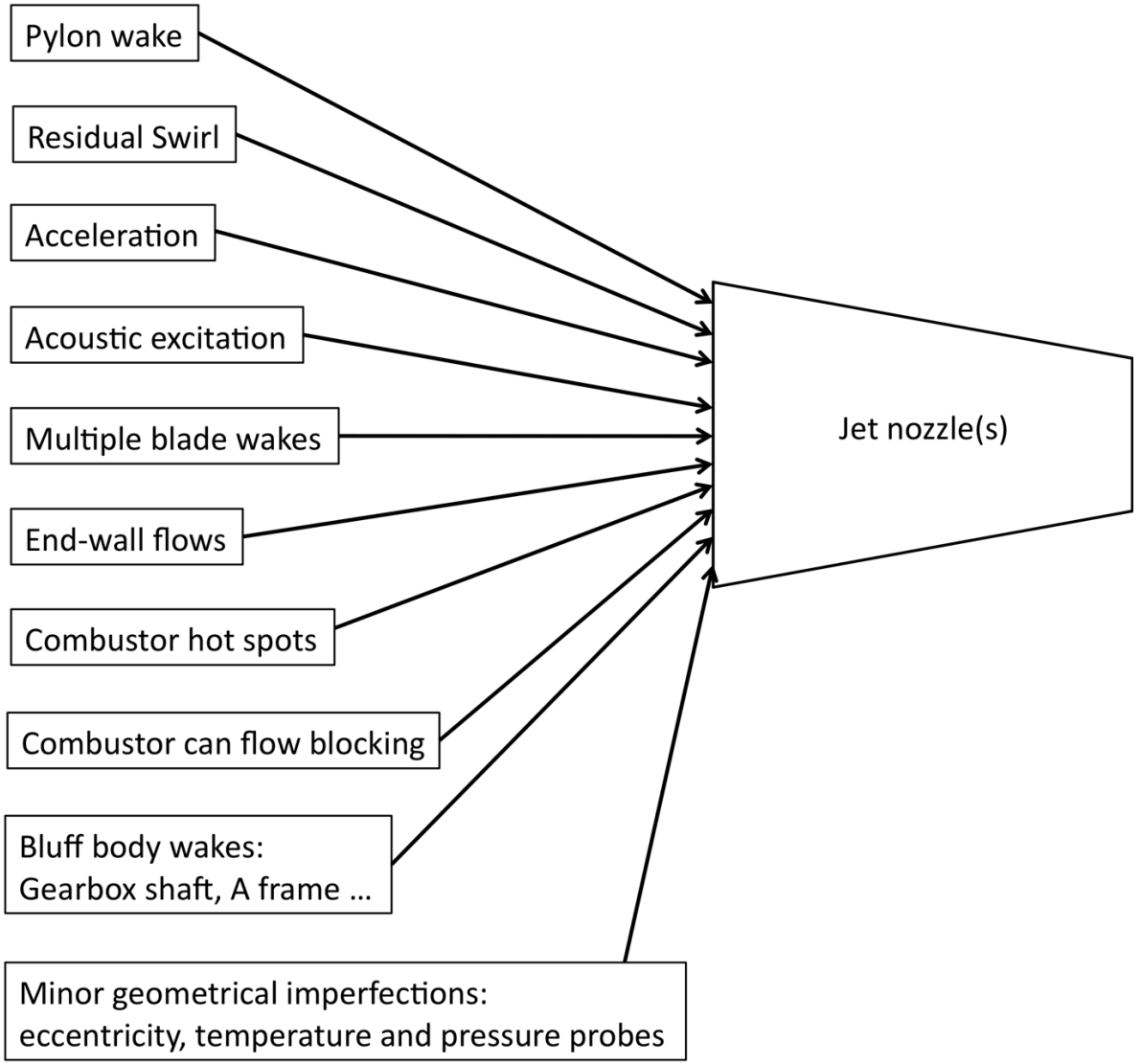

Dirty Inflow

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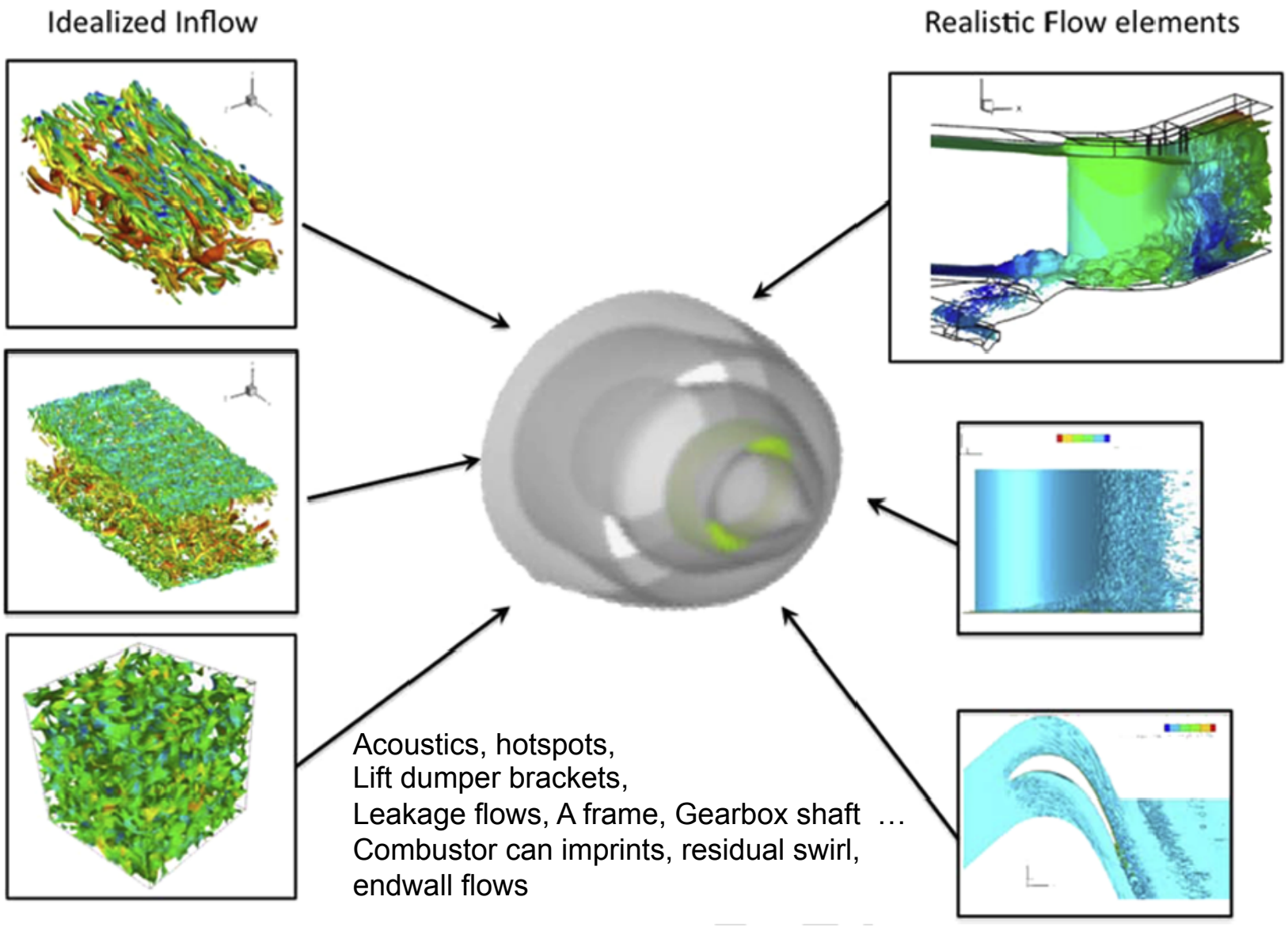

Conclusions

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- Zonalized RANS-(I)LES and (I)LES will increasingly take over
- Flow classification → Expert system
- See greater use in RANS + lower order model calibration/ development
- LES still needs physical insight by analysts but much less than RANS → best practices: easier within a confined application
- Perhaps expand ideas on inflow?

Acknowledgements

Thanks to the research team members who generated the results shown:
James Tyacke, Richard Jefferson-Loveday, Iftekhar Navaqi, Vadlamani Nagabhushana
Jiahuan Cui, Mahak Mahak; Xiaoyu Yang and Rob Watson

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