Multi-scale Method Development for Turbine Heat Transfer and Aerodynamics

(MUSAF II, Toulouse, Sept 18-20, 2013)

L. He

Rolls-Royce/Royal Academy of Engineering Professor

of Computational Aerothermal Engineering,

Department of Engineering Science, Oxford University

OUTLINE

- Background Problem Statement

  - ***scale disparities*** *in turbine aero-thermal problems*

- Unsteady Conjugate Heat Transfer ***(in time)***

  - *fluid-solid interfacing (for periodic unsteadiness & LES)*

- 'Block-spectral' Method ***(in space)***

  - *resolving micro scales (film cooling, surface roughness)*

High Pressure Turbine - *'Core of the Heart'*

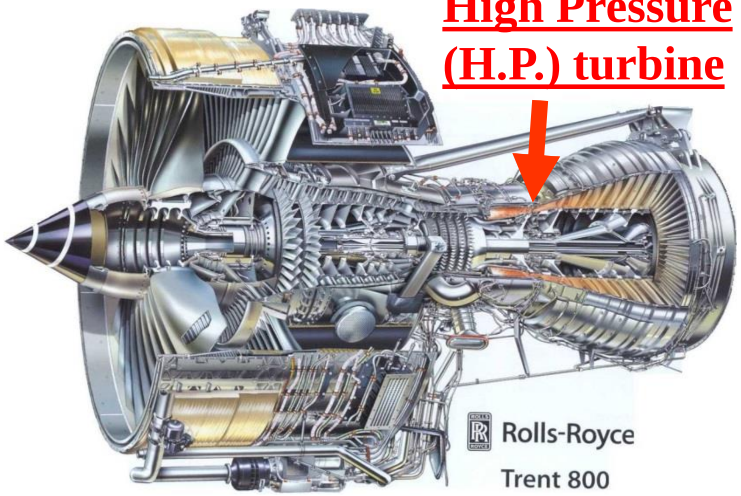
UNIVERSITY OF OXFORD

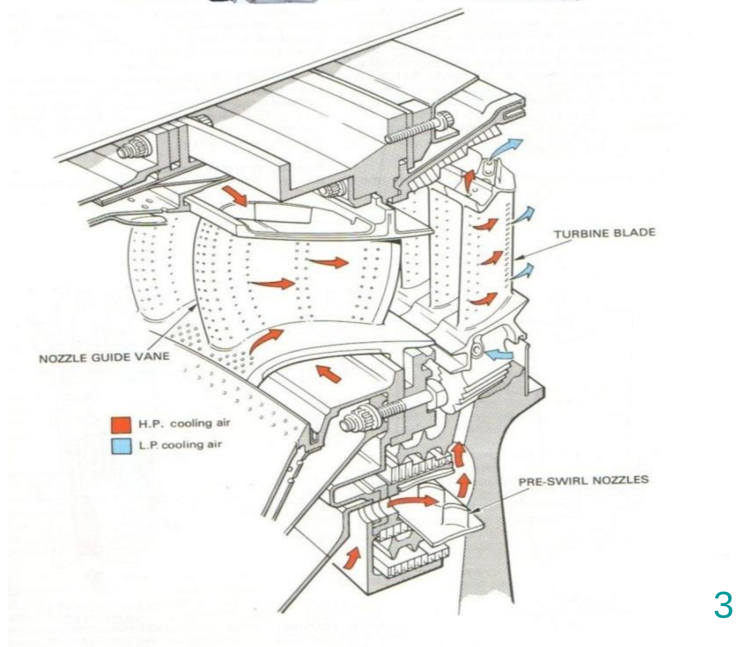
- **High Pressure, High Speed**
  - *- Pressure ratio ~ 40+*
  - *- HP Turbine shaft ~ 10,000 RPM*
  - *- Transonic flow (Mach No >1)*

- **High Temperature**
  - *- high gas temperature (1800°K+),*
    (for high efficiency & work output)
  - *- Blade metal melts at 1200°K!*

- **Multi-scales** *(in time & space)*
  Fluid – fast convection
  Solid – slow conduction (t_S / t_F ~ 10^3)

  Main flow path – blade chord C
  Cooling holes ~ 10^{-2} *C*

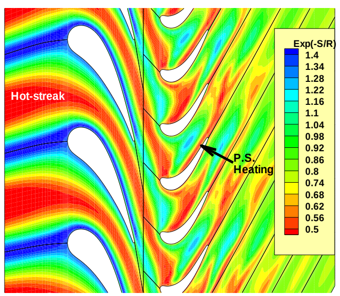




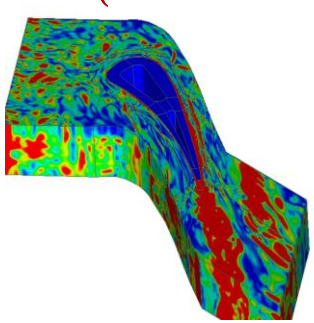
Timescale Disparity in Aero-Heat Transfer Interaction

(wall condition for the energy equation if non-adiabatic ?)

HP turbine with combustor exit hot streaks *(Khanal et al 2012)*



URANS *(He et al 2004)*



LES *(He 2013)*

- **For high-speed flow with high heat transfer**:

  large T & ρ variations in near-wall/wakes (i.e. work load/losses)

  ➔ **erroneous flow-only (adiabatic) solution** *(regardless of flow model fidelities!)*

- **Fluid-solid 'Conjugate Heat Transfer' (CHT)**

  - STEADY: *working with domain dependent stepping*

  - UNSTEADY: *limited by conflicting requirements*

    - *Maximum Time Step* dictated by resolving fast unsteadiness ***(fluid);***

    - *Minimum Time Scale* dictated by covering slow conduction ***(solid).***

Hybrid Time/Frequency-domain Approach:

(to 'realign' mismatched time scales)

- **Fluid:** *solved in time-domain;*

- **Solid:** *solved in frequency domain:*

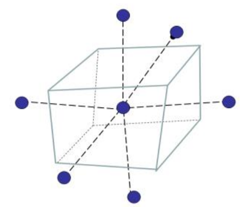
  $$T_s = T_{0s} + \Sigma\, A_s \cos(\omega t) + B_s \sin(\omega t)$$

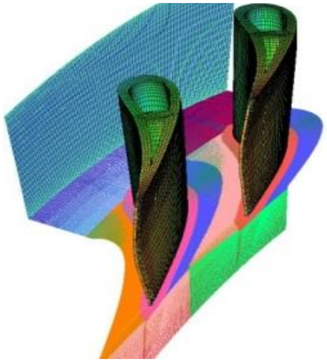
  (T_{0s} A_s , B_s are all *time-independent* ("*steady*")

• Unsteady solid domain solved in a Steady manner

Implemented in a density based solver (He 2000)

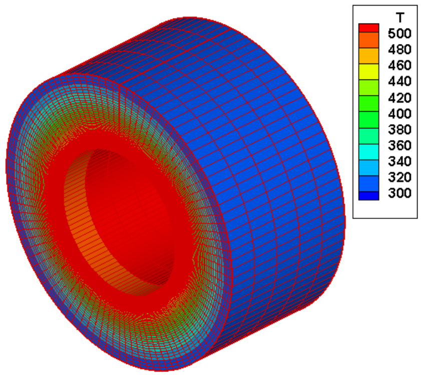
3-D Unsteady Navier-Stokes in multi-block meshed domain;
Hex cell-centred upwind (AUSM) finite volume;
4-stage Runge-Kutta time-marching;
Local time stepping & multi-grid;
Implicit dual timing for unsteady flow;

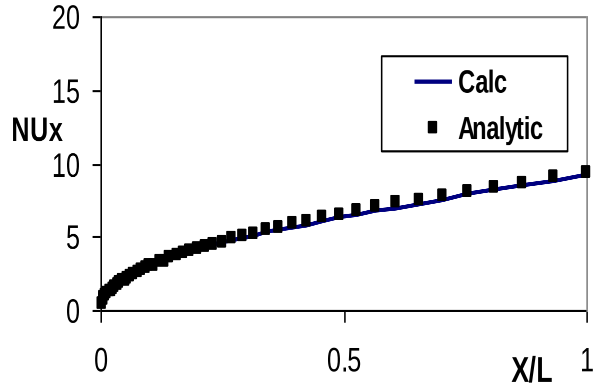


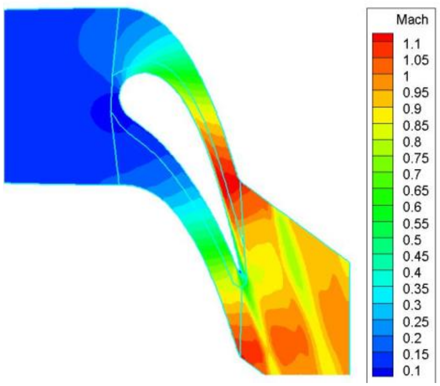


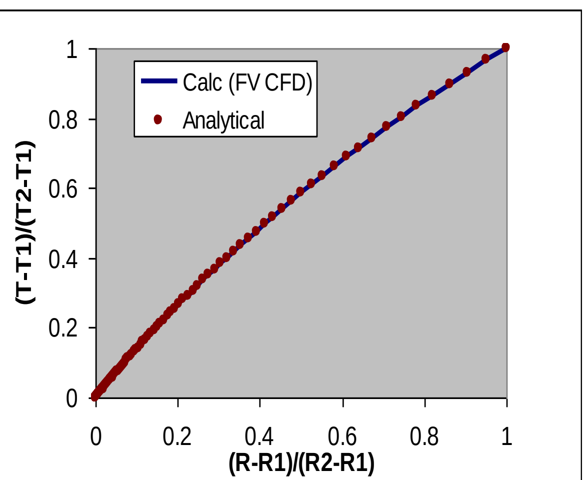
(solid domain: fluid energy equation with zero velocity)

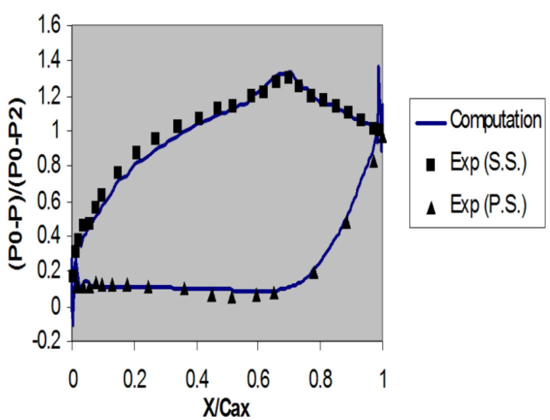
Verification of Conduction and Convection Solution Capabilities of CFD solver

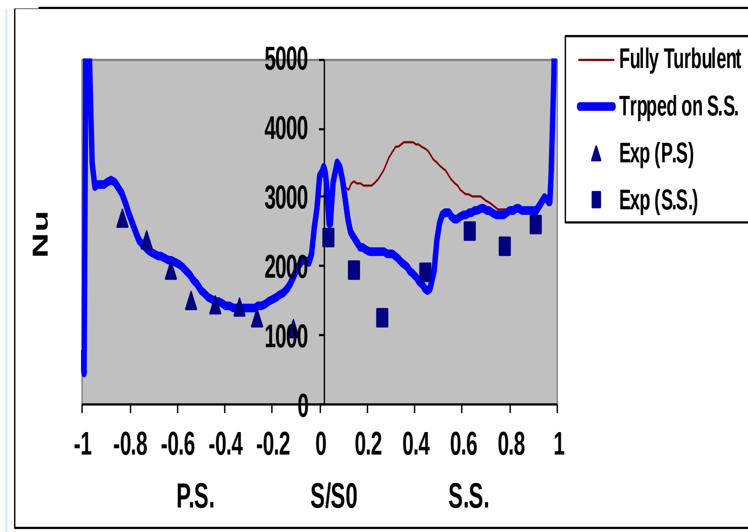












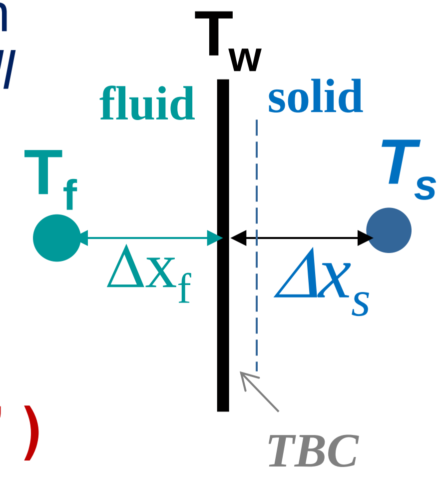
Conduction Solution

Blade Surface HTC

Semi-Analytical Unsteady Interface Method

(He and Oldfield, 2009)

- **Basic assumption**: locally 1D semi-infinite solid domain *(valid for high frequencies with small 'penetration depth' in solid)*



- **Analytical link in harmonics**
  between heat flux (q_w) and temperature (T_w):

$$\hat{q}_w = TF_{Tq}\,\hat{T}_w$$

(TF_{Tq} – "transfer function")

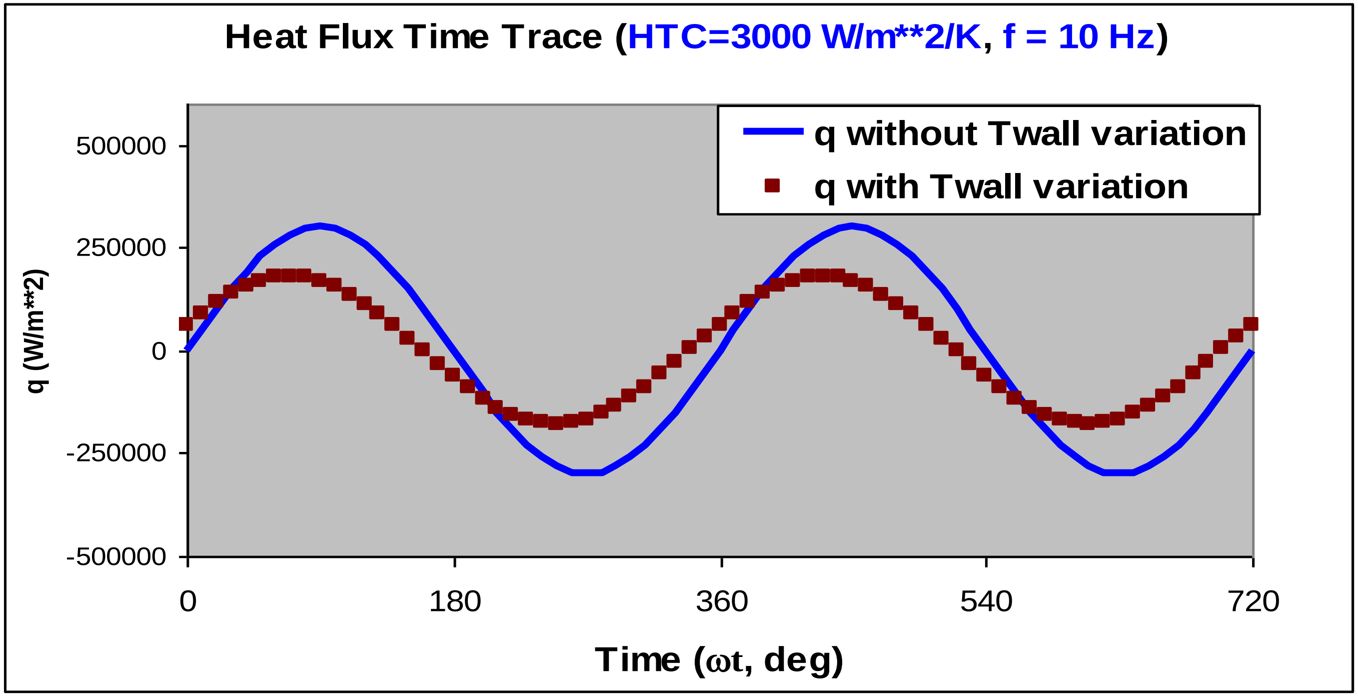
- **Harmonic Balancing** *(heat flux / temperature continuity):*

$$(\hat{q}_F)_n = (\hat{q}_S)_n \qquad (n = 0,1,2, \ldots\ldots N_h)$$

- **Discrete for fluid side (FD) & Analytical for solid side**:

$$(\hat{T}_w)_n = \mathrm{f}[(\hat{T}_f)_n,\ (TF_{Tq})_n] \qquad (n = 0,1,2, \ldots\ldots N_h)$$

Impact of Unsteady Surface Temperature on Heat-flux Prediction *(single harmonic)*



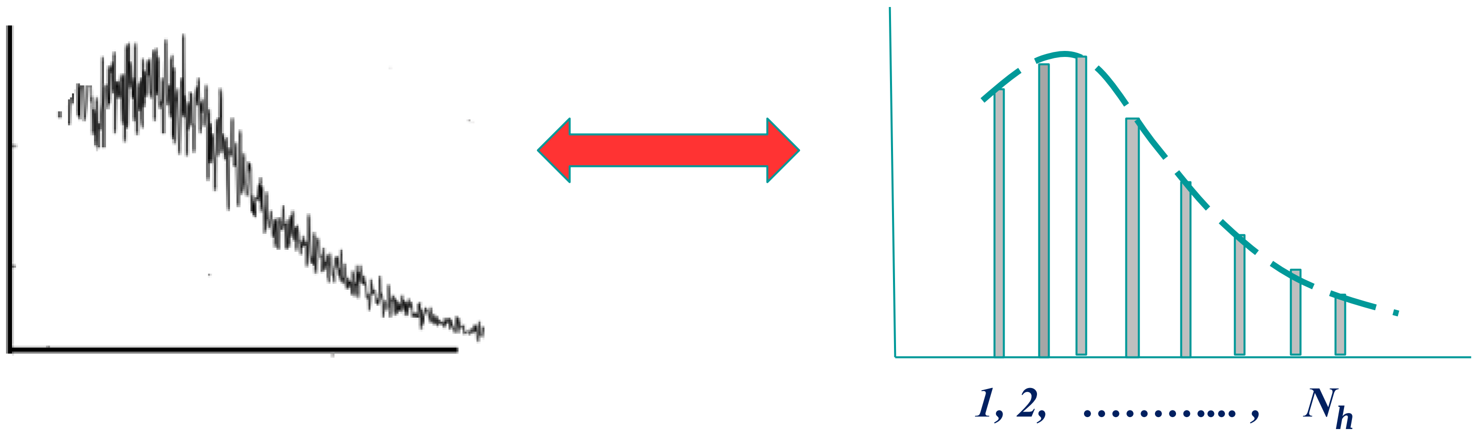
At 10 Hz , ~33% over-prediction in unsteady heat flux

At 100 Hz, ~18% over-prediction

At 1000 Hz, ~6% over-prediction

Conjugate Heat Transfer with LES

Basic Hypothesis: Turbulence at a spatial point '*deterministically*' manifested by the corresponding Fourier spectrum



Tu Intensity: analogue of 'Deterministic Stress' for N_h harmonics

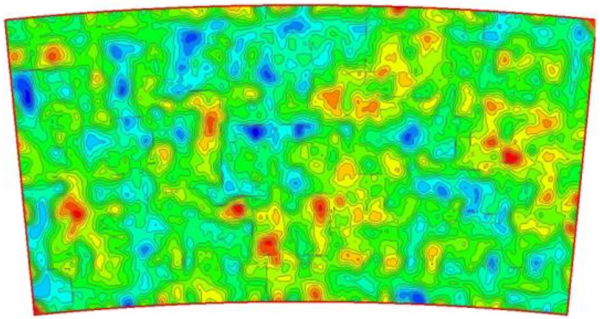
$$(\overline{u'u'}) = \frac{1}{2}\sum_{n=1}^{N_h}[(\hat{u}_n)_r(\hat{u}_n)_r + (\hat{u}_n)_i(\hat{u}_n)_i]$$

Tu Length-scale: Shape of the spectrum

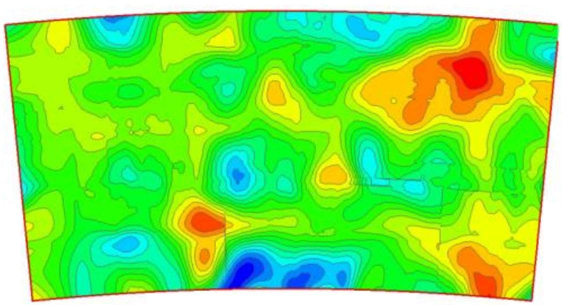
- ***FT on the fly*** ➔ **input to the semi-analytical interface condition**

Inflow Turbulence Fluctuations

(Synthetically Randomised Vortices)

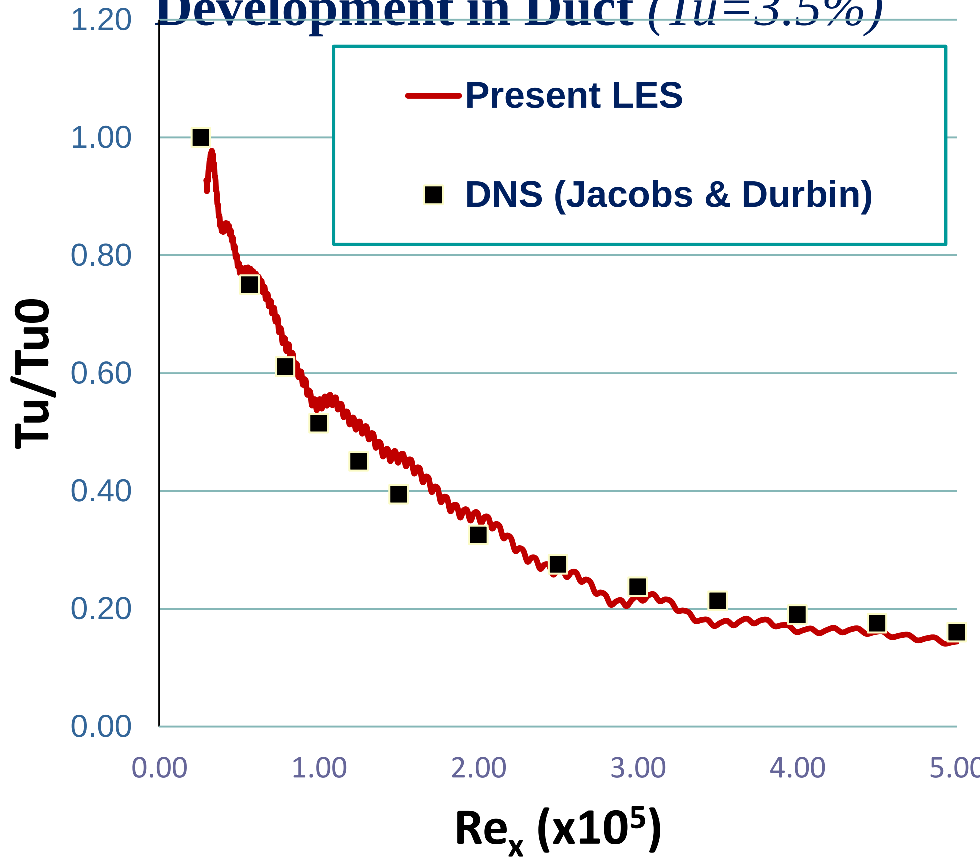


Short scale



Long scale

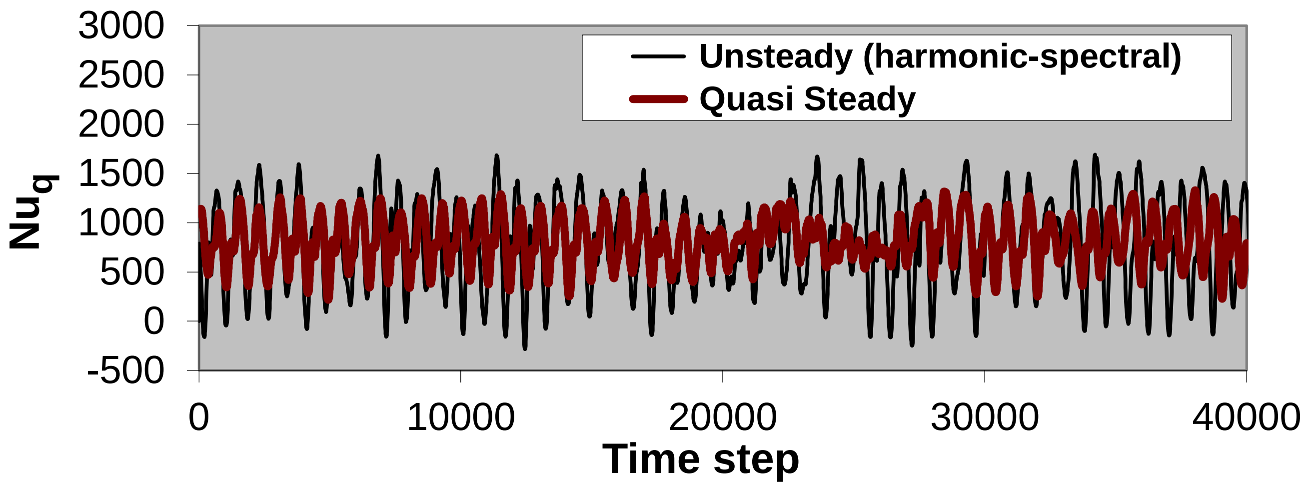
Validation for Inflow Turbulence Development in Duct *(Tu=3.5%)*

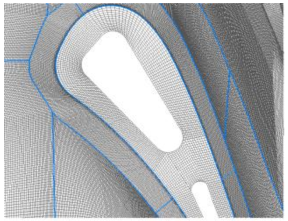


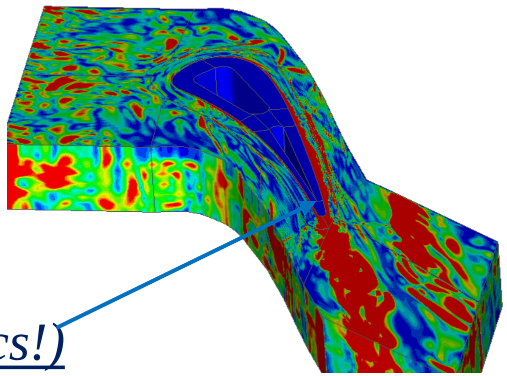
LES Conjugate Heat Transfer

(Aerothermal Characteristics, Internal Cooled Nozzle, 30 Fourier modes)

Heat Flux *(Quasi-steady vs Unsteady Wall BC)*

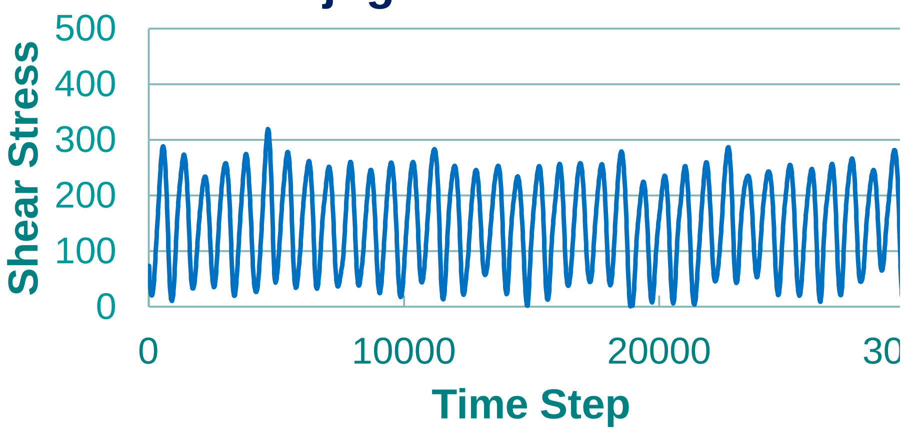




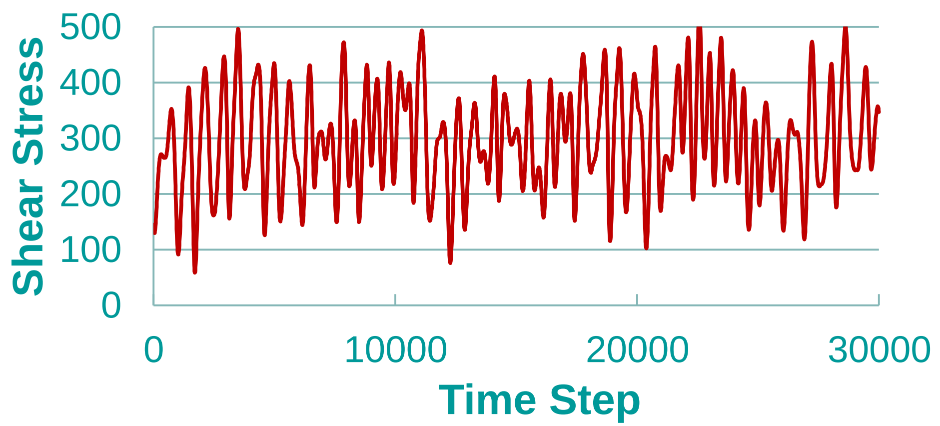


Shear Stress *(Influence of Heat Transfer on Aerodynamics!)*

Conjugate HT LES



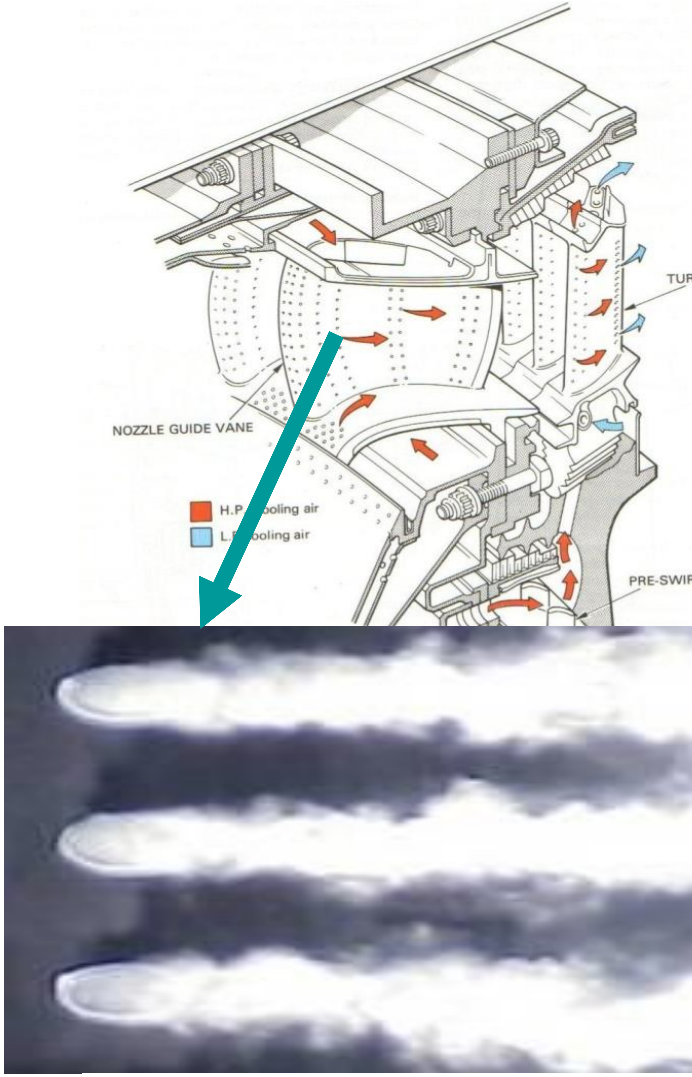
Adiabatic LES



Spatial Length-scale Disparity in Film-Cooling etc

- ***Macro:***
  Blade Chord (passage P & Vel field)
- ***Micro:***
  Film cooling hole (< 1%C),
  (mixing of coolant with mainstream)
- ***Compounding Challenge:***
  Large number of cooling holes
  (~10^{2+})

➔ ***Direct solutions with all holes resolved are prohibitively costly!***



(Oldfield, 2007)

Scale-dependent Solvability

Macro & Micro scales exist in many problems:

- Film/effusion cooling: *Cooling hole vs Blade*
- Surface treatment/roughness: *Dimple* vs *Blade*

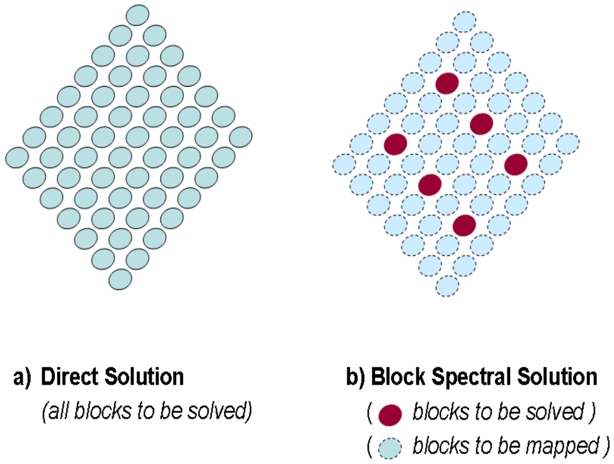
Scale-Dependent Solvability Behaviour

- Locally: micro scales of high gradient *(needing high resolution)*
- Globally: smooth variation among 'similar' meso-structures

'Block-Spectral' Model *(He 2010)*

- *Resolve micro scales (RANS /LES);*
- *Avoid solving large domain with very fine mesh.*

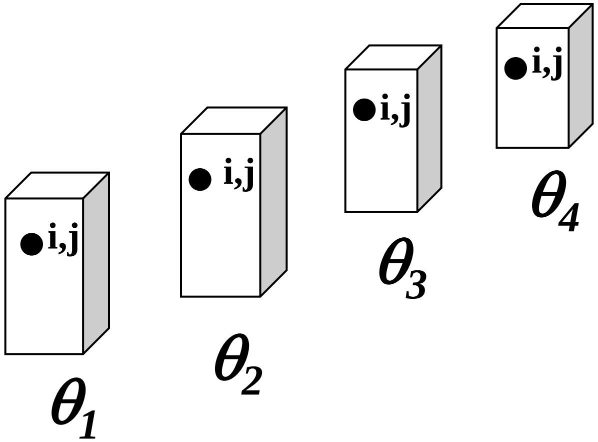
- *Set up spectral block-block variations (pointwise)*
- *Simultaneous 'mapping' to the full domain;*



Pointwise Spectrum for Block Boundary Points

- Main (macro) stream only 'sees' small (micro) blocks through boundary faces

- For each boundary point **(i, j),**
  variable changes from block to block
  (1-D variation wrt block index).



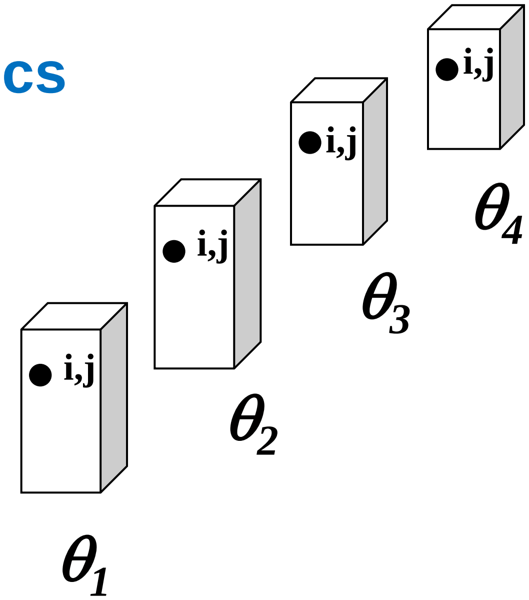
For N_B blocks:

$$U_{i,j}(\theta) = (U_{i,j})_0 + \sum_{1}^{N_B} F_{i,j} G(\theta)$$

For a given basis function $G(\theta)$, only need to solve enough blocks to determine the coefficients $F_{i,j}$

Pointwise Fourier Spectrum
(periodic, or “mirroring”/padding for non-periodic)

- **Fourier Shape of variation with N_F harmonics for each mesh point (i,j) for Block L :**



$$U_{i,j,L} = (U_{i,j})_0 + \sum_{n=1}^{N_F}[(A_n)_{i,j}\cos(n\theta_L) + (B_n)_{i,j}\sin(n\theta_L)]$$

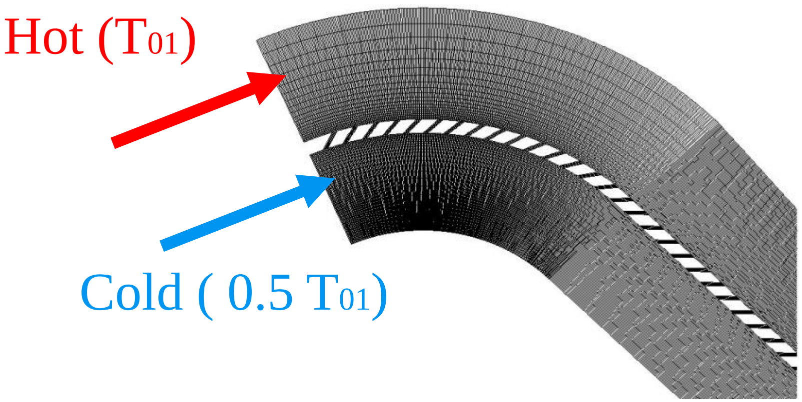
- $2N_F$+1 blocks to be solved to fix the spectrum

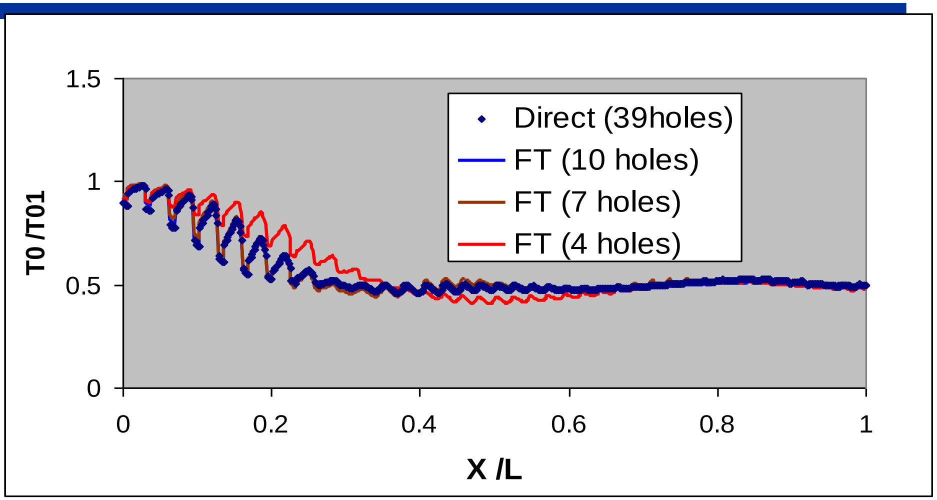
- **Double Fourier Series Shape (M x N):**

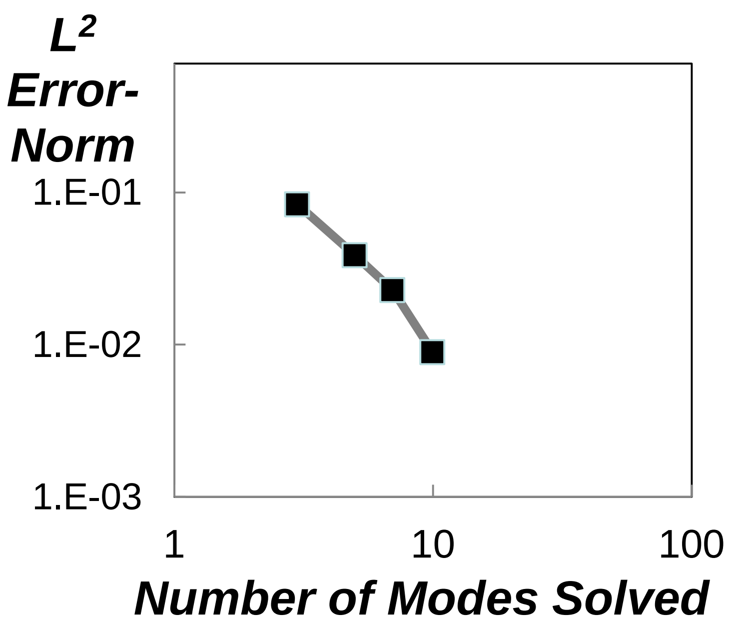
$$(U)_{I,J} = \sum_{m=0,n=0}^{M_h,N_h}\lambda_{m,n}[A_{m,n}\cos(m\alpha_I)\cos(n\beta_J) + B_{m,n}\sin(m\alpha_I)\cos(n\beta_J)$$
$$+ C_{m,n}\cos(m\alpha_I)\sin(n\beta_J) + D_{m,n}\sin(m\alpha_I)\sin(n\beta_J)]$$

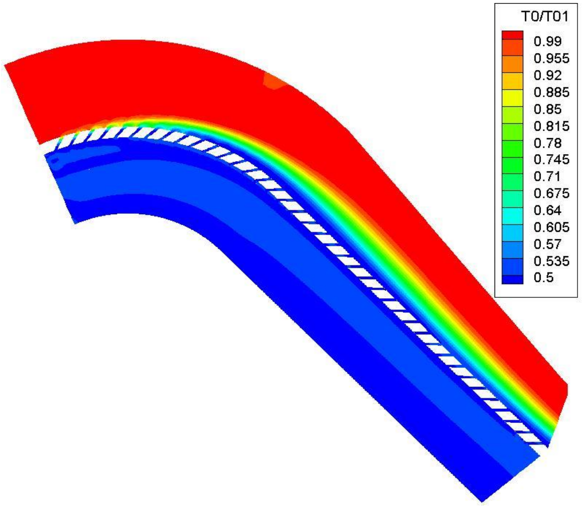
- (2M+1)(2N+1) blocks to be solved

Sample 2D Film-cooling Test Cases

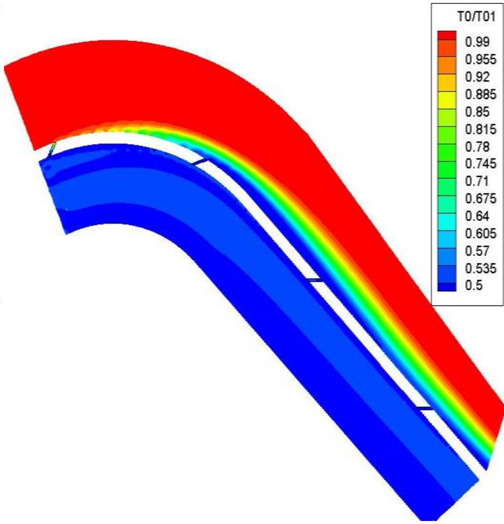






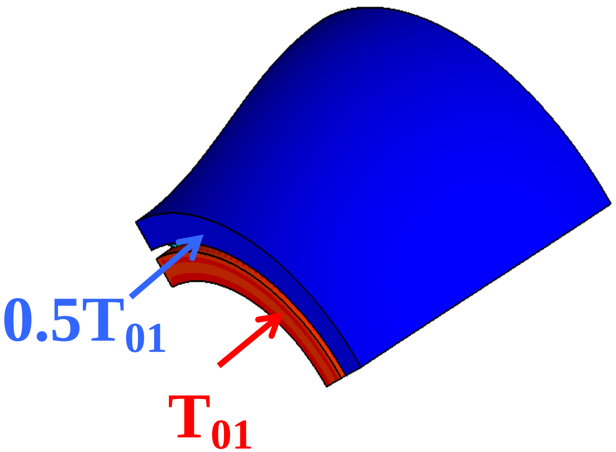


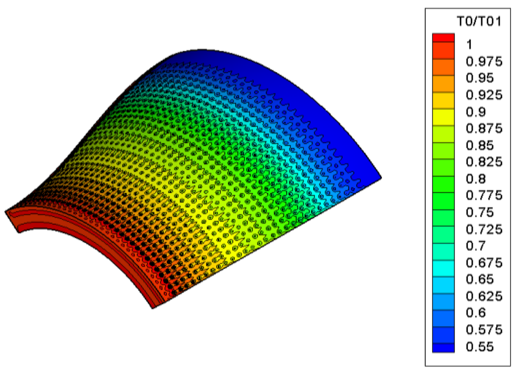
Direct (39 holes)



Spectral (4 holes)

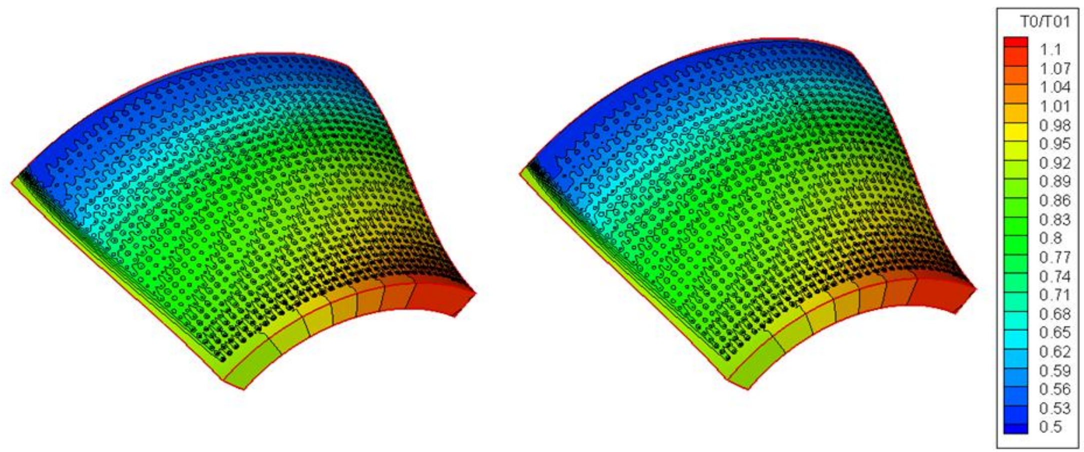
3D Effusion Cooling
(mass & heat transfer via large number of micro holes)





Direct Solution *(solving 992 holes)*

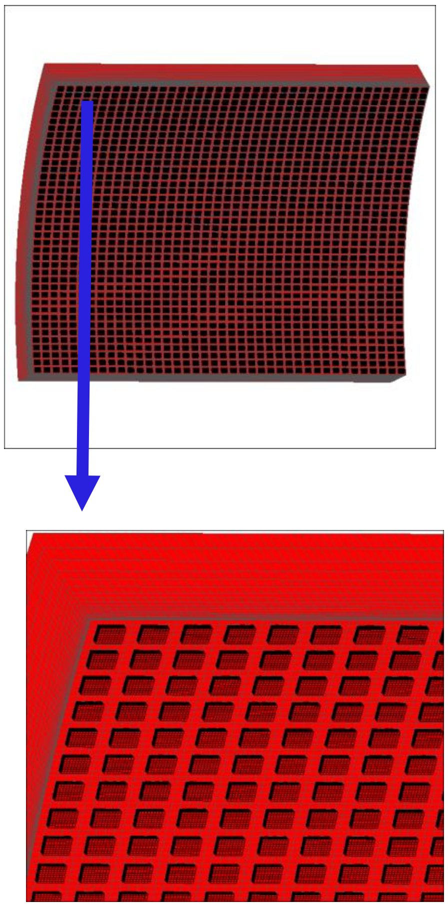
Block-Spectral *(solving 8 holes)*



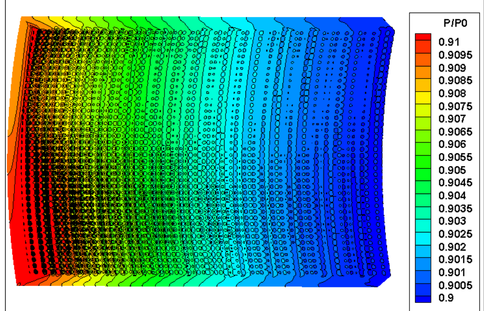
Surface temperature under a distorted infow

Surface Pressure and heat flux (*1600 dimples)*

(with inlet P0 distortion)

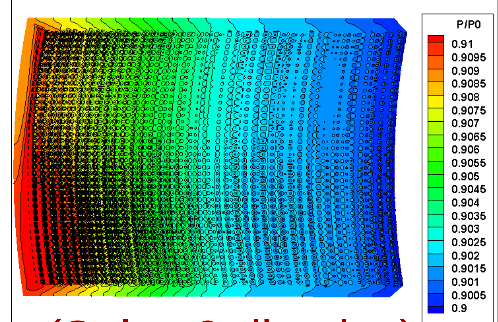


Direct Solution

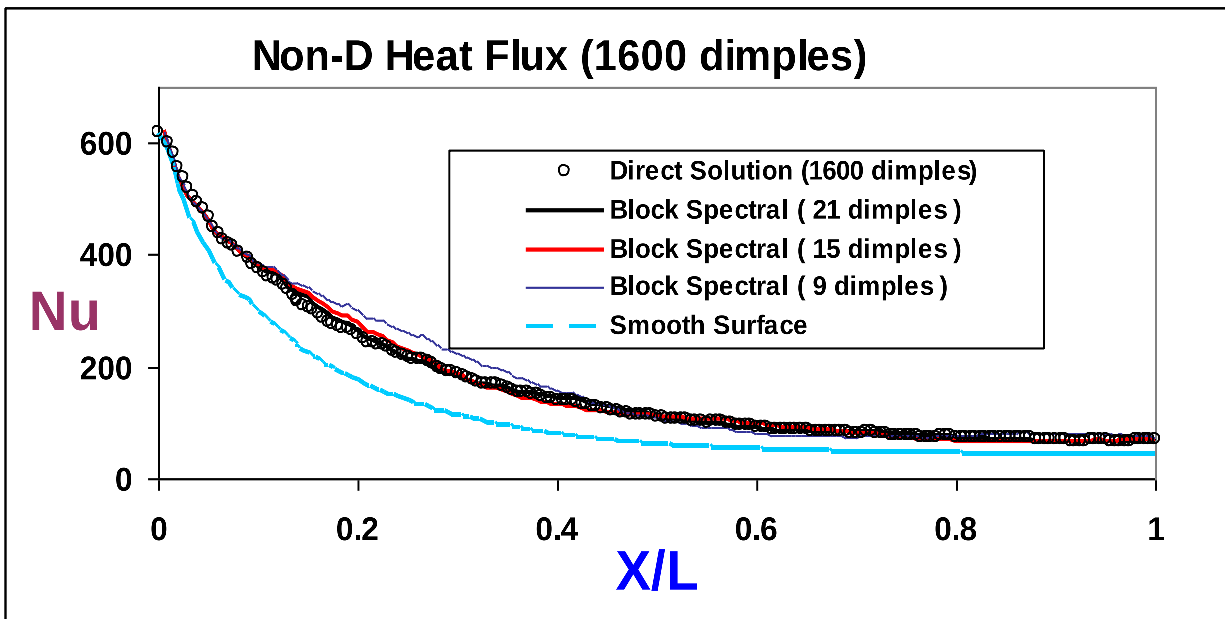


(Solve 1600 dimples)

Block Spectral



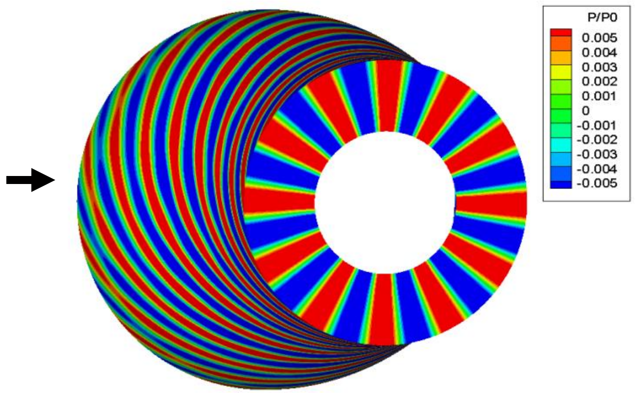
(Solve 9 dimples)

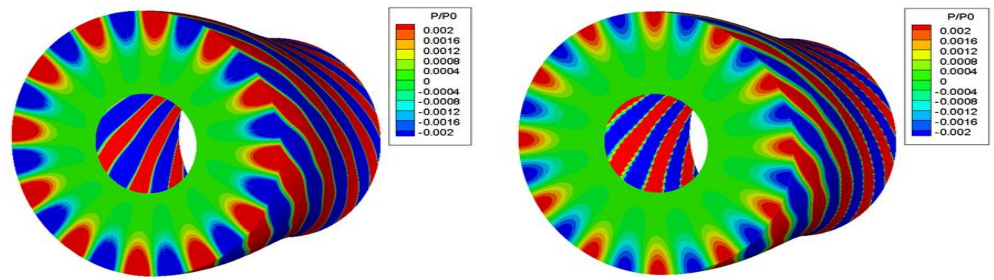


Duct Acoustic Liner for Noise Reduction

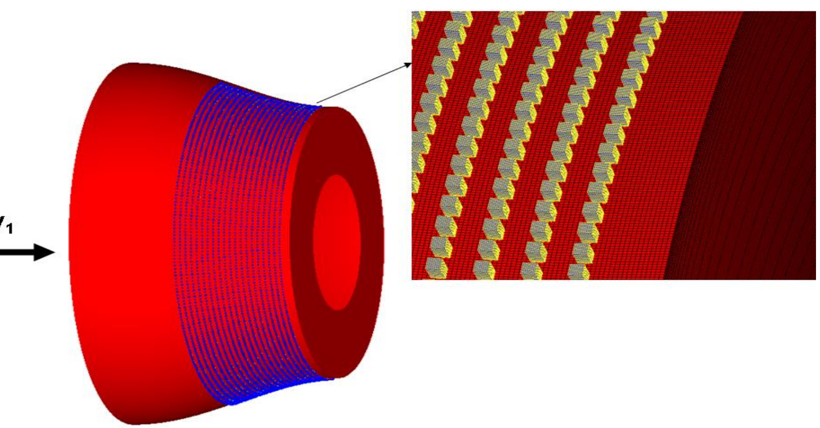
(Block spectral model of solving 1/30 micro-cavities)

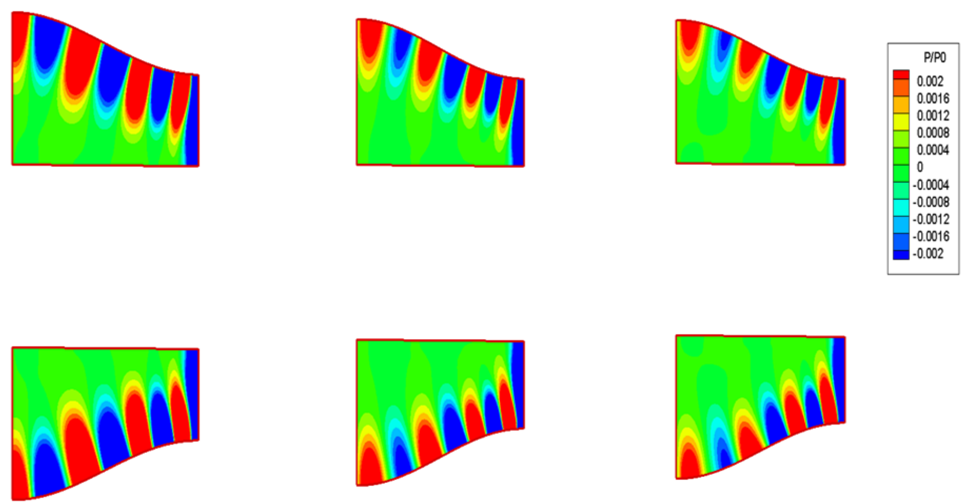
UNIVERSITY OF OXFORD





a) Smooth Casing b) Lined Casing





a) Smooth Casing b) Lined Casing *(Direct Solution)* c) Lined Casing *(Block Spectral)*

Summary

UNIVERSITY OF OXFORD

Two Methods for Multi-scale Problems:

- **Time scale disparity** (fluid-solid heat transfer)

  - *Harmonic transfer function method:*

  ➔ *unified and consistent interfacing condition/framework for periodic & turbulence unsteady simulations.*

- **Spatial scale disparity** (cooling, micro structures)

  - *Block-spectral method:*

  ➔ *macro & micro scales resolved by the same model/numerics*

Some Refs:

L. He, "Block-spectral Mapping for Multi-scale Solution", J. of Computational Physics, Vol.250 (2013).

L. He, "Fourier Spectral Method for Multi-scale Aerothermal Analysis", International J. of Computational Fluid Dynamics, Vol.27, No2 (2013).