TURBOMACHINERY AERODYNAMICS

Lect- 39

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In this lecture...

- Computational Fluid Dynamics for turbomachinery
  - Turbulence modelling
  - Prediction of 3D flows: case studies
  - Computing requirement
  - Errors and uncertainties

Turbulence models

- Reynolds averaging of the Navier-Stokes equation can be expressed as time, space or ensemble.
- The main idea of Reynolds averaging is to decompose the mean and fluctuating components: Reynolds decomposition.
- However this introduces additional variables for which there are no available relations: closure problem.
- Modelling this is a major challenge in CFD even today.

Turbulence Models

- Zero equation or algebraic eddy viscosity model
  - Use an algebraic form for the turbulent stresses
  - Valid for simple 2D shear flows
  - Mild pressure gradient
  - 3D boundary layers with small cross flows
  - Not accurate for flows with pressure or turbulence driven secondary flows
  - Cannot predict shock-induced separated flows

Turbulence Models

- One equation model: Spalart Allmaras
  - Employ an additional PDE for a turbulence velocity scale
  - Usually used in design-iteration type simulations
  - Popular in recent times due to inherent problems with more refined models
  - Very robust models, rarely produce completely unphysical results

Turbulence Models

- Two equation models:K-ε,K-ω models
  - One PDE for turbulence length scale and one PDE for velocity scale
  - Good for 2D flows with moderate pressure gradients
  - Not satisfactory for flows with rotation, strong swirl, and separated flows
  - Modified two equation models: improved results
  - Modified via ARSM
  - Coupled K-ε/ARSM
  - Realizable K-ε

Turbulence Models

- Near wall treatment
  - On-design flows without large separated regions, wall function model close to the wall
  - Off-design, low Re model, over production of turbulent KE must be checked
- Menter’s SST K-ω and Durbin’s v2f
  - Works well for adverse pressure gradients and separating flows

Turbulence Models

- Reynolds stress models
  - Use seven different PDEs for all the components of the turbulence stresses.
  - Reasonably better in cases where two-equation models were not satisfactory
  - More realistic physical simulation of turbulent flows

Transition prediction

- Natural and by-pass transition
- Turbomachinery flows usually involve by-pass transitions: wakes, vortices etc
- Separate transition model may be required
- Common models: Abu-Ghannam and Shaw (1980), Mayle (1991), Menter (2003)

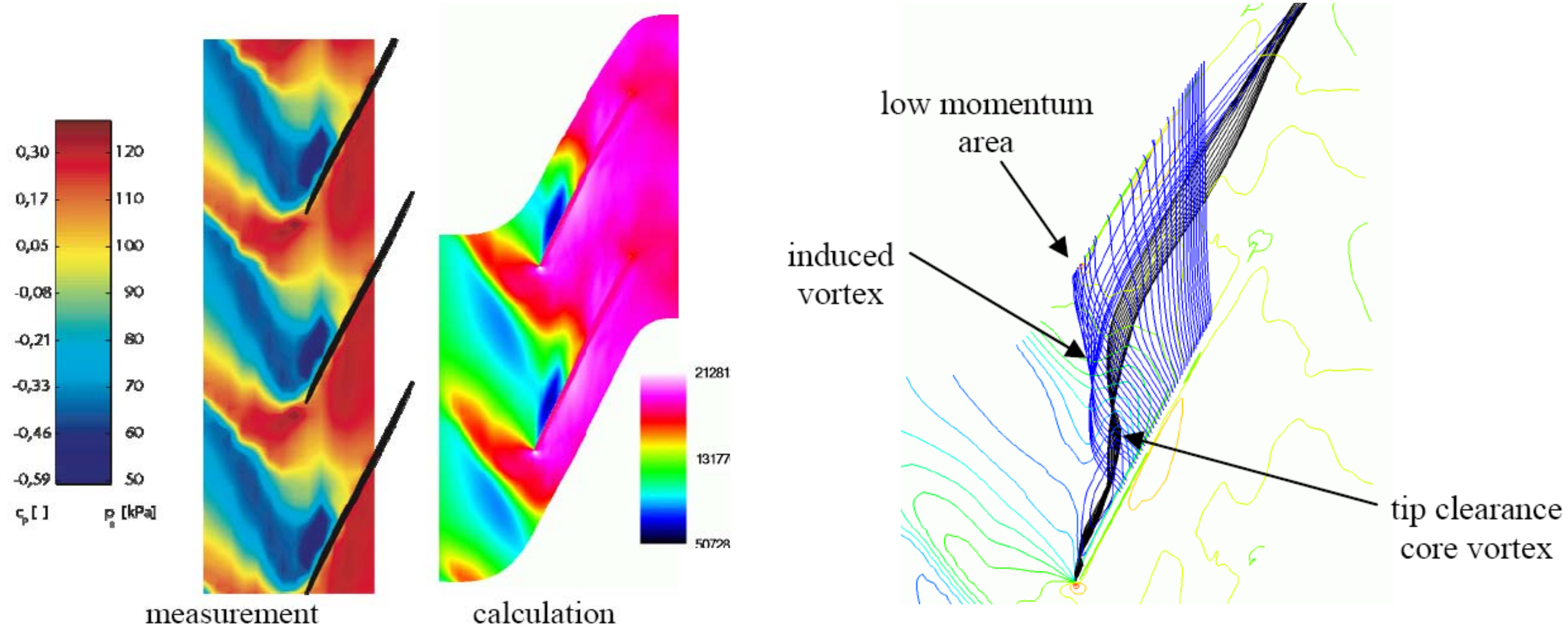
Case studies

- Types of shear flows
  - Tip leakage flow
  - Scraping vortex
  - Corner separation
  - Passage vortex
  - Secondary flows
  - Shock boundary layer interaction
  - Inflow distortion

Tip leakage flows

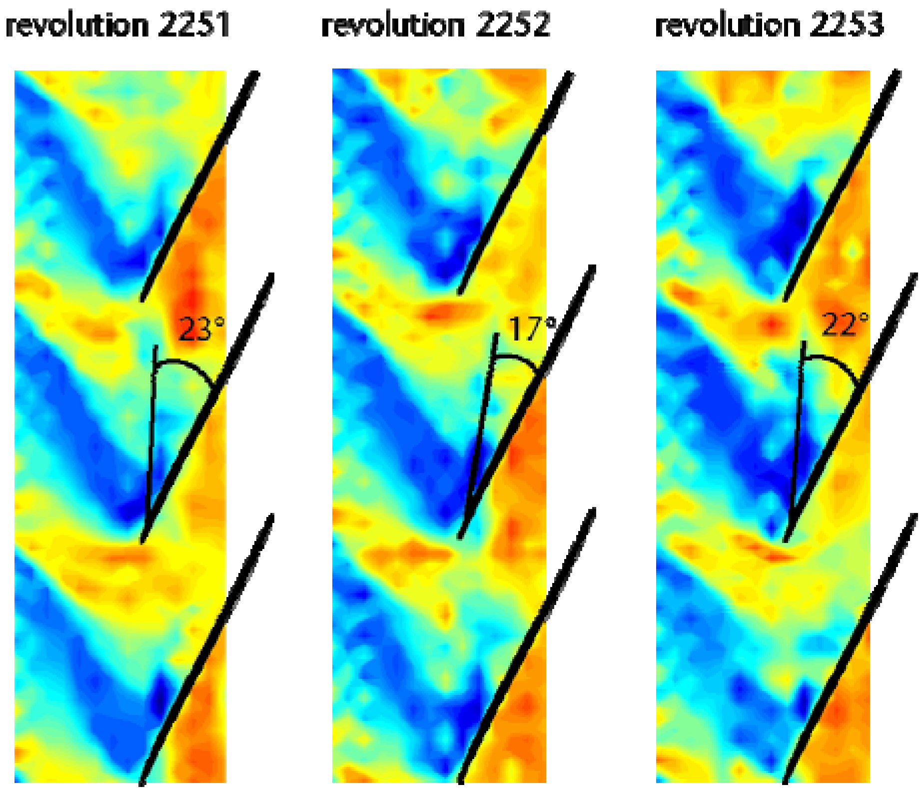
- Several papers on simulation of tip leakage flows
- Steady computations reasonably good
- Vortex fluctuations close to compressor stall for eg. not predicted well.
- Case: Hah et al. 2008
  - Full annulus flow simulation
  - LES of Darmstadt transonic rotor
  - 25 million grid points
  - 60 CPU hours on 124 CPU NASA's Columbia!
  - Results compared with experimental data from TU Darmstadt

Tip leakage flows

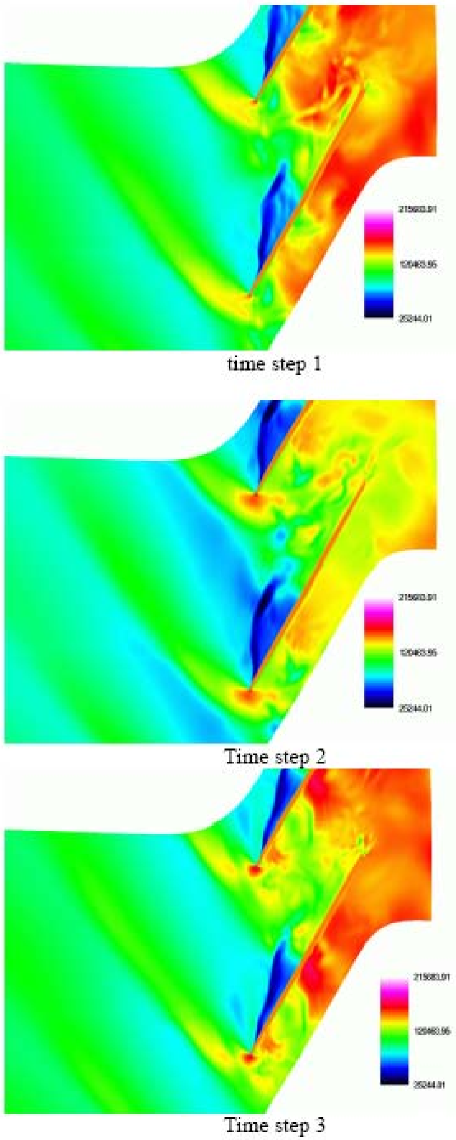


Casing static pressure distribution and particle traces near stall (Hah et al. (2008)

2008 ASME TURBO EXPO Conference, Berlin, Germany



Measured



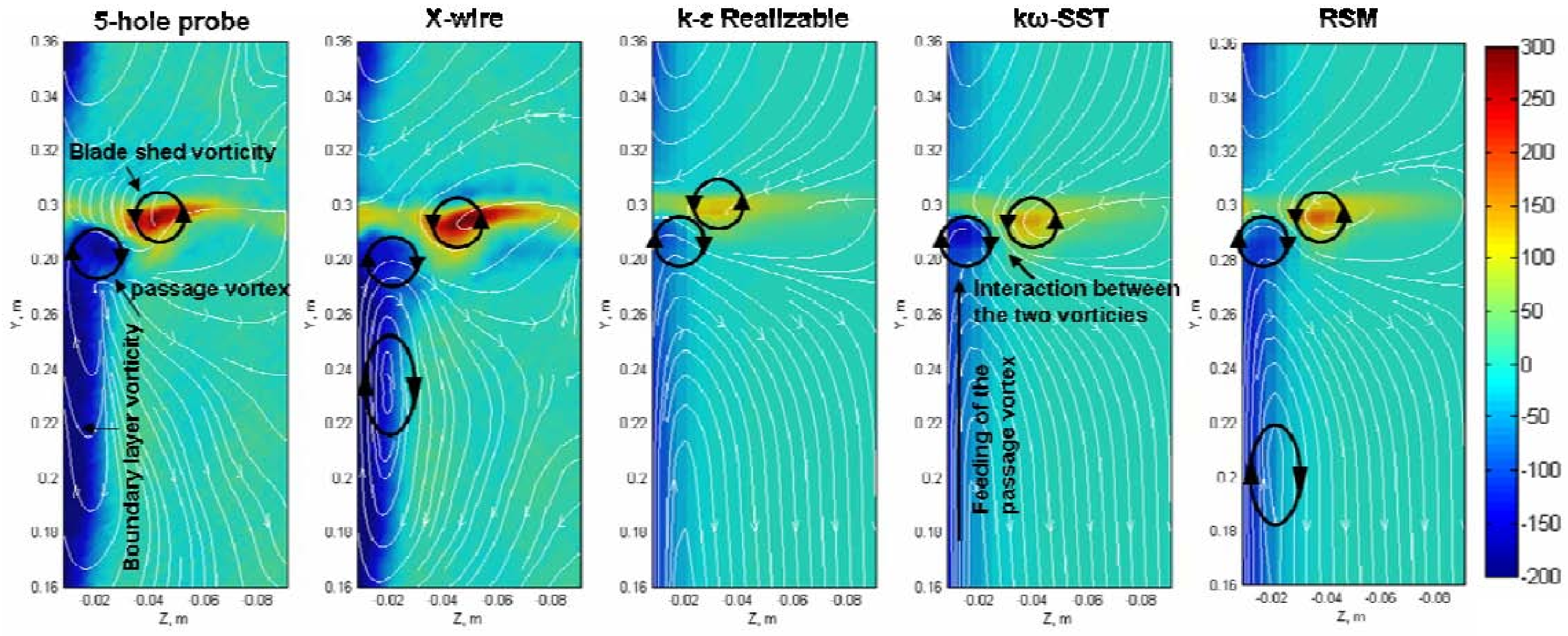
Computed

Vortex fluctuations close to stall (Hah et al. 2008)

Passage vortex

- Strength of secondary flows, passage vortices depend upon the blade loading
- Case: Hjarne et al. , 2007
  - Secondary flow studies on turbine OGV cascade
  - Different turbulence models
    - Realizable K-ε, SST K-ω and RSM
  - Simulations compared with experimental data

Passage vortex



Streamwise vorticity at downstream location of 0.5C of the blade (Hjarne et al. 2007)

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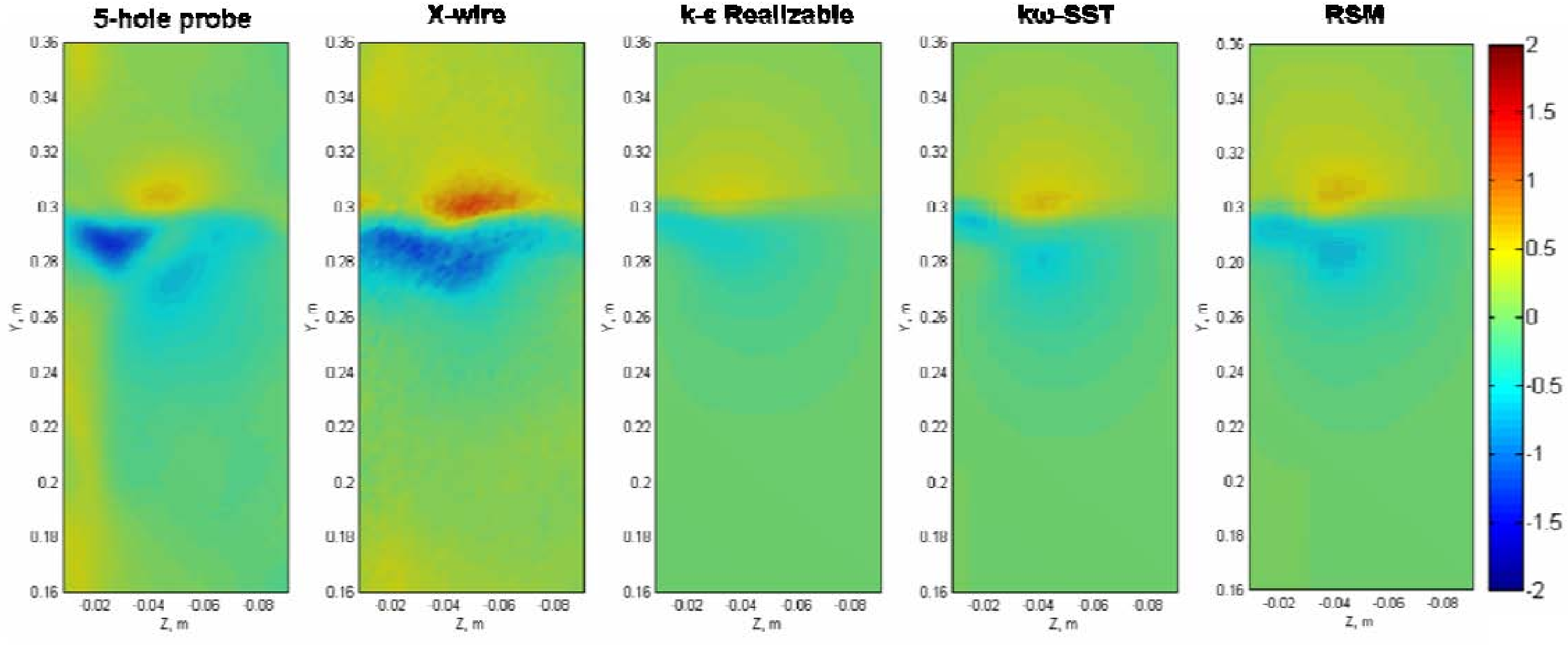
Passage vortex



W-velocity at downstream location of 0.5C of the blade (Hjarne et al. , 2007)

Transonic rotor: shocks, tip flow unsteadiness

- Tip flow
  - Significant effect on flow stability, pressure rise, and efficiency
  - Self induced unsteadiness related to spike initiated stall?
  - Role of shock wave in the flow physics
  - Experimentally capturing the tip flow dynamics very challenging

Transonic rotor: shocks, tip flow unsteadiness

- Case: Du et al. 2008
  - Studies on NASA rotor 67
  - Used Fluent with standard and realizable K-ε
  - Validation of total pressure ratio and efficiency with experimental data
  - Effect of increasing tip clearance

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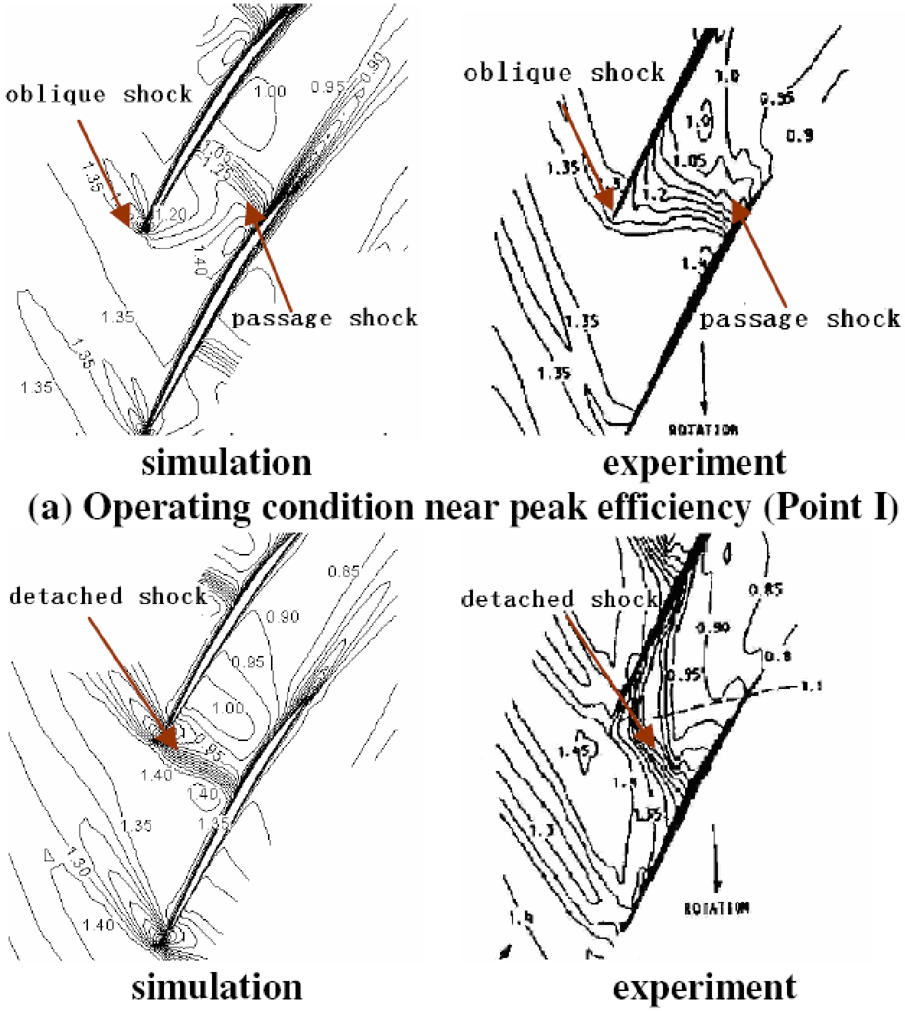
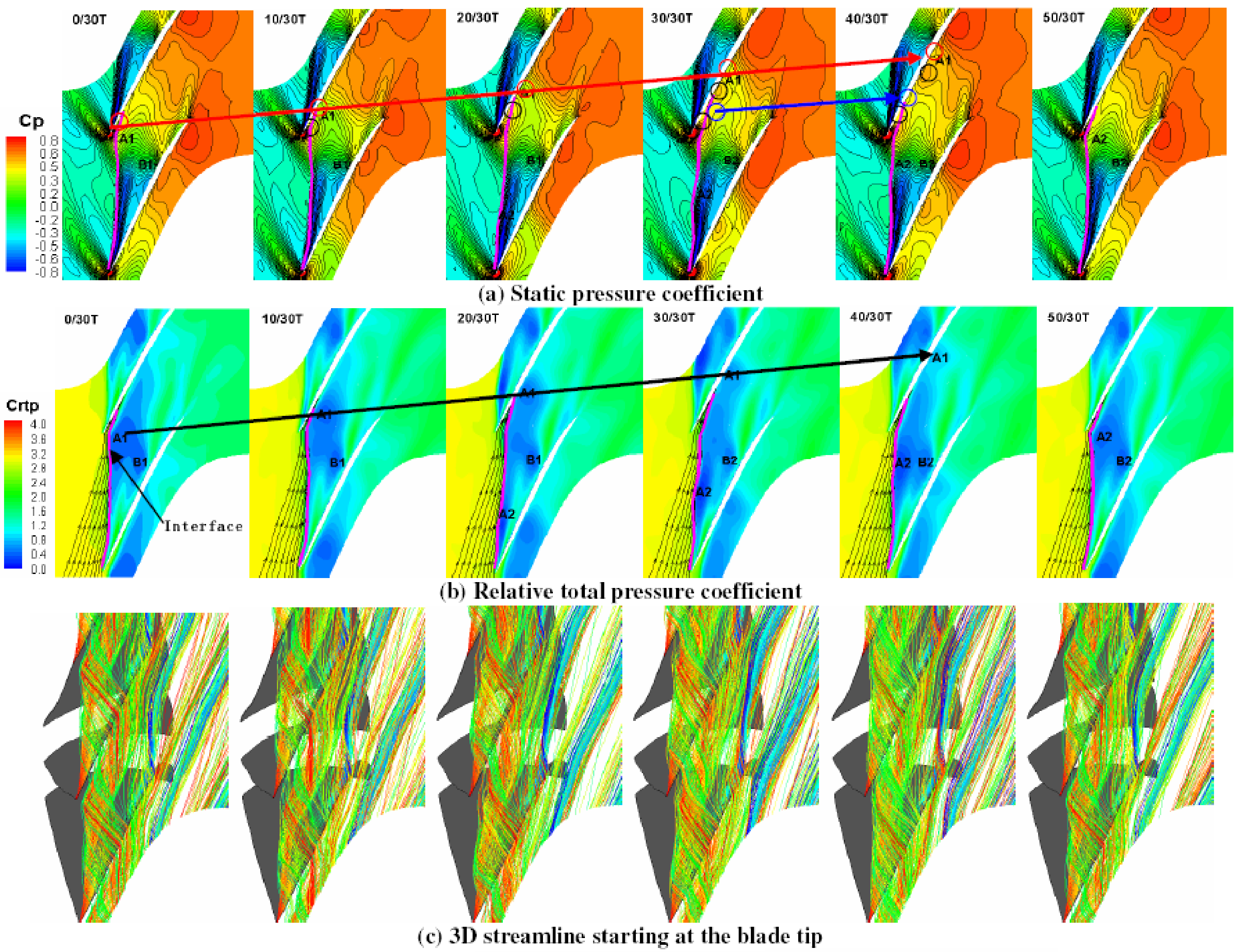


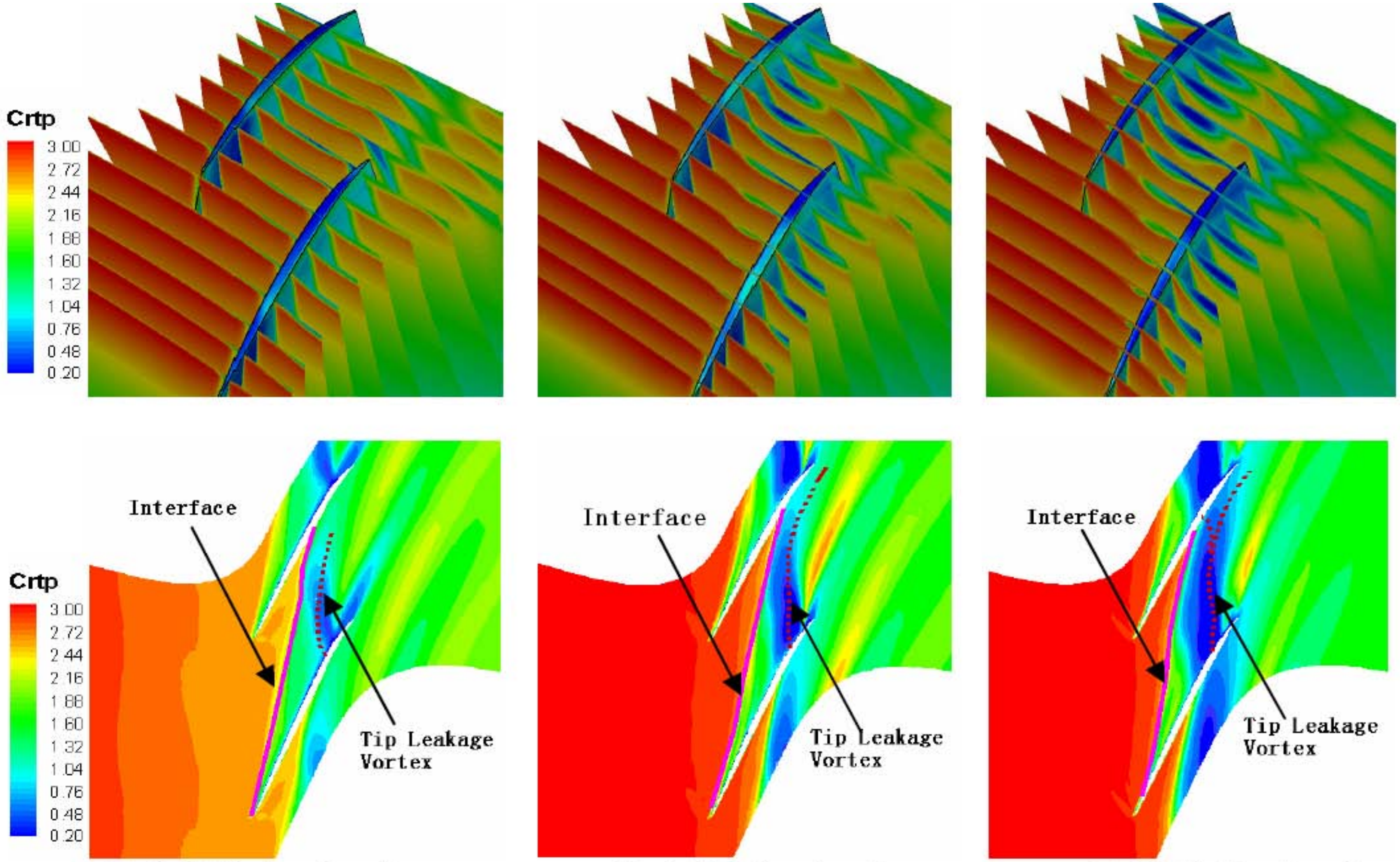
(a) Operating condition near peak efficiency (Point I)

(b) Operating condition near stall (Point II)

Shock positions at two operating points (Du et al , 2008)



Property variation transience during stalled operation (Du et al , 2008)



(a) 0.25% tip chord (b) 1.1% tip chord (c) 2.2% tip chord

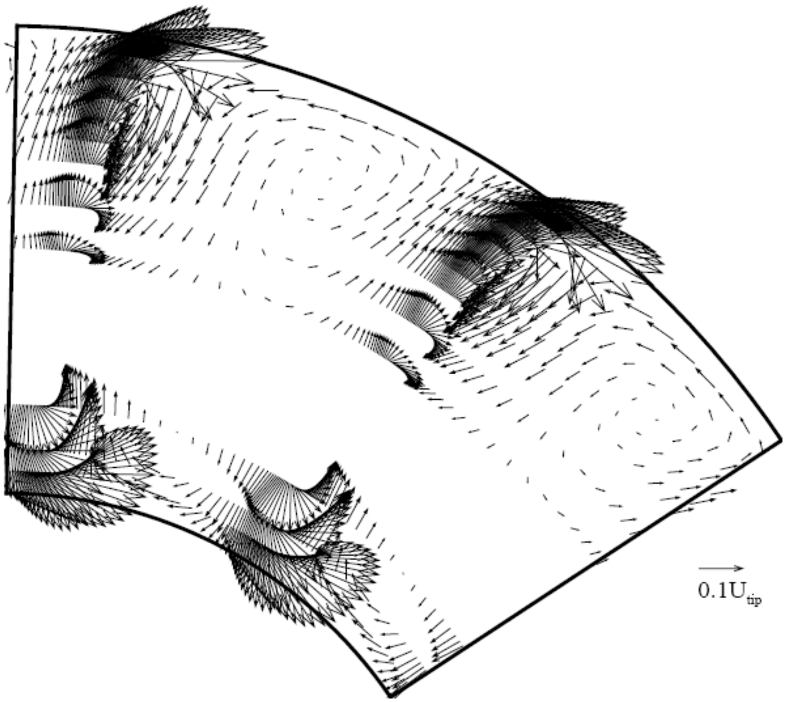
Relative total pressure distribution for three tip clearances (Du et al , 2008)

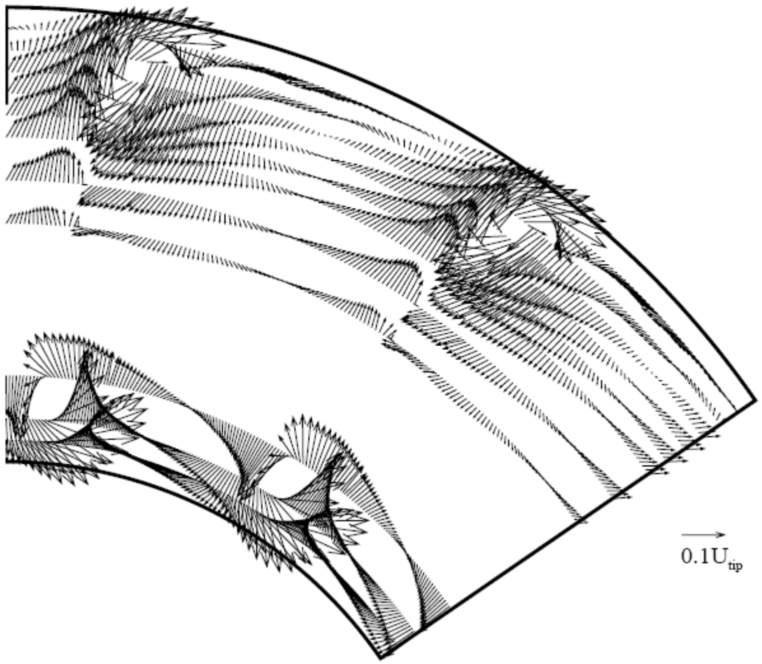
Secondary flows

- Secondary flow losses: significant portion of the total losses
- Accurate prediction of secondary flow: reduction in total losses
- Literature on secondary flows: mostly cascades
- Case 2: Yu (2004)
  - Turbine flow simulations using structured and unstructured grids
  - In-house code (Penn State)
  - Secondary flow structures well captured
  - Validation with experimental data

Tran. ASME, Journal of turbomachinery, 2004

Secondary flows





Secondary flow vectors downstream of a turbine IGV (Yu, 2004)

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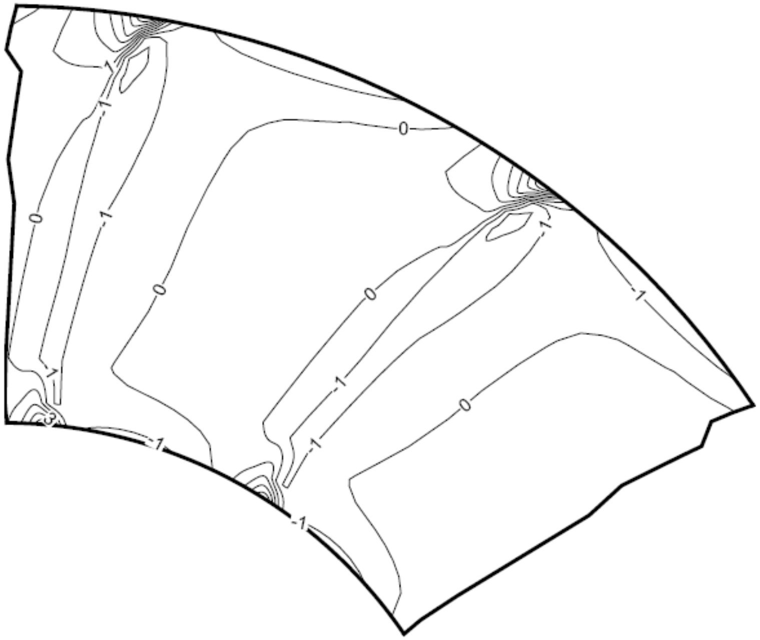
Secondary flows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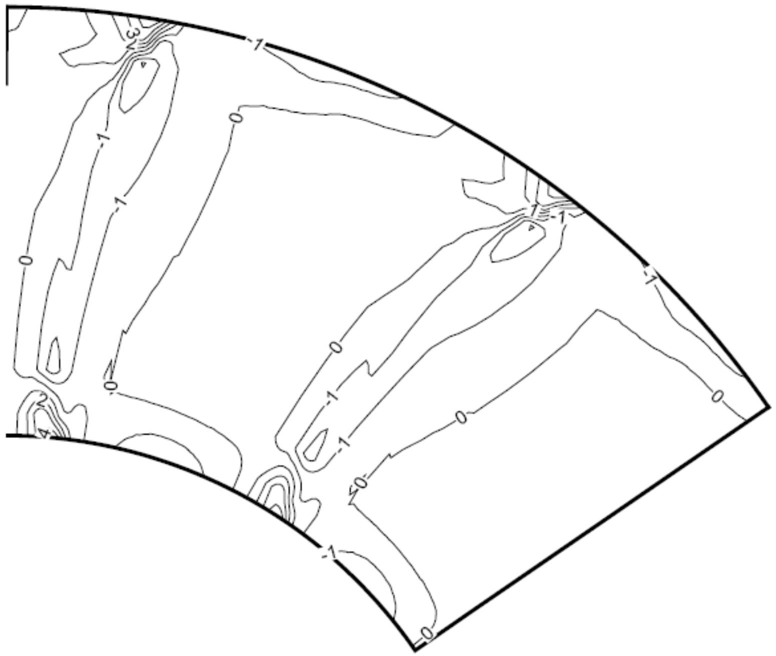
Experimental

Flow deviation angles downstream of a turbine IGV (Yu, 2004)

Aeroelasticity

- Blade flutter, inflow distortion effect on fan blades
- Fluid structure coupling
- Calls for real-time FEM-CFD interface
  - Grid interpolation between FEM and CFD
  - Grid deformation under aerodynamic loads
  - Efficient transfer to data between FEM and CFD

Computing requirements

- 3D compute requirements (Pullan, 2008)
- Steady computations
    - 1 blade 0.5 – 1 M cells (1-2 CPU hours)
    - 1 stage 1-2 M cells (3 CPU hours)
- Unsteady computations
    - 1 stage 50 – 100 M cells (20000 CPU hours)
    - 1 component (5 stages) 500 M cells (0.1 M CPU hours)!

Errors and uncertainties

- **Sources**
  - Type of simulation
  - Geometry errors
  - Modeling errors
  - Boundary conditions
  - Numerical errors
    - Discretization
    - Round-off
    - Convergence

} Systematic procedure for estimating these errors like say the ASME / AIAA standards for experimental uncertainty analysis

Some concluding remarks

- Combine a simpler code like MISES with a commercial package
  - Use MISES for preliminary blade design optimization
- Efficient grid generation tools
- "Hybrid" turbulence models
- Improved transition models
- Acoustics and noise predictions
- Real time aeroelastic computations

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