An Exact 3D Non-Reflecting Boundary Condition and Wet Steam Flow Modelling for Flutter Analysis

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Outline of Presentation

Outline

- Linearised 3D Viscous Flow Solver
- Exact 3D Non-Reflecting Boundary Condition
- Test Case: 3D Standard Configuration
- Wet Steam Flow Modelling

Linearised Flow Solver

Philosophy

- Steady flow condition known
- Flutter: known grid motion: $\mathbf{x} = \bar{\mathbf{x}} + \tilde{\mathbf{x}} e^{\jmath\omega t}$
- Discretised unsteady flow model: $\frac{d\mathbf{U}}{dt} = \mathbf{R}(\mathbf{U}, \mathbf{x}, \dot{\mathbf{x}})$
- Unknown flow perturbation: $\mathbf{U} = \overline{\mathbf{U}} + \tilde{\mathbf{U}} e^{\jmath\omega t}$
- Linearisation: $\mathbf{R} \approx \overline{\mathbf{R}} + \frac{\partial \mathbf{R}}{\partial \mathbf{U}} \mathbf{\Delta U} + \frac{\partial \mathbf{R}}{\partial \mathbf{x}} \mathbf{\Delta x} + \frac{\partial \mathbf{R}}{\partial \dot{\mathbf{x}}} \mathbf{\Delta} \dot{\mathbf{x}}$
- $\left[\jmath\,\omega - \frac{\partial \mathbf{R}}{\partial \mathbf{U}}\right] \tilde{\mathbf{U}} \approx \mathbf{R}(\overline{\mathbf{U}}, \bar{\mathbf{x}} + \tilde{\mathbf{x}}, 0) + \jmath\,\omega\ \mathbf{R}(\overline{\mathbf{U}}, \bar{\mathbf{x}}, \tilde{\mathbf{x}})$
- 100 to 1000 times faster than time domain methods
- Single passage for turbomachinery
- Can apply exact non-reflecting boundary conditions

Linearised Flow Solver

RPMTurbo Linearised Flow Solver

- 3D viscous flow with Spalart and Allmaras turbulence model
- Efficient parallel solver for linear systems
- 3D Euler 140 000 cells in 2 minutes (10 procs.)
- 3D Viscous 500 000 cells in 20 minutes (30 procs.)
- Validated - Standard Configuration 10 and 11
- Non-reflecting boundary condition

Non-Reflecting Boundary Condition

Philosophy

- Allow outgoing waves to exit domain without reflection
- Reflected waves can pollute solution
- Decompose unsteady flow into waves (modes)
- 2D and 3D flow: must consider entire boundary
- Determine direction of each wave
- Prescribe incoming waves
- Extrapolate outgoing waves

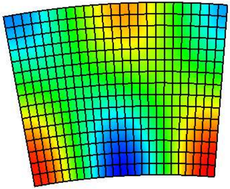
Non-Reflecting Boundary Condition

Current Methods

- Commercial Software: use steady boundary conditions
- Assume 1D waves: apply locally
- Giles: 2D analytical modes for uniform flow
- Strip Method: apply 2D method at radial slices
- Hall/Montgomery: numerically determine 3D modes

3D Non-Reflecting Boundary Condition

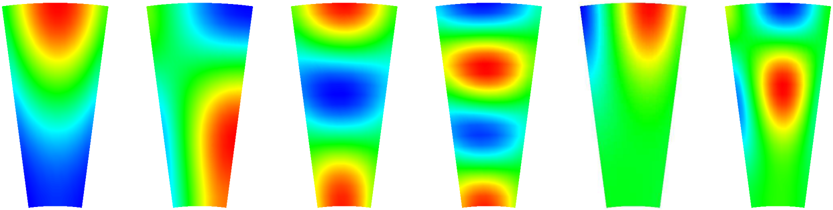
Numerically determine aerodynamic modes at far-field



- Create 2D mesh for far-field
- Semi-discretized flow equations
  $\frac{\partial \mathrm{U_f}}{\partial t} = \mathrm{A_f}\frac{\partial \mathrm{U_f}}{\partial x} + \mathrm{D_f}\mathrm{U_f}$
- Assuming wave-like solution
  $\mathrm{U_f} = \mathrm{U_m}(y,z)\,\exp\{\imath(k\ x + \omega\ t)\}$
- Solve eigen problem to determine modes
  $\mathrm{A_f}^{-1}[\omega \mathrm{I} + \imath \mathrm{D_f}]\mathrm{U_m} = k\mathrm{U_m}$
- Steady flow at far-field can be non-uniform and swirling

3D Non-Reflecting Boundary Condition

Example Far-field Acoustic Modes

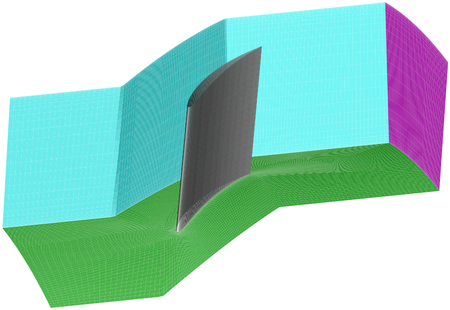


(-8,0) (-8,1) (-8,2) (-8,3) (16,0) (16,1)

3D Standard Configuration 10

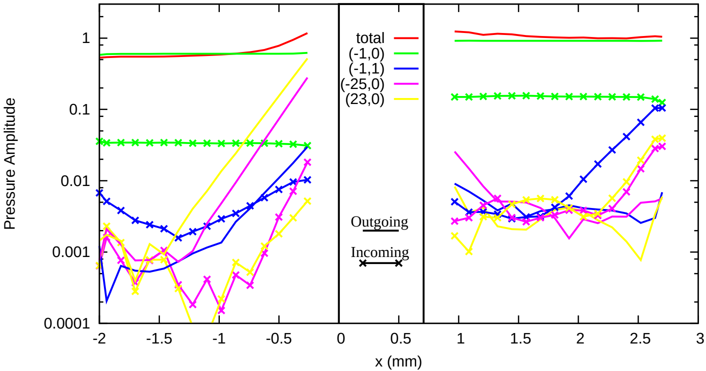
Geometry and Flow Conditions

Number of Blades	24
Blade Shape	untwisted
Chord Length	100 mm
Hub Radius	339.5 mm
Shroud Radius	424.4 mm
Stagger Angle	45.0^o
Inlet Mach Number	0.7
Inlet Flow Angle	55.0^o
Reynolds Number	1.25×10^6



3D Standard Configuration 10

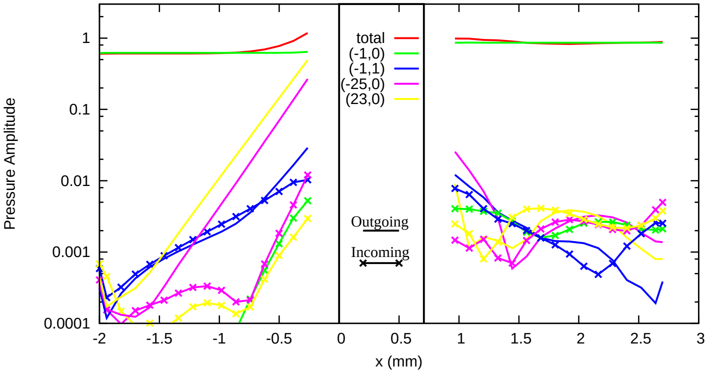
Unsteady Linearised Inviscid Flow Solution with 1D NRBC



Wave Plot for Torsion Mode (ND=-1) ($\omega^* = 0.5$)

3D Standard Configuration 10

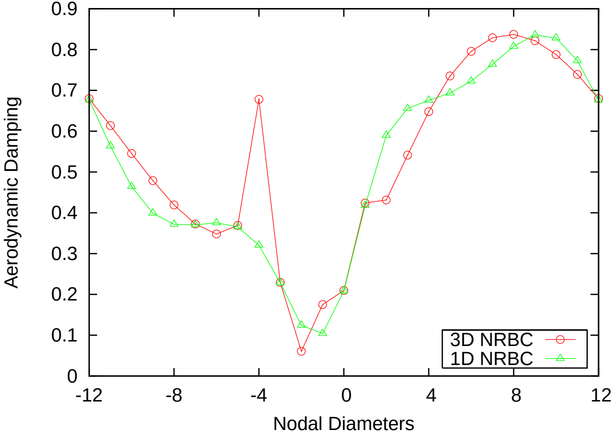
Unsteady Linearised Inviscid Flow Solution with 3D NRBC



Wave Plot for Torsion Mode (ND=-1) ($\omega^* = 0.5$)

3D Standard Configuration 10

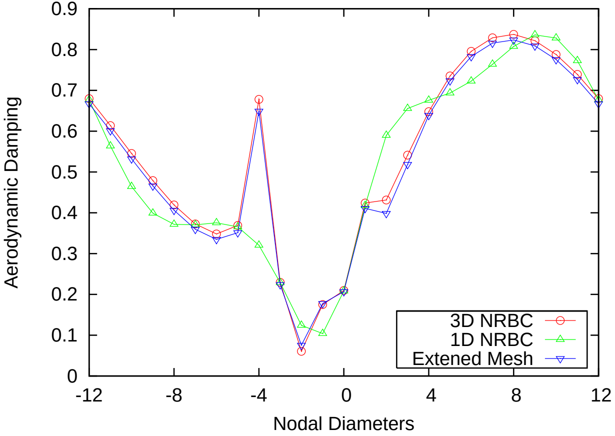
Unsteady Linearised Inviscid Flow Solution with 3D NRBC



Damping Plot for Torsion Mode ($\omega^* = 0.5$)

3D Standard Configuration 10

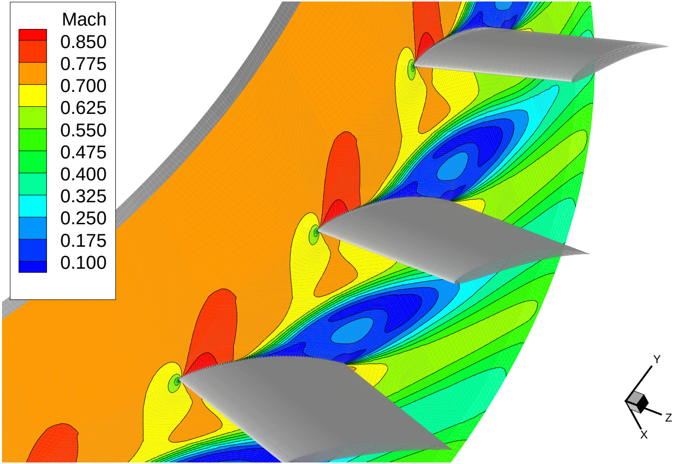
Unsteady Linearised Inviscid Flow Solution with 3D NRBC



Damping Plot for Torsion Mode ($\omega^* = 0.5$)

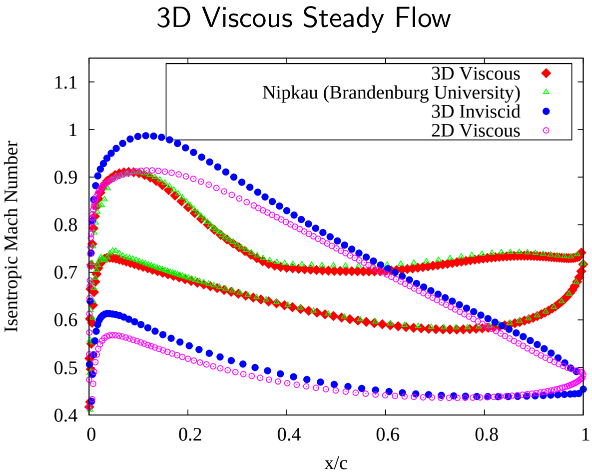
3D Standard Configuration 10

3D Viscous Steady Flow: $M_1 = 0.7$, $\beta_1 = 55.0^o$



Flow Mach Number at 10% Blade Height

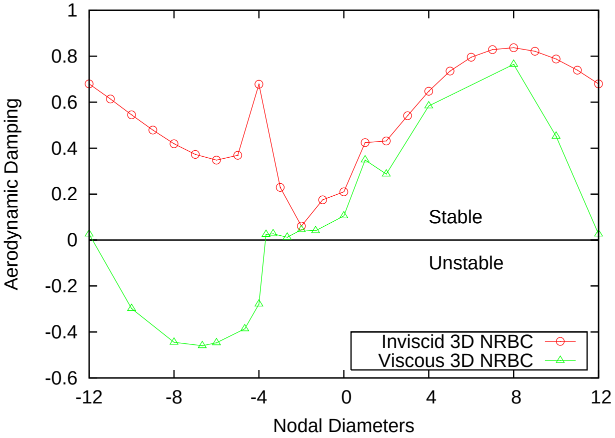
3D Standard Configuration 10



10% blade height $M_1 = 0.7$, $\beta_1 = 55.0^o$

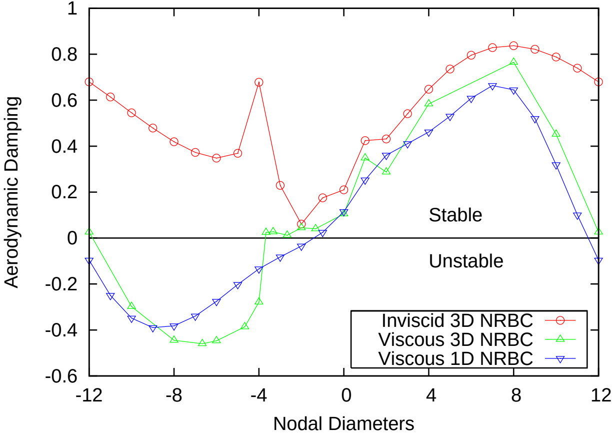
3D Standard Configuration 10

Unsteady Linearised Viscous Flow Solution with 3D NRBC



Damping Plot for Torsion Mode ($\omega^* = 0.5$)

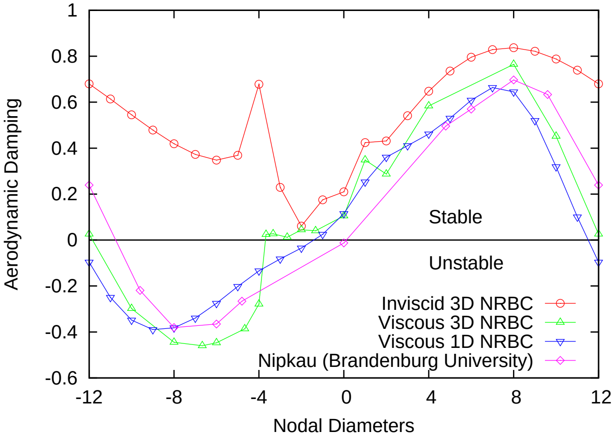
Unsteady Linearised Viscous Flow Solution with 3D NRBC



Damping Plot for Torsion Mode ($\omega^* = 0.5$)

3D Standard Configuration 10

Unsteady Linearised Viscous Flow Solution with 3D NRBC



Damping Plot for Torsion Mode ($\omega^* = 0.5$)

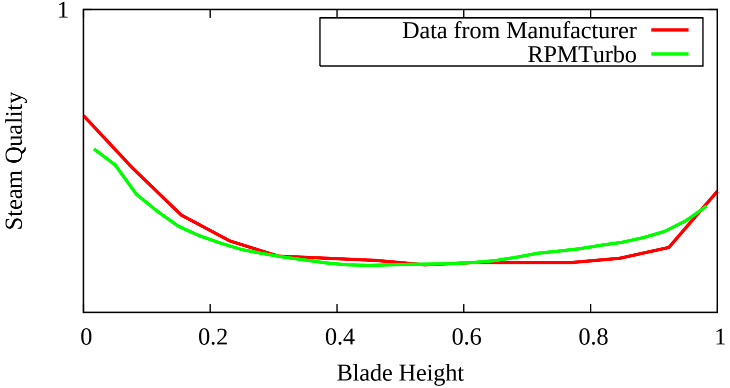
Wet Steam Flow Modelling

RPMTurbo Wet Steam Equation of State

- assume equilibrium and treat as single gaseous phase
- remove all perfect gas assumptions and use equation of state
- conserved variables: density, momentum and total energy
- Formulae from IAPWS-IF97: International Association for the Properties of Water and Steam - Industrial Formulation 1997 used to calculate pressure, temperature, speed of sound, entropy and enthalpy

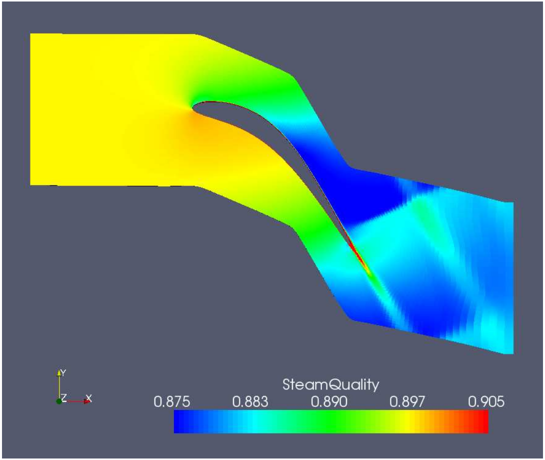
Wet Steam Flow Modelling

Steady-State Flow



Exit of an Industrial Steam Turbine

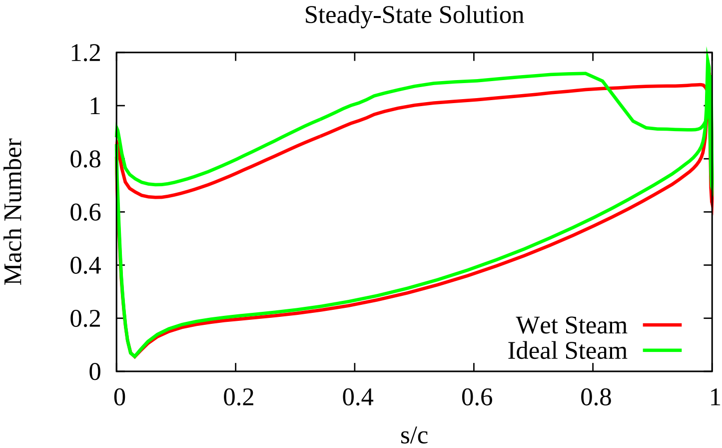
Standard Configuration 11



Steady Flow ($P_0 = 13$ kPa, $T_0 = 324$ K, $P_2 = 7500$ Pa)

Wet Steam Flow Modelling

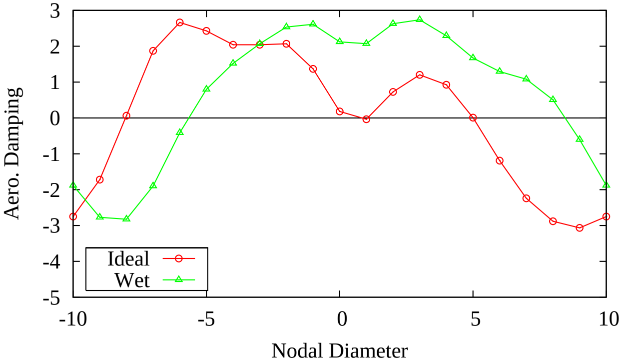
Standard Configuration 11



Steady Flow ($P_0 = 13$ kPa, $T_0 = 324$ K, $P_2 = 7500$ Pa)

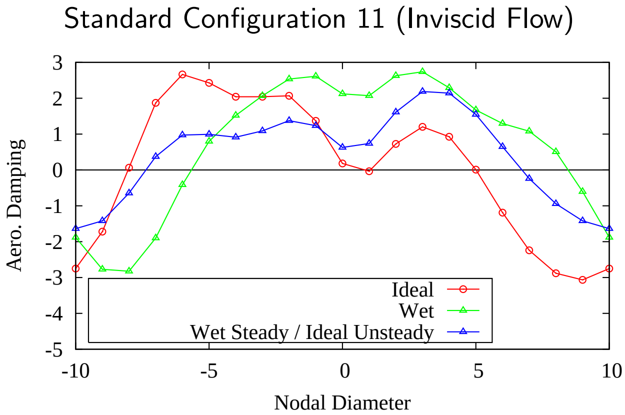
Wet Steam Flow Modelling

Standard Configuration 11 (Inviscid Flow)



Torsion Mode ($f = 212$ Hz)

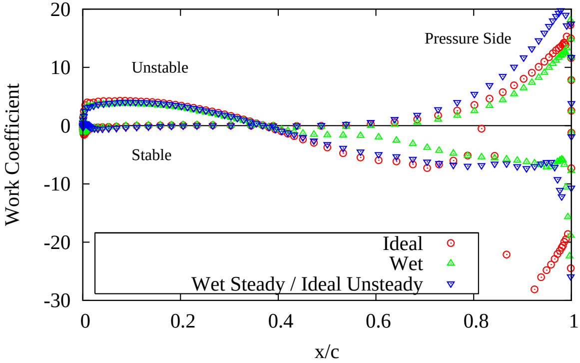
Wet Steam Flow Modelling



Torsion Mode ($f = 212$ Hz)

Wet Steam Flow Modelling

Standard Configuration 11 (Inviscid Flow)



Torsion Mode (f = 212 Hz, ND=-6)

Conclusion

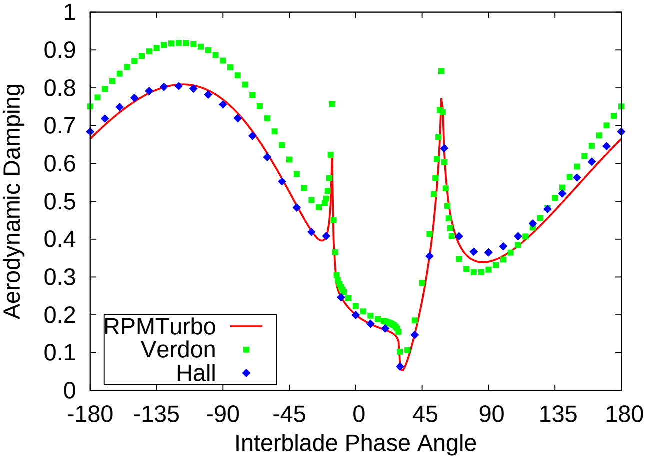
Conclusions

- Exact 3D non-reflecting boundary condition has been developed and appears to be working well
- Wet steam flow model has been developed
- Good comparison with manufacturers data for steady-state
- Wet steam effects appear to be significant for unsteady flow

Extra Slides

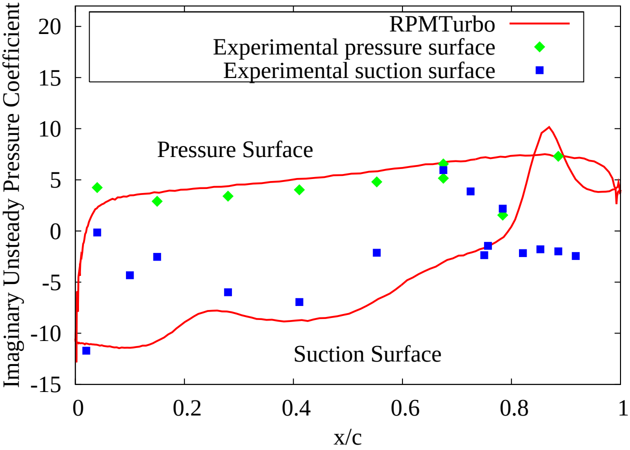
EXTRA SLIDES

Code Validation - Standard Configuration 10



Aerodynamic damping for torsion mode ($\omega^* = 0.5$)

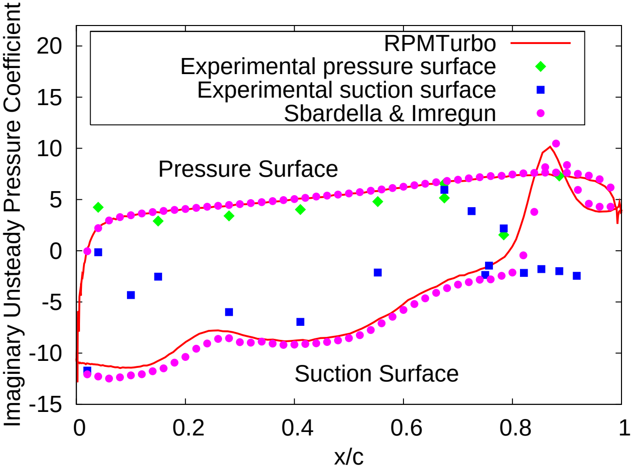
Test Case: Standard Configuration 11



Unsteady solution due to flap mode

($\omega^* = 0.309$, $\sigma = 180.0^o$)

Test Case: Standard Configuration 11

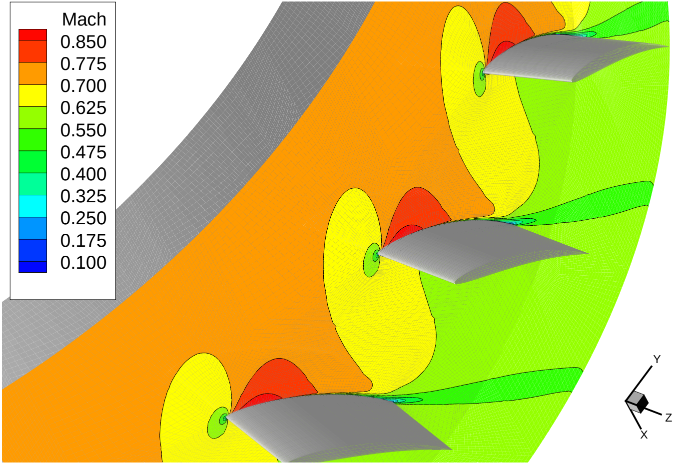


Unsteady solution due to flap mode

($\omega^* = 0.309$, $\sigma = 180.0^o$)

3D Standard Configuration 10

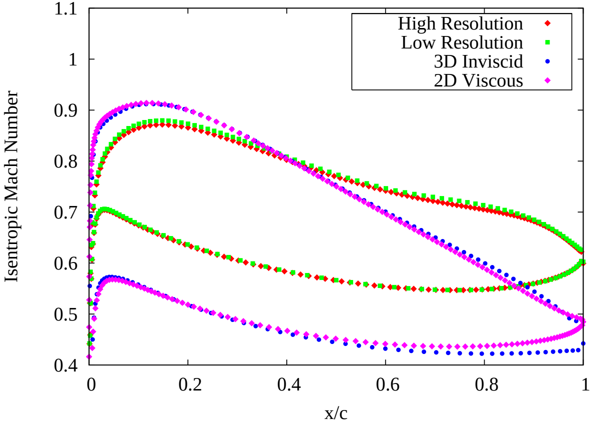
Standard Configuration 10: $M_1 = 0.7$, $\beta_1 = 55.0^o$



Flow Mach Number at 50% Blade Height

3D Standard Configuration 10

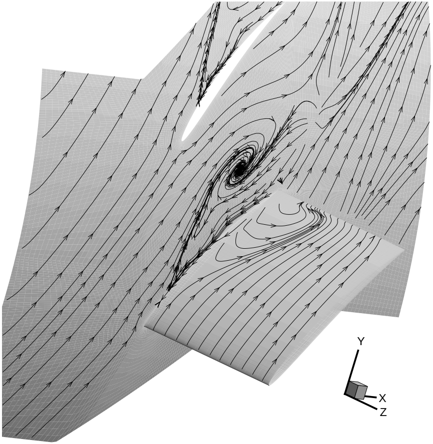
3D Viscous Steady Flow



50% blade height $M_1 = 0.7$, $\beta_1 = 55.0^o$

3D Standard Configuration 10: Steady-State

3D Viscous Flow



Stream lines on hub and profile: $M_1 = 0.7$, $\beta_1 = 55.0^o$