THREE-DIMENSIONAL NON-REFLECTING BOUNDARY CONDITION FOR LINEARIZED FLOW SOLVERS

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Outline of Presentation

THREE-DIMENSIONAL NON-REFLECTING BOUNDARY CONDITION FOR LINEARIZED FLOW SOLVERS

- Linearised 3D Viscous Flow Solver
- Exact 3D Non-Reflecting Boundary Condition
- Aero-acoustic Test Case: Category 4 Benchmark Problem from 3rd CAA Workshop
- Flutter Test Case: 3D Standard Configuration 10

Linearised Flow Solver

Philosophy

- Steady flow condition known
- Flutter: known grid motion: $\mathbf{x} = \overline{\mathbf{x}} + \tilde{\mathbf{x}} e^{\jmath \omega t}$
- Acoustics: known incoming disturbance
- 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: $\mathbf{R} \approx \overline{\mathbf{R}} + \frac{\partial \mathbf{R}}{\partial \mathbf{U}} \mathbf{\Delta U} + \frac{\partial \mathbf{R}}{\partial \mathbf{x}} \mathbf{\Delta x} + \frac{\partial \mathbf{R}}{\partial \dot{\mathbf{x}}} \mathbf{\Delta} \dot{\mathbf{x}}$
- $\left[\jmath\, \omega - \frac{\partial \mathbf{R}}{\partial \mathbf{U}}\right] \tilde{\mathbf{U}} \approx \mathbf{R}(\overline{\mathbf{U}}, \overline{\mathbf{x}} + \tilde{\mathbf{x}}, 0) + \jmath\, \omega\ \mathbf{R}(\overline{\mathbf{U}}, \overline{\mathbf{x}}, \tilde{\mathbf{x}})$
- 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

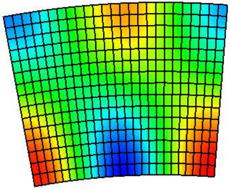
Non-Reflecting Boundary Condition

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

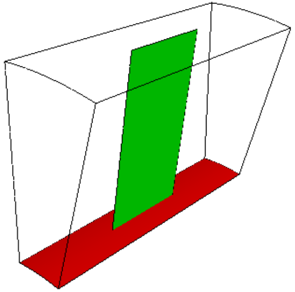


- Create 2D mesh for far-field
- Semi-discretized flow equations
  $\frac{\partial \mathrm{U_f}}{\partial t} = \mathrm{A_f}\frac{\partial \mathrm{U_f}}{\partial x} + \mathrm{D_f}\mathrm{U_f}$
- Assuming wave-like solution
  $\mathrm{U_f} = \mathrm{U_m}(y, z)\,\exp\{\imath(k\ x + \omega\ t)\}$
- Solve 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

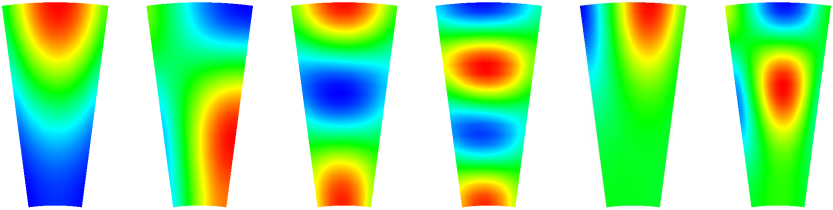
Aeroacoustic Test Case

Category 4 Benchmark Problem from 3rd CAA Workshop

Number of vanes	24
Number of blades	16
Axial Mach number	0.5
Hub to tip ratio	0.5
Gap to chord ratio at tip	1.0
Mach tip (incoming wake)	0.783
Incoming amplitude	0.1 U_∞



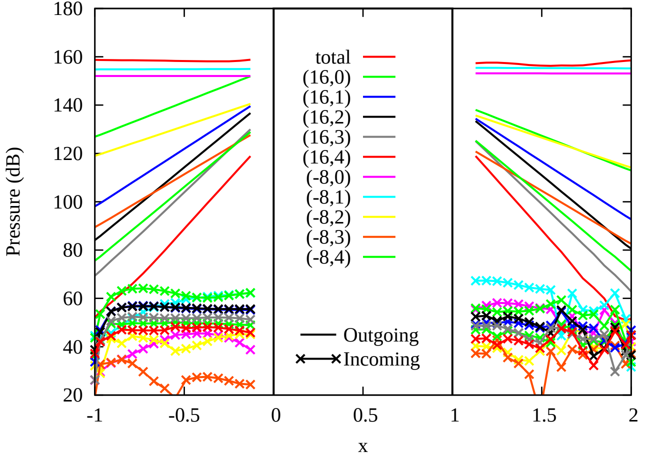
Example Far-field Acoustic Modes



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

Aeroacoustic Test Case

Category 4 Benchmark Problem from 3rd CAA Workshop: Case 4



Wave plot

Category 4 Benchmark Problem from 3rd CAA Workshop: Case 4

m	μ	Namba	Schulten	RPMTurbo
16	0	7.395E-04	7.064E-04	6.225E-04
16	1	2.417E-05	2.487E-05	2.226E-05
16	2	3.326E-06	3.329E-06	3.442E-06
16	3	7.577E-07	7.299E-07	7.711E-07
-8	0	1.178E-02	1.174E-02	1.096E-02
-8	1	1.930E-02	1.906E-02	1.481E-02
-8	2	2.201E-04	1.346E-04	2.393E-04
-8	3	5.283E-06	4.248E-06	8.079E-06

Case 4: Amplitudes of Outgoing Acoustic Modes at Inlet

Aeroacoustic Test Cast

Category 4 Benchmark Problem from 3rd CAA Workshop: Case 4

m	μ	Namba	Schulten	RPMTurbo
16	0	1.045E-04	1.053E-04	1.335E-04
16	1	1.172E-05	1.025E-05	1.230E-05
16	2	2.237E-06	2.375E-06	2.393E-06
16	3	4.373E-07	5.301E-07	4.354E-07
-8	0	1.714E-02	1.497E-02	1.243E-02
-8	1	1.895E-02	1.785E-02	1.561E-02
-8	2	1.863E-04	2.670E-04	1.457E-04
-8	3	2.804E-06	4.294E-06	3.885E-06

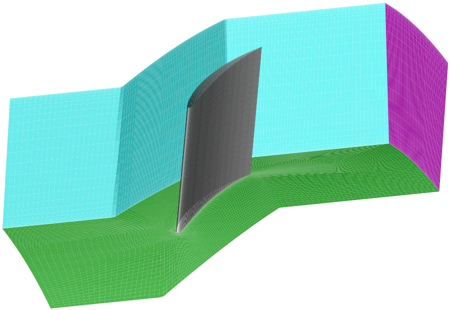
Case 4: Amplitudes of Outgoing Acoustic Modes at Exit

Flutter Test Case

3D Standard Configuration 10

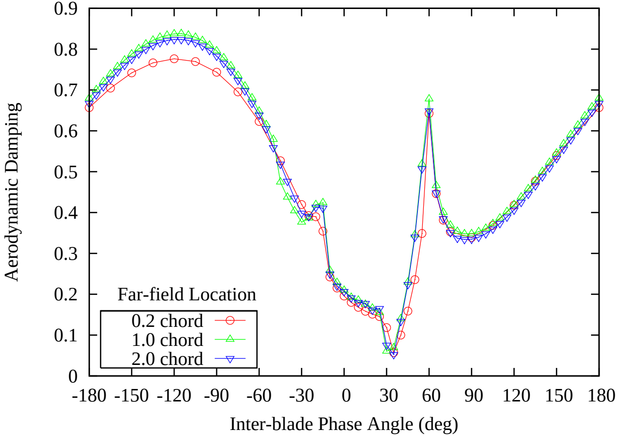
Geometry and Flow Conditions

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



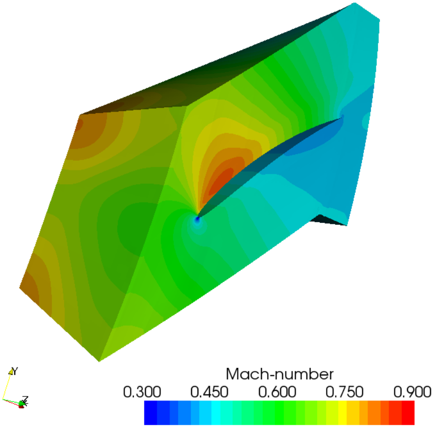
3D Standard Configuration 10

Unsteady Linearised Inviscid Flow Solution with 3D NRBC



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

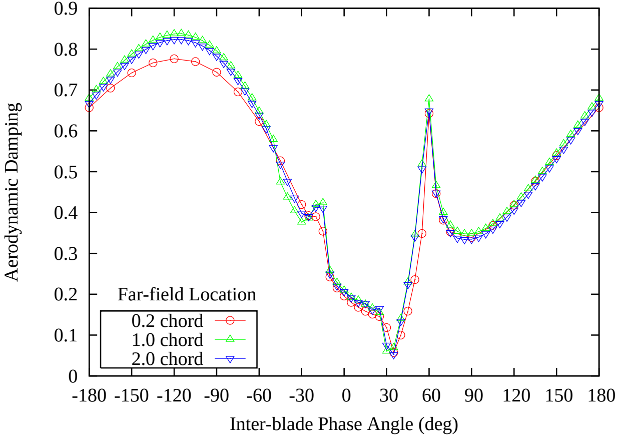
3D Standard Configuration 10



Short Flow Domain: Far-field @ 0.2 chord

3D Standard Configuration 10

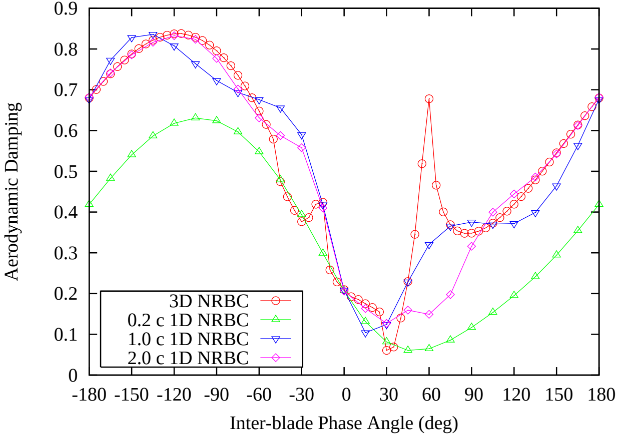
Unsteady Linearised Inviscid Flow Solution with 3D NRBC



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

3D Standard Configuration 10

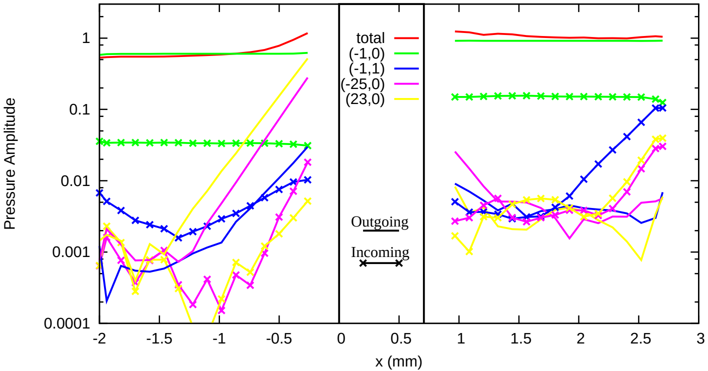
Unsteady Linearised Inviscid Flow Solution with 1D NRBC



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

3D Standard Configuration 10

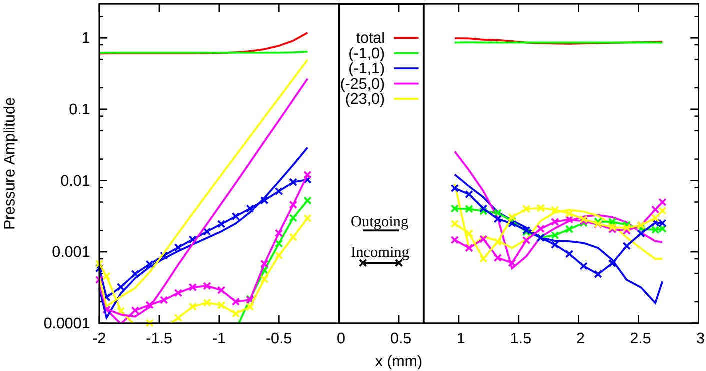
Unsteady Linearised Inviscid Flow Solution with 1D NRBC



Wave Plot for Torsion Mode ($\sigma = 15^o$, $\omega^* = 0.5$)

3D Standard Configuration 10

Unsteady Linearised Inviscid Flow Solution with 3D NRBC



Wave Plot for Torsion Mode ($\sigma = 15^o$, $\omega^* = 0.5$)

Conclusion

Conclusions

- Exact 3D non-reflecting boundary condition has been developed
- Aeroacoustic test case: Category 4 Benchmark Problem. Solution agrees well with other solutions.
- Flutter test case: 3D Standard Configuration 10. Solution independent of far-field location.