Numerical Simulations of Turbine Blade Flutter

Ing. Marek Pátý

Supervisor: doc. Ing. Jan Halama, PhD.

Field of Study: Mathematical and Physical Engineering

Motivation

The design of a turbomachine needs to be executed with a careful consideration of aeroelastic effects in order to guarantee a long and safe operation. One of the greatest risks represent self-excited vibrations, called flutter. Once initiated, their rapidly increasing magnitude threatens to induce a catastrophic failure within a very short time. An accurate prediction of the phenomenon is complicated by the compact spatial arrangement of turbomachines, due to which a perturbation formed at the inlet or outlet boundary impacts directly the near-blade flow solution. A correct formulation of boundary conditions is especially important in last-stage steam turbine rotors which may encounter supersonic inflow conditions at higher spans and feature an upstream propagating bow-shock. This thesis introduces a model for flutter prediction and focuses on the treatment of non-reflecting boundary conditions (NRBC).

Aims of the Thesis

1. Implement and validate a computational model for blade cascade flutter predictions.
2. Analyse the performance of the Spectral NRBC in nonlinear flows.
3. Quantify the impact of unsuppressed wave reflections on aeroelastic assessments.
4. Assess the sensitivity of flutter predictions to domain extent.

Computational Model

The aeroelastic analysis is primarily based on the energy method with prescribed harmonic blade oscillations, but a fully coupled solution of fluid-structure interaction (FSI) with two structural degrees of freedom (DOF) is also provided.

Flow Model

The solution of unsteady aerodynamics adopts Euler equations in 2D, cast in the Arbitrary Lagrangian-Eulerian formulation and discretised with a FVM. The in-house solver implemented in C++ features:

- AUSM$^+$-up scheme for inviscid fluxes (Liou, 2006)
- Gradient reconstruction with weighted least squares method
- Multidimensional face-based gradient limiter (Delis and Nikolos, 2014)
- Temporal integration with an implicit second-order accurate scheme compliant with the Geometric Conservation Law
- Local time-stepping and implicit residual smoothing

Boundary Conditions

The implemented NRBC for inflow and outflow are based on the theory of Giles (1988). The flow equations are linearised:

$$\frac{\partial \boldsymbol{q}}{\partial t} + A\frac{\partial \boldsymbol{q}}{\partial x} + B\frac{\partial \boldsymbol{q}}{\partial y} = 0 \qquad (1)$$

and the boundary flow-field is reconstructed as a superposition of a mean state and perturbations in the form:

$$\boldsymbol{q} = \mathrm{Re}(\hat{\boldsymbol{q}} e^{\mathrm{i}(kx+my+\omega t)}). \qquad (2)$$

Based on the solution of an eigenvalue problem, the incoming and outgoing waves can be distinguished. The following boundary conditions are implemented:

- The *Spectral NRBC* (Schlüß et al., 2016) prescribes zero amplitude to all spatial and temporal modes of incoming waves
- The *Exact Steady NRBC* (Giles, 1988) treats only spatial modes
- The *Simple Turbomachinery BC* is unrelated to Giles' theory and lacks a non-reflecting treatment

Acknowledgements

I gratefully acknowledge that this work was supported by the Grant Agency of CTU in Prague, namely grants No. SGS16/206/OHK2/3T/12 and No. SGS19/154/OHK2/3T/12, and by the Center of Advanced Aerospace Technology (CZ.02.1.01/0.0/0.0/16_019/0000826) in the framework of ESIF, EU Operational Programme Research, Development and Education.

Results

Airfoil NACA 0012

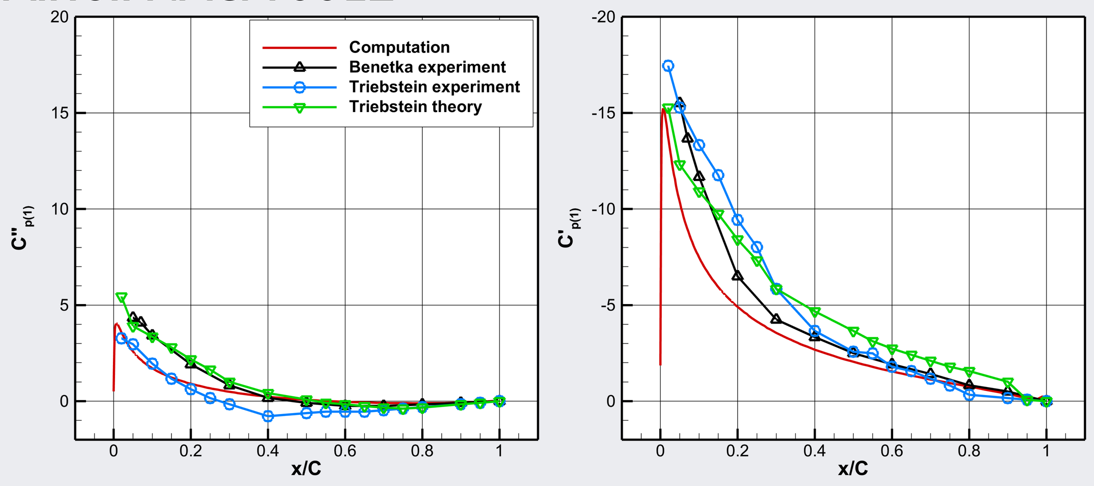

Fig. 1. Real (left) and imaginary (right) part of the 1st unsteady pressure harmonic on airfoil surface, prescribed oscillations

- Solution of unsteady aerodynamics for harmonic pitching oscillations validated by comparison with experimental data
- Fully-coupled FSI computations predict transition from damped oscillations through torsional divergence to flutter instability with freestream velocity increase

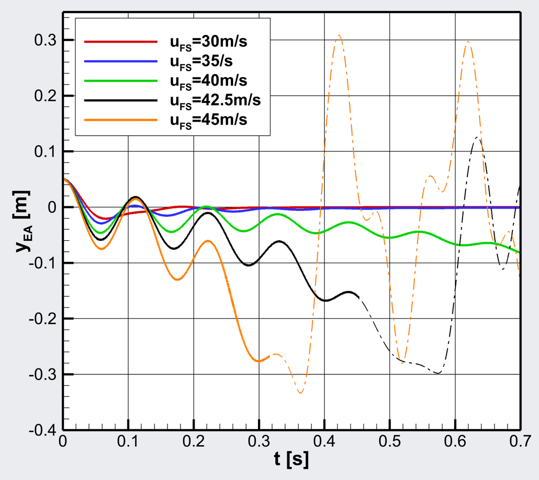

Fig. 2. Coupled FSI with 2 DOF

Transonic Turbine Cascade STCF4

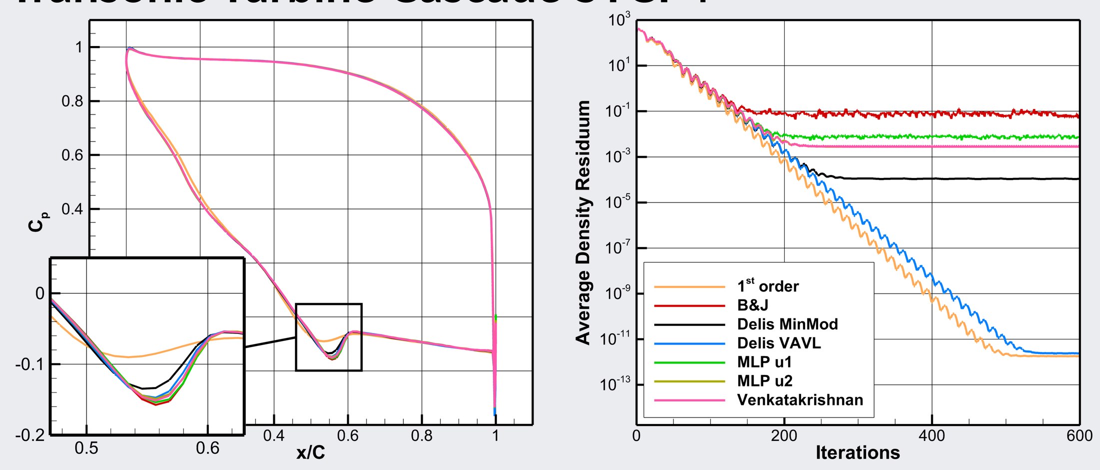

Fig. 3. Pressure coefficient distributions on blade surface (left) and convergence histories (right) with different limiters

- The Delis & Nikolos limiter is the best performing
- Aerodynamic damping predictions of the Spectral NRBC and the Exact Steady NRBC match closely

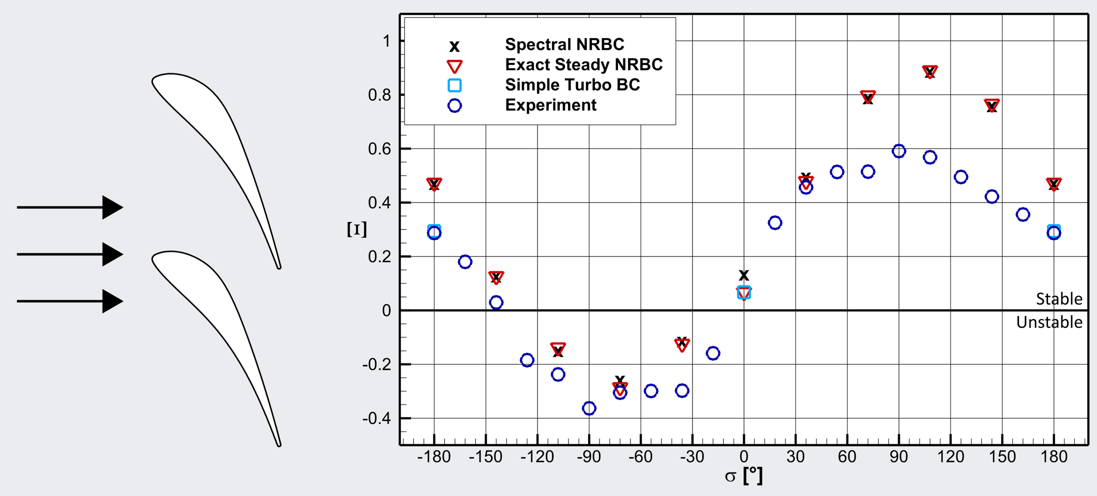

Fig. 4. Aerodynamic damping curve

Subsonic Compressor Cascade STCF10

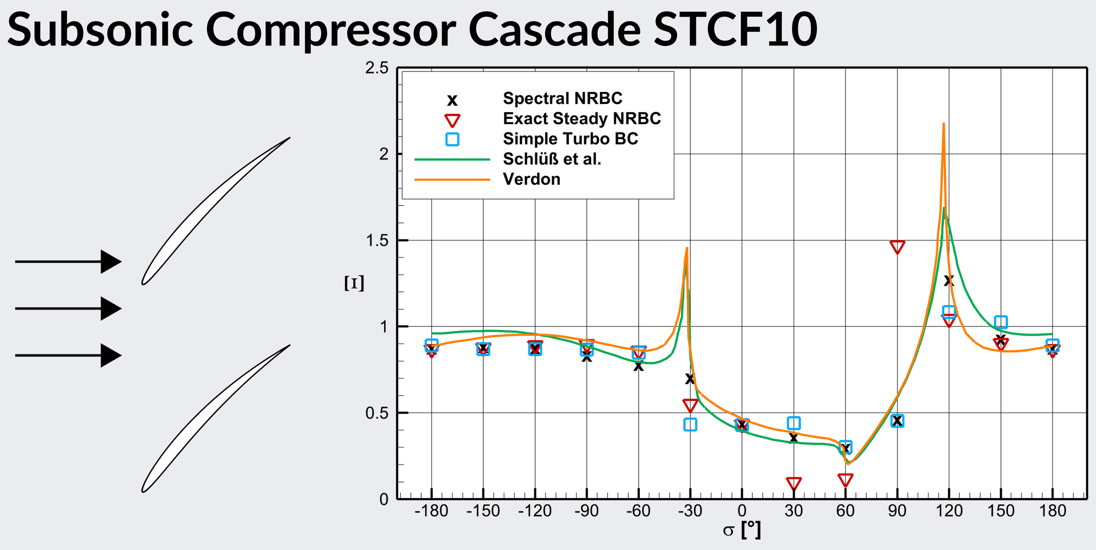

Fig. 5. Aerodynamic damping curve

- Spectral NRBC predictions of aerodynamic damping match numerical results of other authors
- The other two BCs produce spurious perturbations

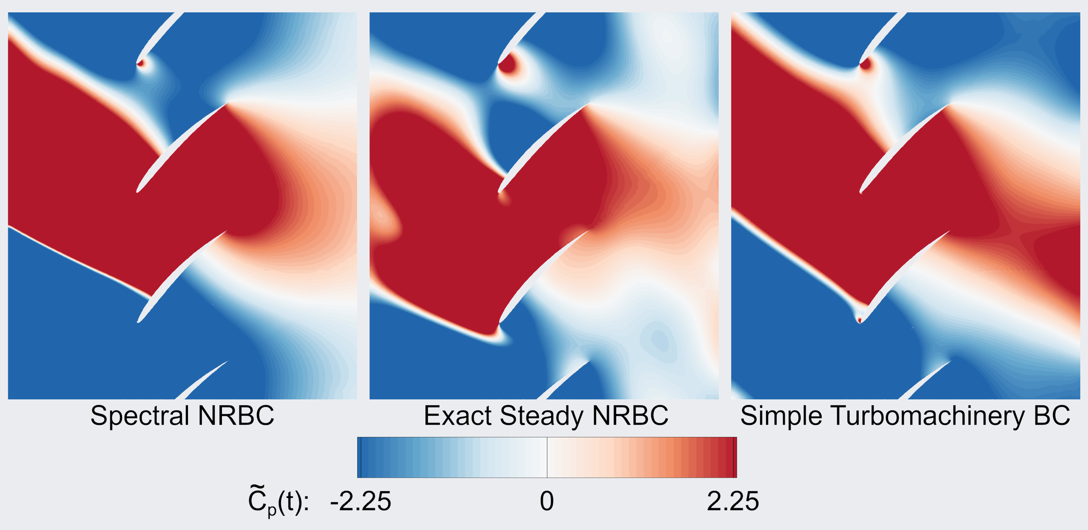

Fig. 6. Instantaneous unsteady pressure fluctuations, $\sigma = 120°$

Supersonic Turbine Cascade M8

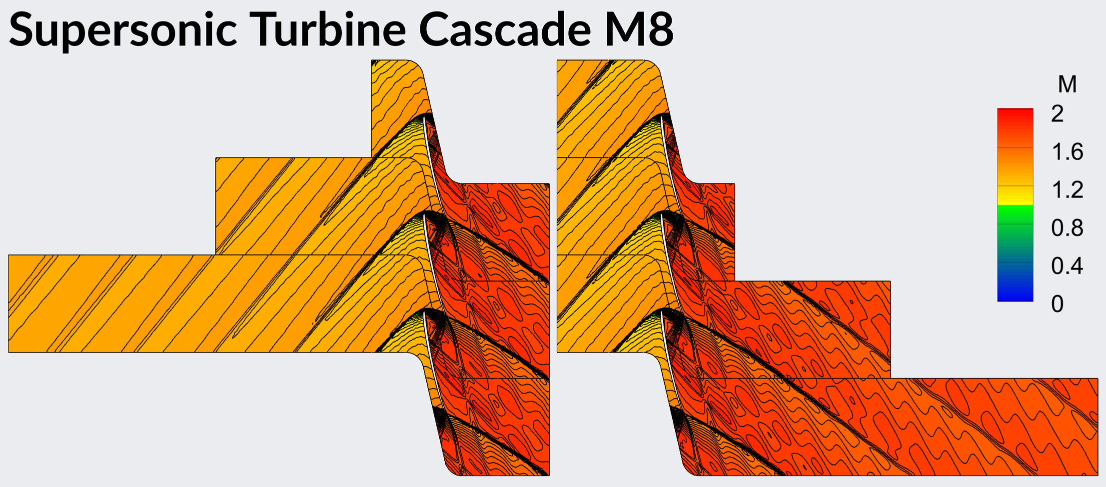

Fig. 7. Steady-state Mach number contours, Exact Steady NRBC

- Steady-state results with the Exact Steady NRBC and damping predictions with the Spectral NRBC exhibit little sensitivity to domain extent
- Discrepancy between the Exact Steady NRBC and the Spectral NRBC near acoustic resonance

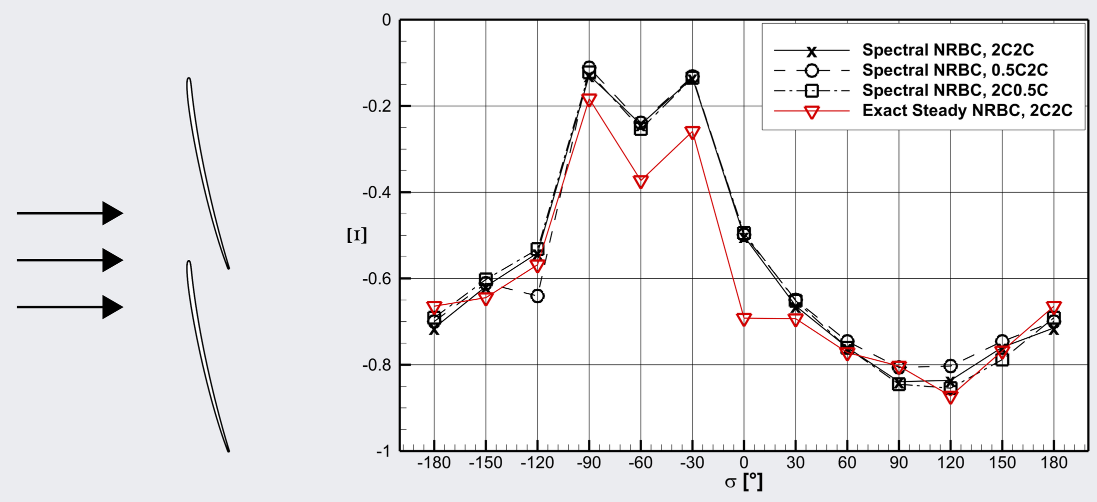

Fig. 8. Aerodynamic damping curve

Conclusions and Outlook

Conclusions

- The Spectral NRBC is highly effective in suppressing wave reflections in complex flow conditions, including a supersonic inflow
- Wave reflections are not completely prevented, but have insignificant effect on the near-blade flow-field
- The Spectral NRBC exhibits only a very mild sensitivity to the inflow and outflow positions
- A BC with insufficient reflection properties (Exact Steady NRBC, Simple Turbomachinery BC) can yield fundamentally incorrect aeroelastic assessments

Research Outlook

- Replace the underlying linearised model of the Spectral NRBC with a higher-order formulation
- Construct a NRBC for aperiodic flows

References

Author's publications

Pátý, M., & Halama, J. (2019). Numerical simulation of aeroelastic effects for an airfoil with two degrees of freedom. *ACC Journal*, *25*(1).

Pátý, M., & Halama, J. (2021). On the use of a flux-splitting scheme in the numerical flutter analysis of a low-pressure turbine stage. *Acta Polytecnica*, *61*(SI).

Pátý, M., & Halama, J. (2020). On the application of non-reflecting boundary conditions to a turbine flutter simulation with a supersonic inlet. *ESCO 2020*.

Bibliography

Delis, A., & Nikolos, I. (2014). On a solution reconstruction and limiting procedure for unstructured finite volumes. *American Institute of Mathematical Sciences (AIMS) Journal Vol 8*, 491–499.

Giles, M. (1988). *Non-reflecting boundary conditions for the Euler equations* (Technical Report). Computational Fluid Dynamics Laboratory, Dept. of Aeronautics & Astronautics, MIT. CFDL-TR-88-1.

Liou, M.-S. (2006). A sequel to AUSM, part II: AUSM+-up for all speeds. *Journal of Computational Physics*, *214*(1), 137–170.

Schlüß, D., Frey, C., & Ashcroft, G. (2016). Consistent non-reflecting boundary conditions for both steady and unsteady flow simulations in turbomachinery applications. *ECCOMAS Congresses, Greece*.