# GT2014-26874:Advanced Flutter Analysis of a Long Shrouded Steam Turbine Blade

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# Outline of Presentation

**Title: Advanced Flutter Analysis of a Long Shrouded Steam Turbine Blade**

- Flutter Analysis for Turbomachinery (Steam Turbines)
- LMZ Steam Turbines
- Current Project: Flutter Analysis of New Blade
- Method Description: Linearized flow solver (multi-row steady-state, URANS, wet-steam, 3D-NRBC)
- Results of current flutter analysis
- Conclusions

**Flutter:** self-excited vibration due to the interaction between aerodynamic and structural dynamic forces. Classical flutter is due to an adverse phase difference between the structural motion and the unsteady aerodynamic forces.

**Aeroelastic System for Turbomachinery**

- Assume each blade is identical (tuned blades)
- Unsteady aerodynamic forces do not alter structural deformation or frequency
- Each blade has only 1 degree of freedom (single structural mode)
- Unsteady flow perturbations are linear with respect to blade vibrations (small perturbation)
- Blades are coupled aerodynamically and possibly structurally
- Each blade has same relative equation of motion (cyclic symmetric)

Aeroelastic eigenmodes are **Travelling Wave Modes** (TWM)

- For each TWM mode the blades are oscillating at equal amplitude with a constant phase shift between adjacent blades
- Inter-blade phase angle:
  $\sigma_n = \frac{2\pi n}{N}$, $(0 < n < N - 1)$

Flutter Analysis for Turbomachinery

- Examine stability for each TWM
- Determine unsteady flow (pressure) response
- Determine work done by unsteady pressure on blade
- Positive work: potential flutter problem

**Logarithmic Decrement:**

$$\delta = \frac{-\mathrm{W}_{\mathrm{aero}}}{2\ \mathrm{K.E.}_{\mathrm{max}}}$$

## Flutter in Steam Turbines

- Flutter vibrations have been observed by several manufacturers
- Occurs at blade mode frequency from first family of modes
- Not associated with an engine order (Campbell diagram)
- Mostly affects the last stage
- Complex blade geometry: long and twisted
- Low blade natural frequency (current case: $\omega^* < 0.2$ to $0.45$)
- High tip speed (current case 700 m/s)
- Transonic flow near tip
- Multi phase flow (wet steam)

# LMZ Steam Turbines

## History

- Founded in 1857, started producing steam turbines in 1907
- Russia's largest manufacturer of power machines
- LMZ turbines installed in 700 power stations in 40 countries
- Since 2000, LMZ is part of Power Machines company

## Today

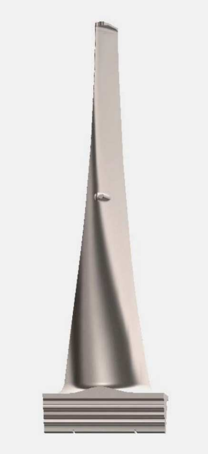
- In late 1970s, LMZ produced steam turbines rated at 1200 MW
- This series of machines have 1.2m titanium blades for the last stage
- Shrouded blade $->$ integral tip covers
- Blades never failed but minor wearing of contact zones
- Occassionally required repair and overhaul

## Vibration Control

- In the 2000s, LMZ installed a system for online vibration control
- Regular vibrations at specific frequencies occurred
- Vibrations corresponded to first group of blade modes at backward-running nodal diameters
- Vibrations were identified as flutter
- Amplitude of vibrations were small and posed no threat to blade but did cause wearing in contant zones

## Flutter Prediction

- In 2007, LMZ began cooperation with RPMTurbo
- Initial project was blind test with 9 OPs
- Some OPs from real machines with field data (not disclosed)
- RPMTurbo performed linearized flow simulations to predict log.-dec
- Results of RPMTurbo flutter analysis agreed with field data



## Scope of Paper

- LMZ designed new series of steam turbines
- Greater exhaust area
- Reduced overall axial length
- Last stage: 1.2m shrouded blade
- Full speed: 3000 RPM
- Aim: Flutter analysis of last stage
- Calculated log.-dec. values compared with values from similar reference blade
- Reference blade has known safe working history

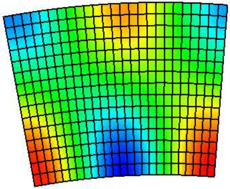
RPMTurbo - LUFT® **L**inearised **U**nsteady **F**low solver for **T**urbomachinery

- 3D URANS flow with Spalart and Allmaras turbulence model
- Turbulence model is fully linearised
- 3D non-reflecting boundary condition (3D-NRBC)
  – solution independent of farfield location
- Wet steam equation of state (equilibrium IAPWS-IF97)
- Tip clearance flow
- Validated - Standard Configuration 10 and 11
- Fast and robust linear solver - 1.1 million cells in 1 hour (1D NRBC ) or 5 hours (3D NRBC)
- Multi-row steady-state
- Complex mode shapes

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

Numerically determine aerodynamic modes at far-field

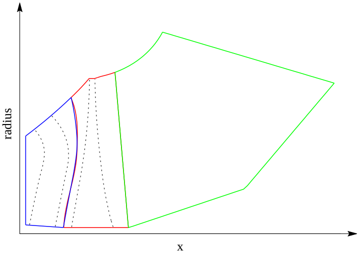


- Create 2D mesh for far-field
- Semi-discretized flow equations
  $\frac{\partial \mathrm{U_f}}{\partial t} = \mathrm{A_f}\frac{\partial \mathrm{U_f}}{\partial x} + \mathrm{D_f U_f}$
- Assuming wave-like solution
  $\mathrm{U_f} = \mathrm{U_m}(y,z)\,\mathrm{exp}\{\imath(k\ x + \omega\ t)\}$
- Solve 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
- Method presented at 2010 Turbo Expo
- Demonstrated that unsteady flow solution is independent of far-field location

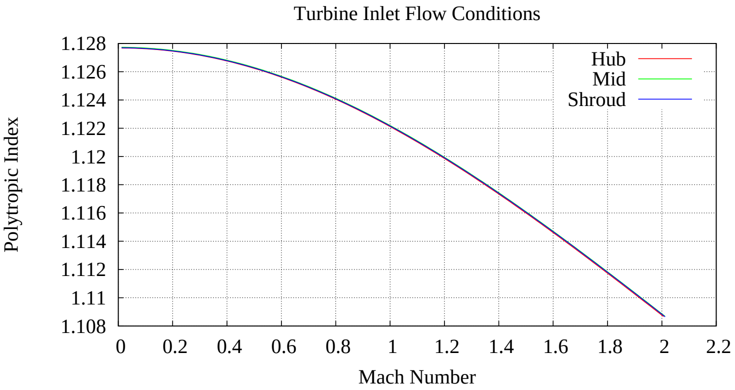
# Computational Model

- Multi-row steady-state simulatons with nozzle & turbine & exhaust
- Flow models: RANS-wet-steam, RANS-ideal, inviscid-wet-steam and inviscid-ideal
- Equilibrium wet-steam equation of state: IAPWS-IF97
- Boundary layer fully resolved ($y^+ < 5.0$) for RANS
- Unsteady single row flutter simulation

| Section | Flow | Number Cells | Min. Angle (degrees) |
|---|---|---|---|
| Nozzle | RANS | 763200 | 24.45 |
| Turbine | RANS | 798208 | 35.44 |
| Exhaust | RANS | 24010 | 69.80 |
| Turbine | Inviscid | 543760 | 34.84 |
| Exhaust | Inviscid | 19110 | 71.19 |

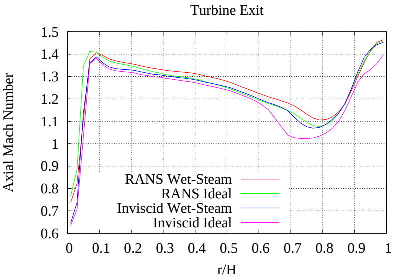


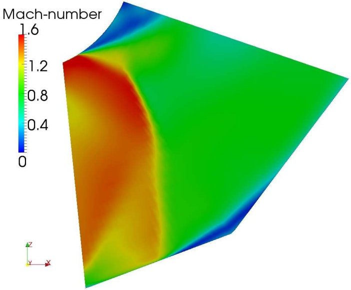
Equilibrium Wet Steam Behaviour

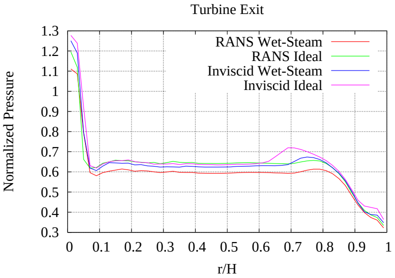


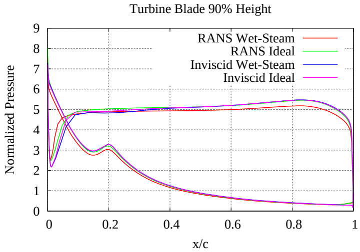

Ideal Gas Model: $k = 1.11$ (match polytropic index)

# Steady-State Results

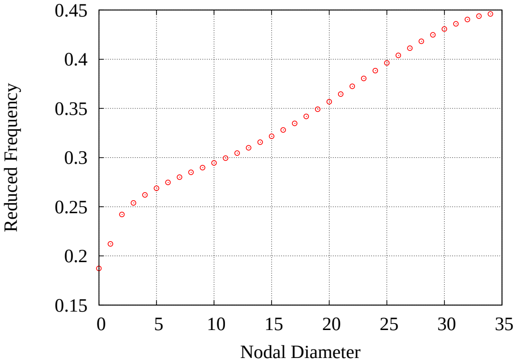


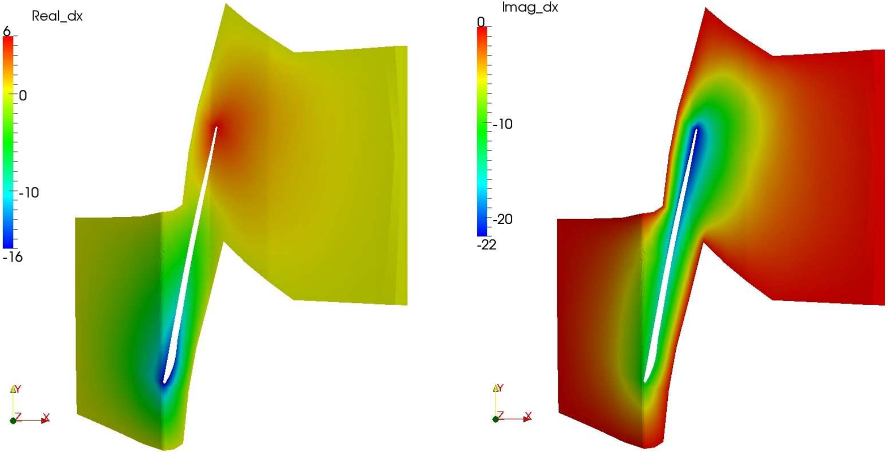



- Shrouded blades have complex mode shape
- Two modes with 90 deg phase difference
- Mode shape and frequency vary with nodal diameter

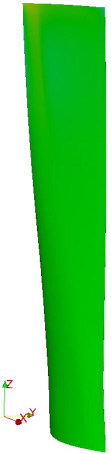


# Mode Shape and Grid Motion

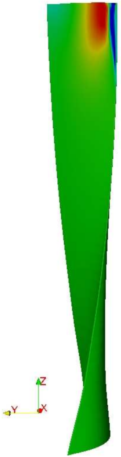



Grid motion at 90% span for nodal diameter 15

Suction Side

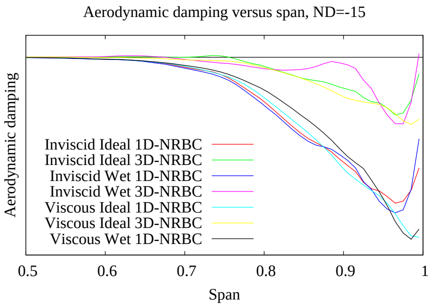


Pressure Side

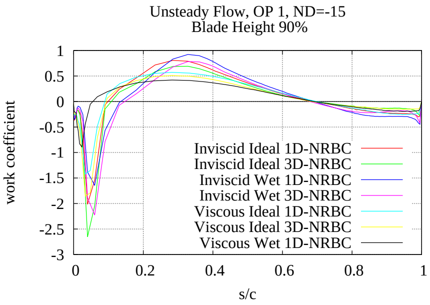


Unsteady Aerodynamic Work

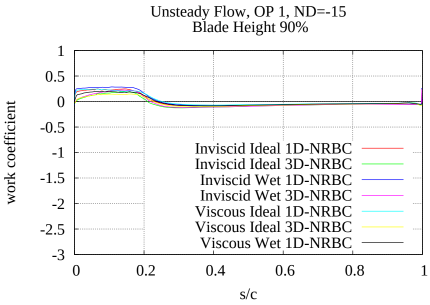
- Most work done near tip




Least stable mode $n = -15$ (Viscous/Ideal/3D-NRBC)

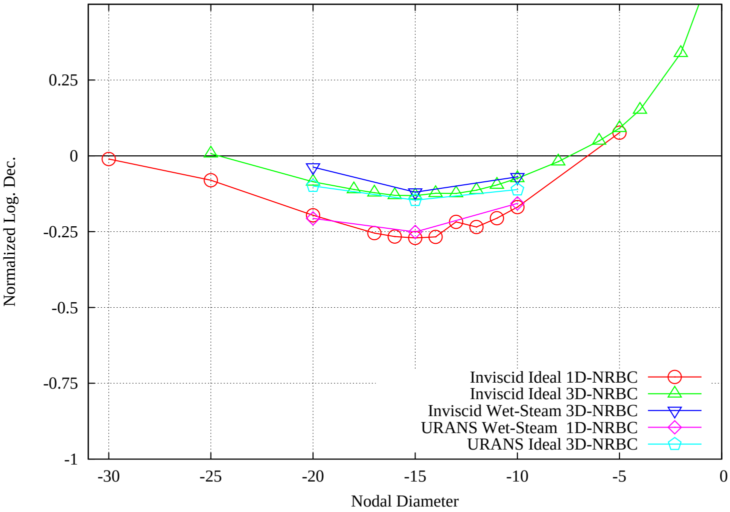



Pressure side

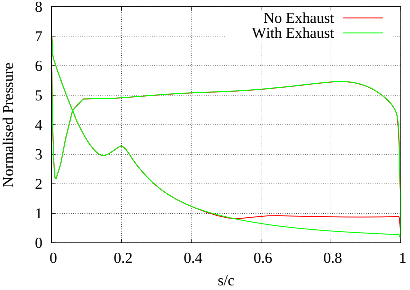



Suction side

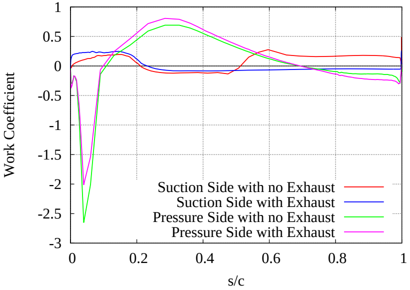
Least stable mode $n = -15$


Normalized Log. Dec.
0.25
0
-0.25
-0.5
-0.75
-1
-30
-25
-20
-15
-10
-5
0
Nodal Diameter
Inviscid Ideal 1D-NRBC
Inviscid Ideal 3D-NRBC
Inviscid Wet-Steam 3D-NRBC
URANS Wet-Steam 1D-NRBC
URANS Ideal 3D-NRBC

## Steady-State

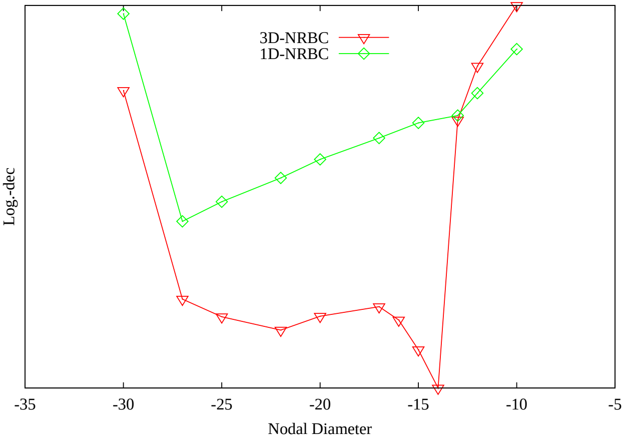



## Unsteady Work




Least stable mode $n = -15$ (Inviscid/Ideal/3D-NRBC)

Different blade, lower pressure ratio, subsonic flow at turbine outlet



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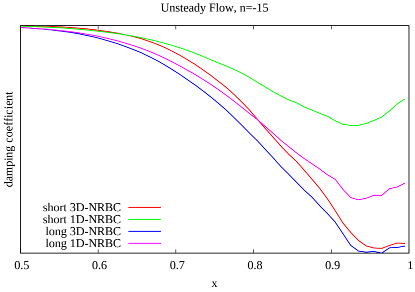


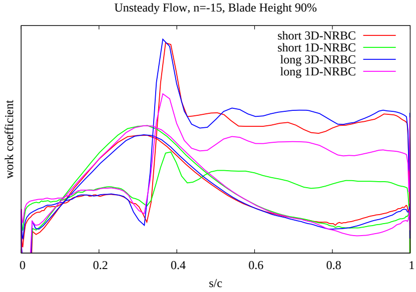


Aerodynamic Damping versus Span

Unsteady Work at 90% Height

Near least stable mode $n = -15$ (Inviscid/Ideal)

- Flutter analysis has been performed on a steam turbine blade from the last stage
- Advanced flow modeling features included: multi-row steady-state, URANS, 3D-NRBC, wet steam
- Calculated minimum log.-dec. value higher (more stable) than reference blade
- Reference blade is similar and has a safe working history
- 3D-NRBC are important for steam turbine flutter
- Viscous and wet-steam effects are minor for the case examined

Thank You for Listening

Vielen Dank für Ihre Aufmerksamkeit