CFD-based Fluid-Structure Interaction Models for Turbomachinery Seals and Gas Turbine Exhaust Systems

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DANSIS Fluid-Structure Interaction Seminar 26 March 2014

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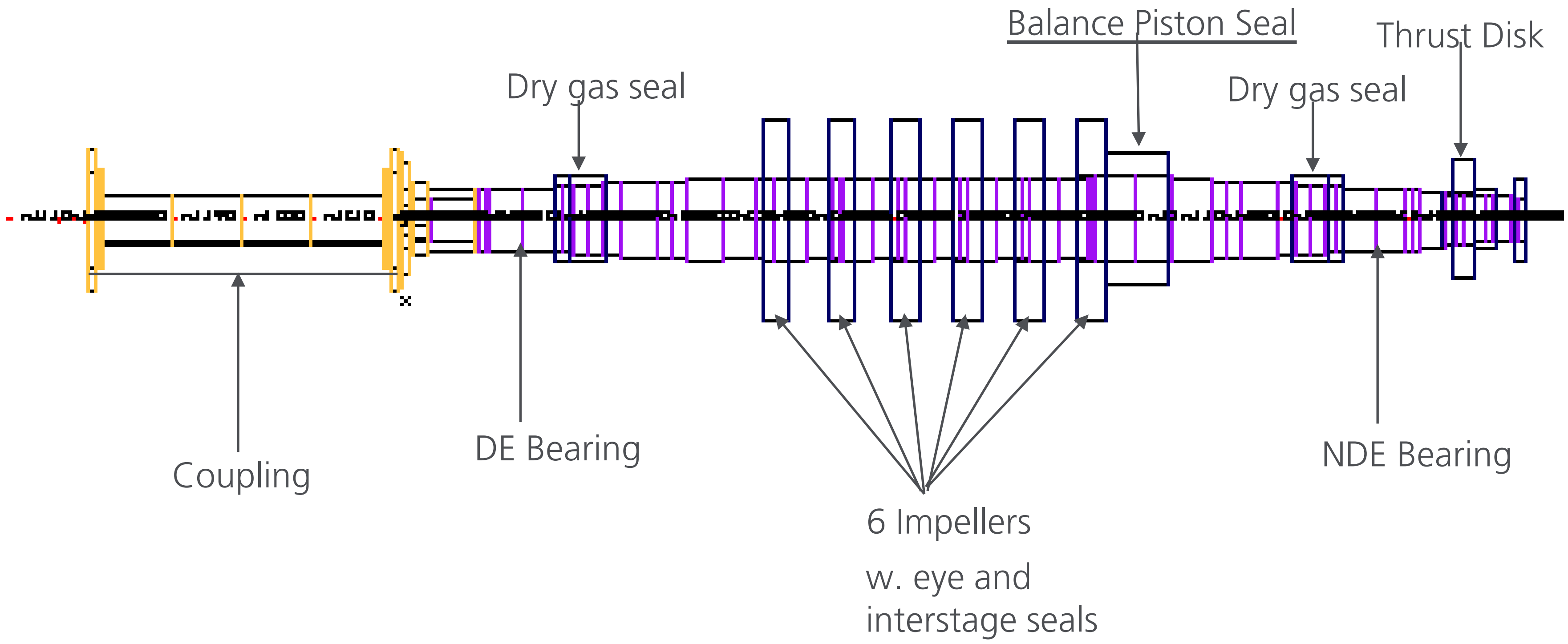
Outline

- Fluid-Structure Interaction Models for Turbomachinery Seals:
  - Rotordynamic models
  - Rotordynamic seal force prediction
  - Grid Perturbation Modelling (GPM)
    - Example
  - Instationary Perturbation Modelling (IPM)
    - Example
- Fluid-Structure Interaction Models for Gas Turbine Exhaust Systems:
  - Overview of typical gas turbine exhaust system
  - CFD analysis techniques and results
  - High Cycle Fatigue (HCF) exhaust failures – caused by vibrations
  - FSI vibration analysis techniques and results
  - On-site vibration measurements
  - Low Cycle Fatigue (LCF) exhaust duct failures - caused by thermal loads
  - FSI thermal analysis techniques and results

Turbomachinery Seals: Rotordynamic Models

- High pressure compressor example (offshore gas injection)



Blind Test Case (Round Robin): Seal Rotordynamic Forces etc

- Kocur and Nicholas at 36th Turbo Symposium
- Labyrinth seal force assessments included here

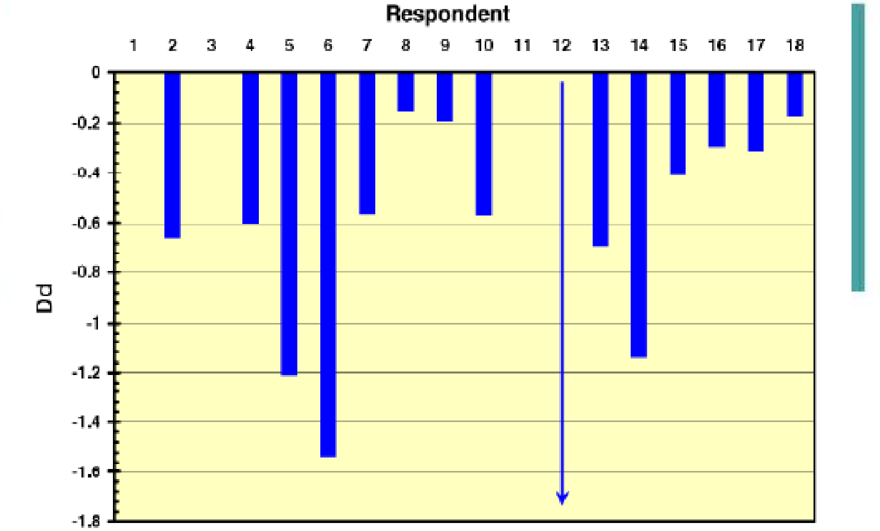


Figure 15. Labyrinth Seal Impact on Predicted Log Dec.

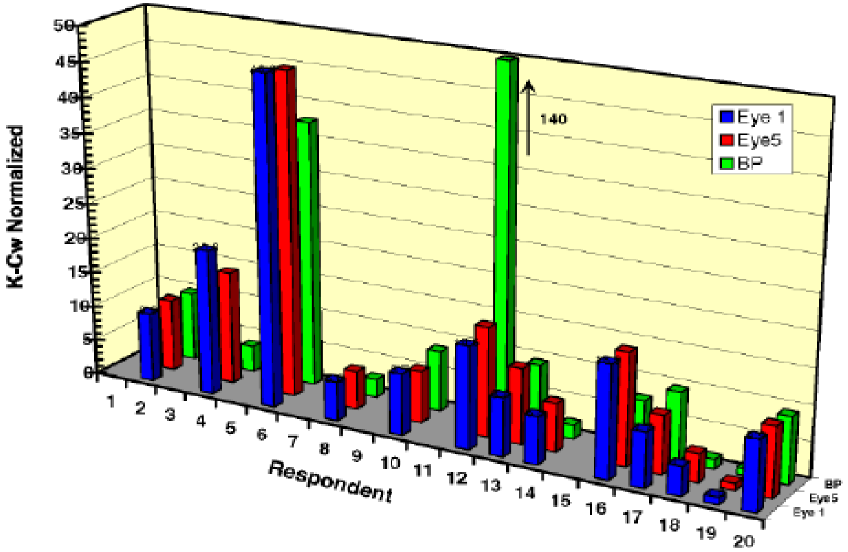


Figure 11. Normalized Destabilizing Force for the Balance Piston Labyrinth.

- Very large spread in seal force predictions
- Dd is the labyrinth seal increment to rotordynamic stability measure "Log Dec" for compressor
- Compressor stability acceptance criterion: Log Dec: 0.2
- Seals often play a critical and maybe not all that well understood role for rotordynamic stability!

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Turbomachinery Seals: Rotordynamic Force Prediction

- How to determine seal rotordynamic forces and coefficients?
- Normal linearized model for reaction forces – assuming small perturbation movements

$$-\begin{Bmatrix}F_x\\ F_y\end{Bmatrix} = \begin{bmatrix}K & k\\ -k & K\end{bmatrix}\begin{Bmatrix}X\\ Y\end{Bmatrix} + \begin{bmatrix}C & c\\ -c & C\end{bmatrix}\begin{Bmatrix}\dot{X}\\ \dot{Y}\end{Bmatrix} + \begin{bmatrix}M & 0\\ 0 & M\end{bmatrix}\begin{Bmatrix}\ddot{X}\\ \ddot{Y}\end{Bmatrix}$$

- Experience or empirical formulas
- Bulkflow seal codes: very fast special purpose codes for specific seal configurations
    - several knobs to turn in order to calibrate against experimental data
- What to do for new advanced seal designs or operation outside experimental data?
- CFD based prediction techniques have proven reliable
    - extensive validation has been undertaken by LRC and other parties
- Description of CFD based methods to follow

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Grid Perturbation Modelling (GPM)

- Whirling rotor model / Grid Perturbation Model (GPM)
- Rotor circular whirl orbit imposed
- Solving for rotating frame of reference model
- Steady state CFD calculation
- 5-20% of clearance imposed as eccentricity
- Force integration

$$F_r = \sum_{rotor} pA_y \qquad F_t = \sum_{rotor} pA_x$$

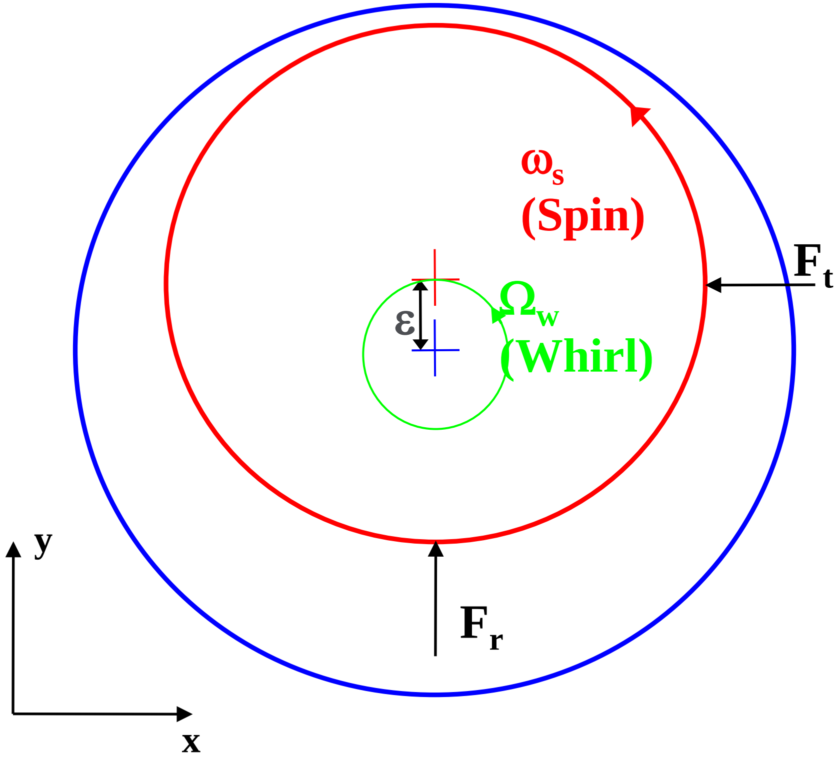
- Several whirl speeds + curve fitting gives coefficients

$$\overline{F_t} = \frac{F_t}{\varepsilon} = k - C\Omega_w - m\Omega_w^{\ 2}$$

$$\overline{F_r} = \frac{F_n}{\varepsilon} = -K - c\Omega_w + M\Omega_w^{\ 2}$$

- GPM neither handles non-axisymmetry geometry nor provides frequency dependent coefficients

Schematic cut through seal (perpendicular to axis of rotation):



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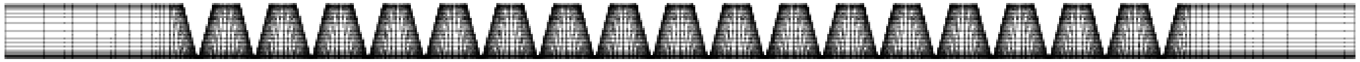
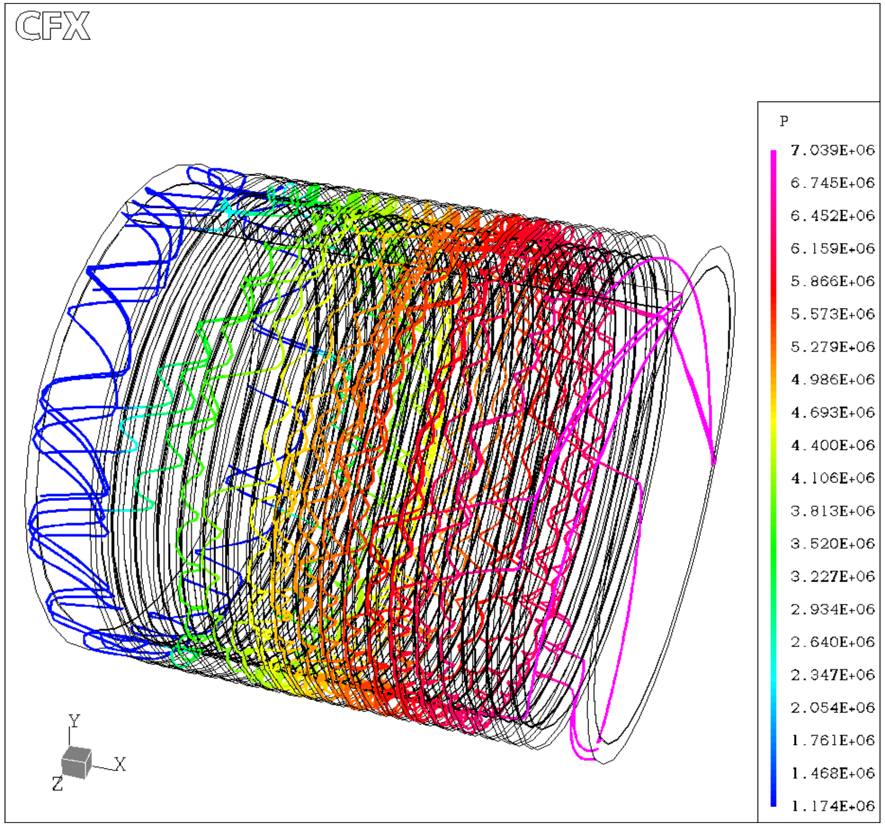
GPM of Long Labyrinth Seal Example





- 18 teeth Teeth-on-Stator labyrinth seal
- Axial cut of seal
- 3D model representation
- Inlet and outlet cavities
- 10% eccentricity
- Model size: 1.5 million nodes

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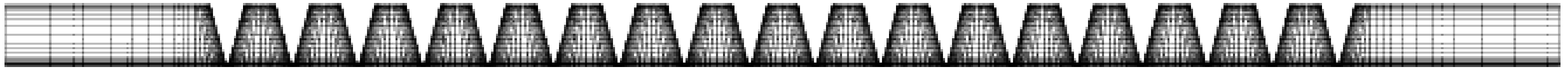
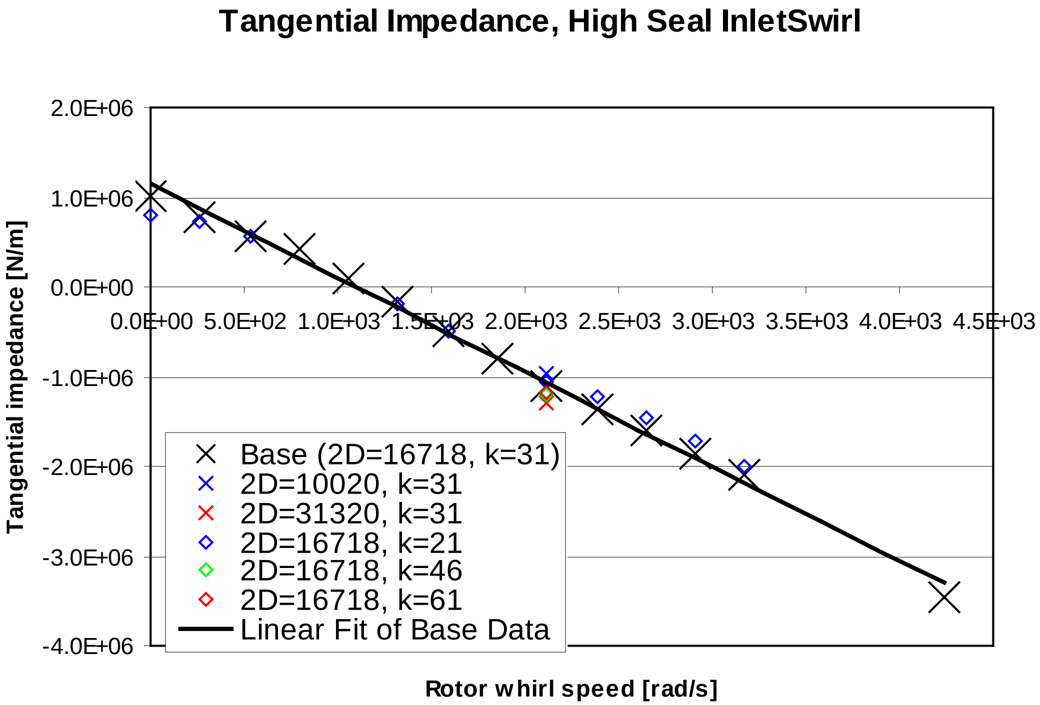
GPM of Long Labyrinth Seal Example





- Typically 4-6 whirl frequencies (14 calculated in this example)
- Excellent linear fit (gives k and C)
- Rotordynamic coefficients and seal leakage flow need to be grid independent

Instationary Perturbation Modelling (IPM)

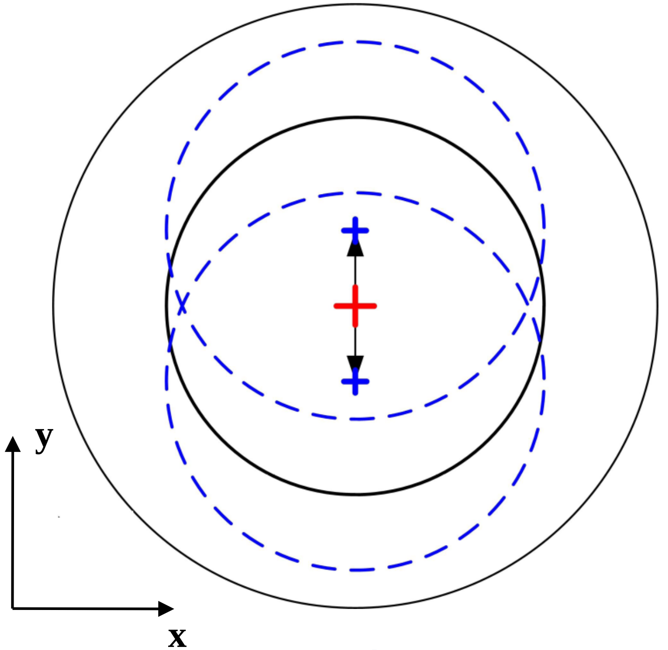
- Handles any geometry, ie. hole-pattern and honeycomb seals
- Prescribed relative movement of rotor wrt stator
- Transient CFD calculations
- Unidirectional sinusoidal motion:

$$Y = A\sin(\Omega t)$$

- Inserted into gas damper seal rotordynamic model:

$$-\begin{Bmatrix} F_x \\ F_y \end{Bmatrix} = \begin{bmatrix} K(\Omega) & k(\Omega) \\ -k(\Omega) & K(\Omega) \end{bmatrix} \begin{Bmatrix} X \\ Y \end{Bmatrix} + \begin{bmatrix} C(\Omega) & c(\Omega) \\ -c(\Omega) & C(\Omega) \end{bmatrix} \begin{Bmatrix} \dot{X} \\ \dot{Y} \end{Bmatrix}$$

Schematic cut through seal (perpendicular to axis of rotation):



- Complex numbers are introduced and the rotordynamic coefficients are given by:

$$Re(-F_y/A) = K(\Omega) \qquad Re(-F_x/A) = k(\Omega)$$

$$Im(-F_y/A) = C(\Omega)\Omega \qquad Im(-F_y/A) = c(\Omega)\Omega$$

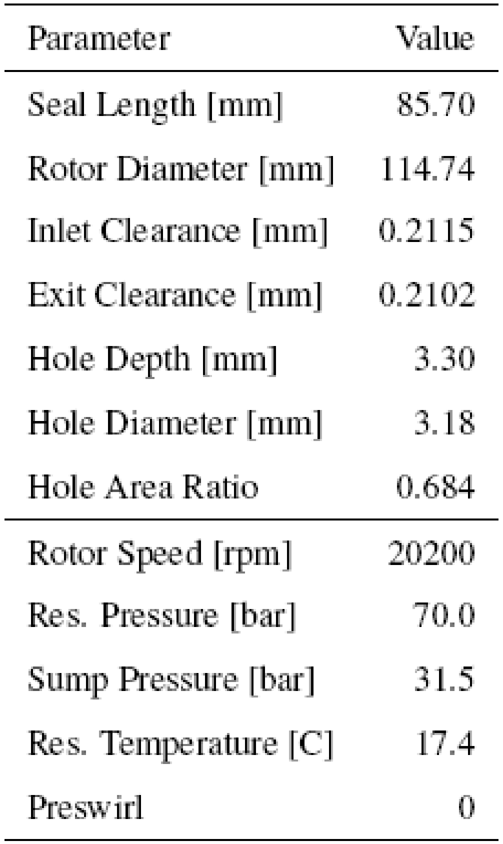
- Reaction forces and the displacement have the same frequency, but are shifted in phase

IPM Setup

- Selected set of perturbation frequencies, typically 3-5 subsynchronous
- Perturbation amplitude: 10% of concentric clearance
- 30-100 time steps per period perturbation period
- Ideal gas fluid properties
- k-ω SST turbulence model
- Scalable wall functions
- ANSYS CFX
- Hole-pattern seals: 2-20 x 10^6 nodes
- Typical run time: 8 hours per point on 64 cores

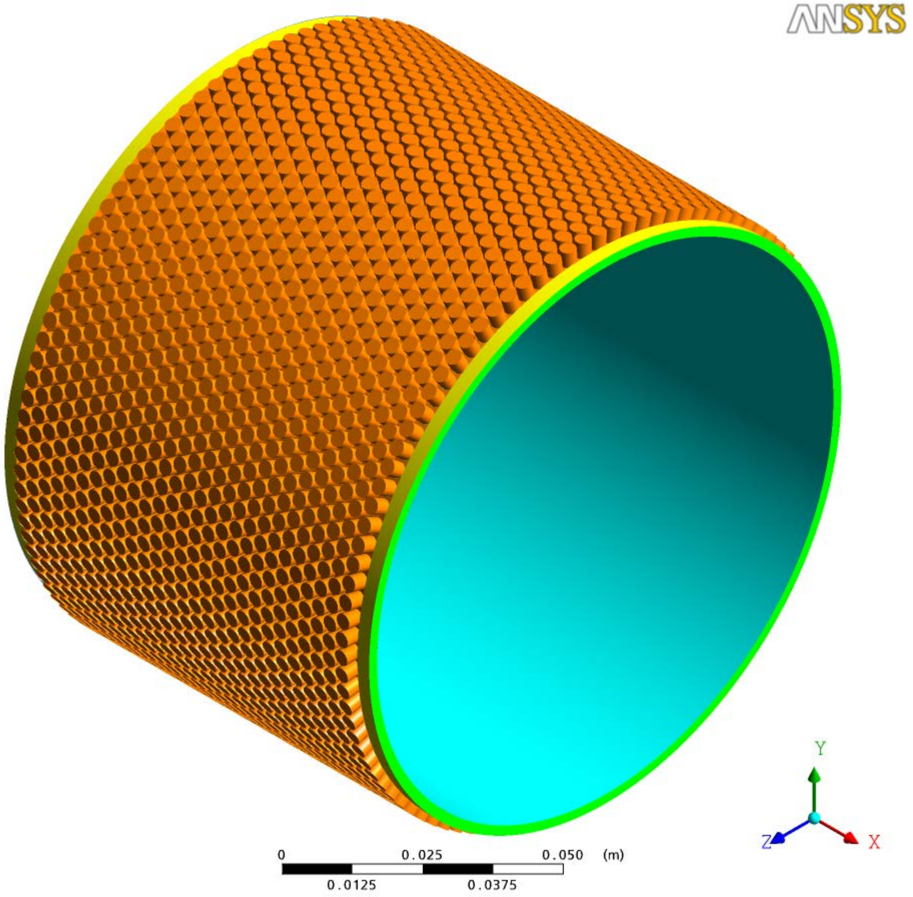
IPM: Constant Clearance Hole-Pattern Seal Example

Seal Data:



Parameter	Value
Seal Length [mm]	85.70
Rotor Diameter [mm]	114.74
Inlet Clearance [mm]	0.2115
Exit Clearance [mm]	0.2102
Hole Depth [mm]	3.30
Hole Diameter [mm]	3.18
Hole Area Ratio	0.684
Rotor Speed [rpm]	20200
Res. Pressure [bar]	70.0
Sump Pressure [bar]	31.5
Res. Temperature [C]	17.4
Preswirl	0

3D Model Representation:



- CFD-based rotordynamic coefficients compared to experimental data and ISOTSEAL bulkflow model predictions
- ISOTSEAL is a state-of-the-art bulkflow model for hole-pattern and honeycomb seals from Texas A&M University TurboLab

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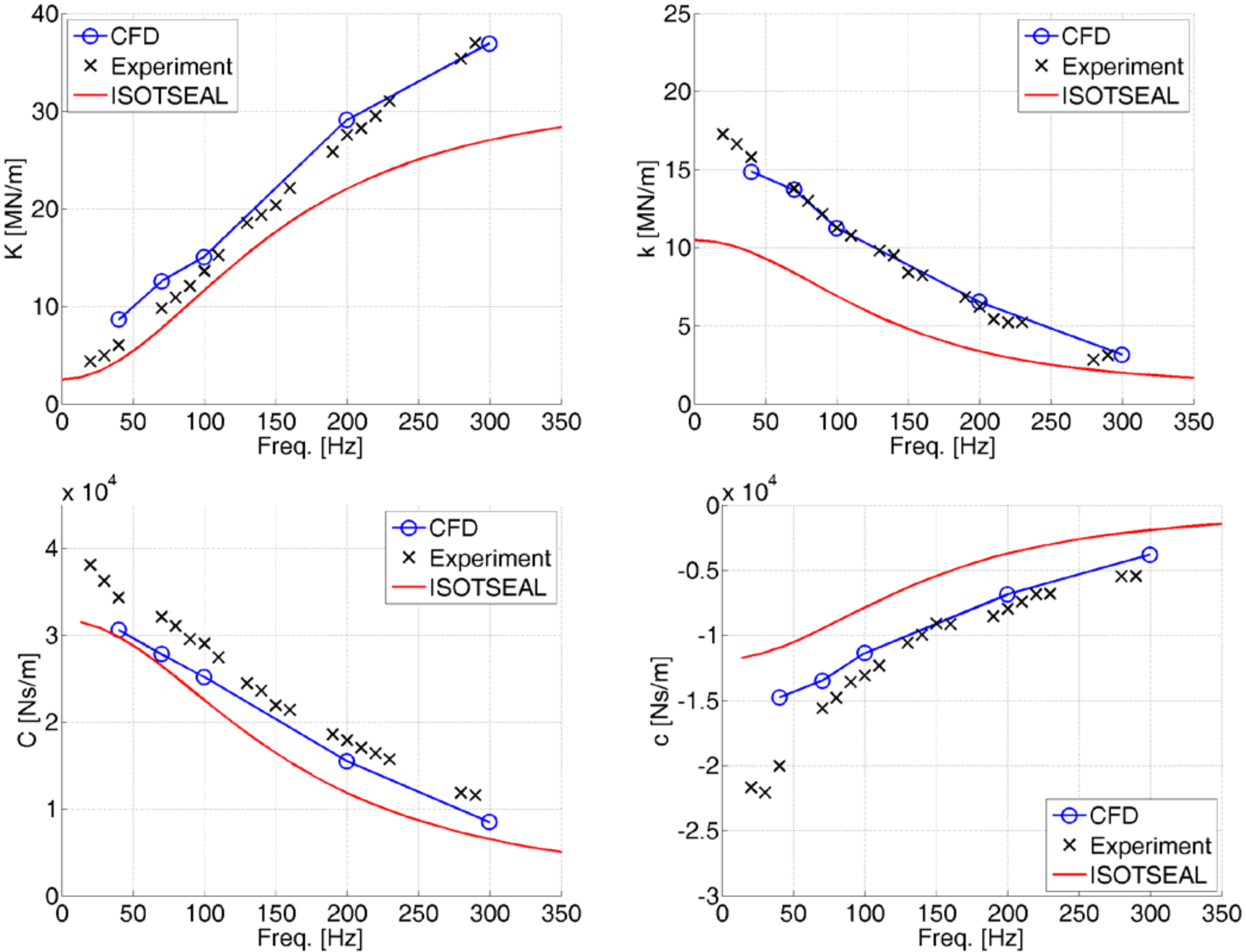
IPM: Constant Clearance Hole-Pattern Seal



- IPM correctly predicts the frequency dependence trends of the rotordynamic coefficients
- Very good agreement with experimental results
- Better prediction than ISOTSEAL for the four coefficients

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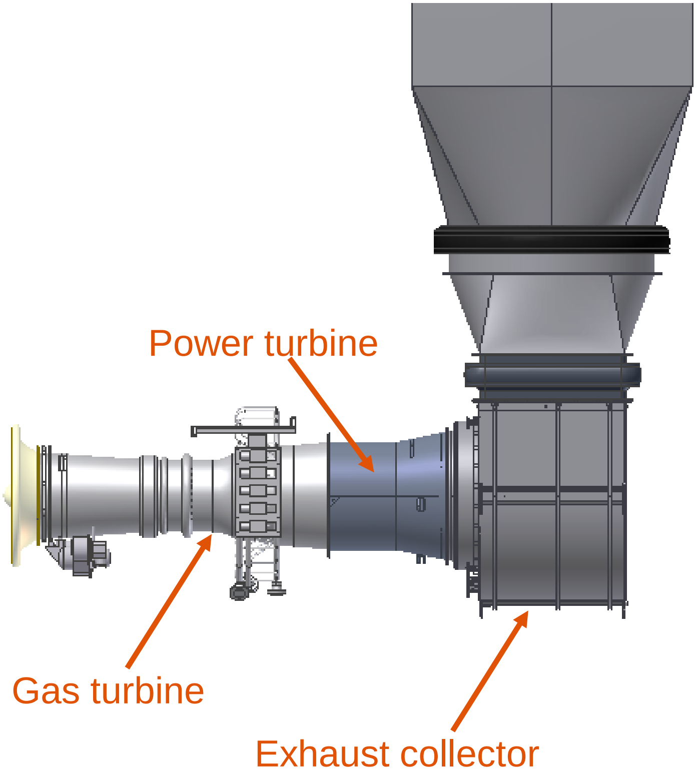
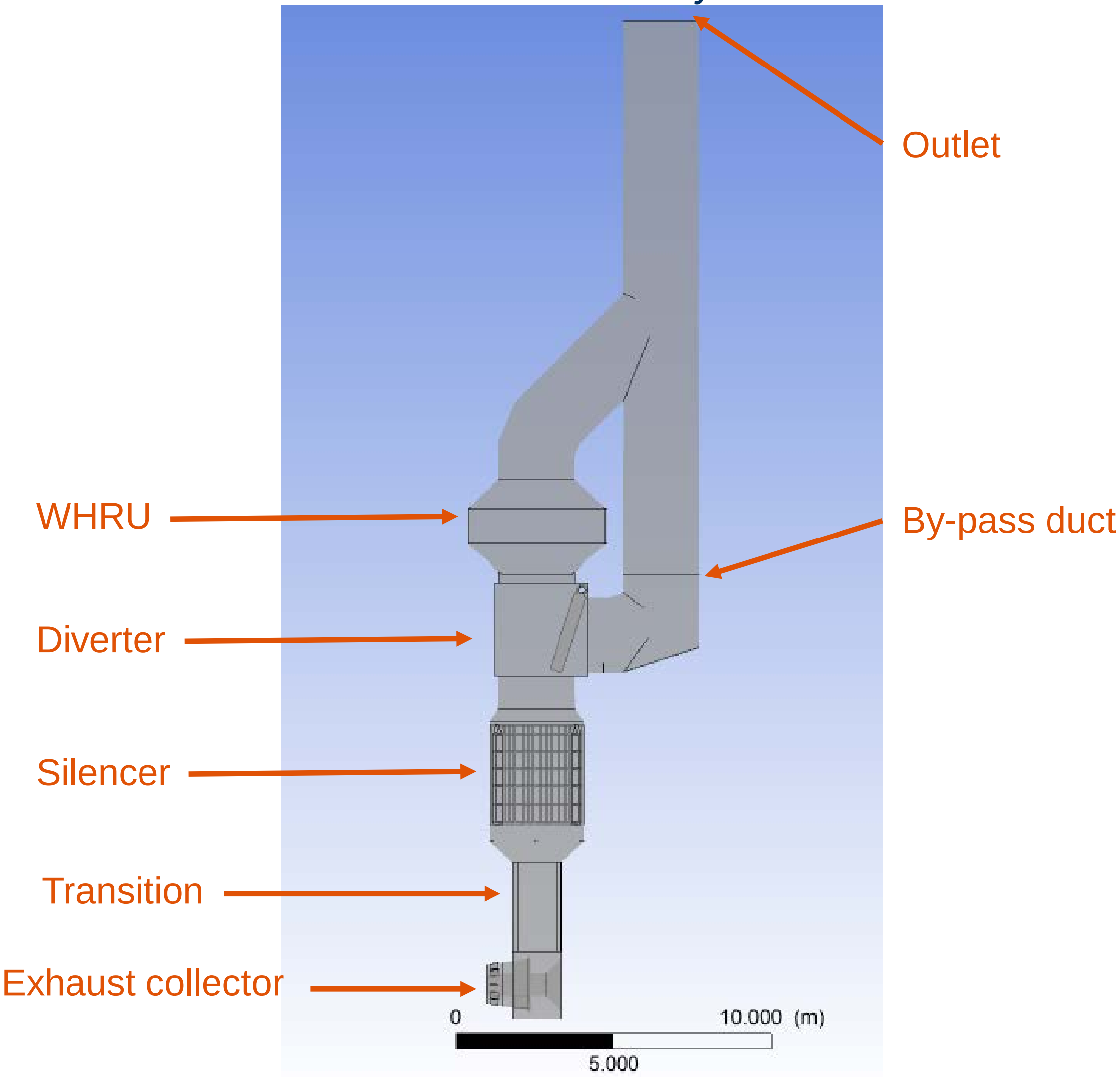
Overview of Typical Gas Turbine Exhaust System

Zoom-in of gas turbine and exhaust collector:



Full exhaust duct system:



- GE LM 2500 and LM 2500+ gas turbines are most frequently used in Norway

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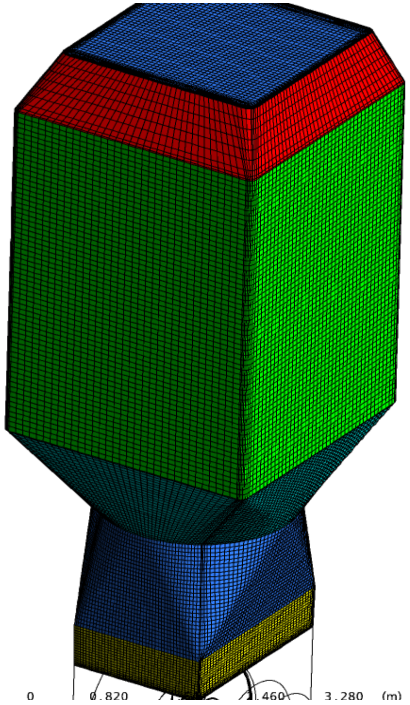
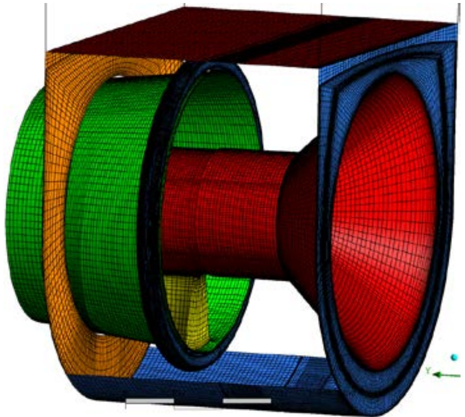
CFD Analysis Techniques

- ANSYS environment: CFX and Fluent CFD codes
- Mesh size: 5-30 million nodes
- y^+ approx. 5-30 for GT exhaust applications
- Law-of-the-wall wall boundary condition
- Time-resolved analyses – required for FSI analyses
- Scale Adaptive Simulation (SAS) turbulence model
- Time step <1*10^{-3} s
- Vendor velocity and temperature profile applied to exhaust collector inlet
- Mass flow at inlet of collector: 70-90 kg/s
- Isothermal, heat transfer and Conjugate Heat Transfer (CHT)
- Temperature ~ 500 degrees Celcius
- Temperature dependent exhaust gas physical properties
- Cluster with 400+ CPU cores





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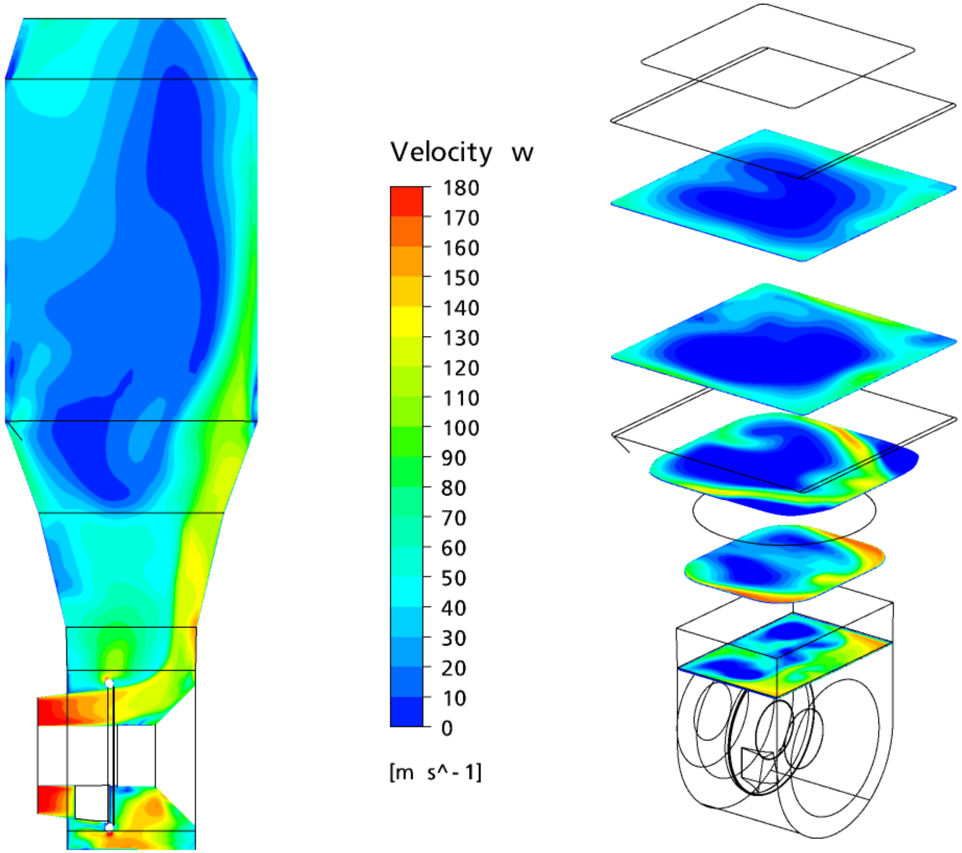
CFD Analysis Results

- Power turbine outlet velocity approx 200 m/s
- Strong power turbine exit jet impacts exhaust collector back wall
- High velocity ”sheet” up along the back wall
- Strongly separated and non-uniform flow
- Secondary flows and high losses
- The traditional exhaust collector design is ”flow-wise” not optimum – “root cause” of many problems!



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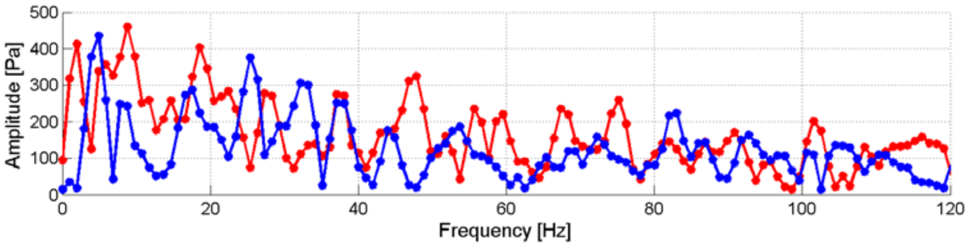
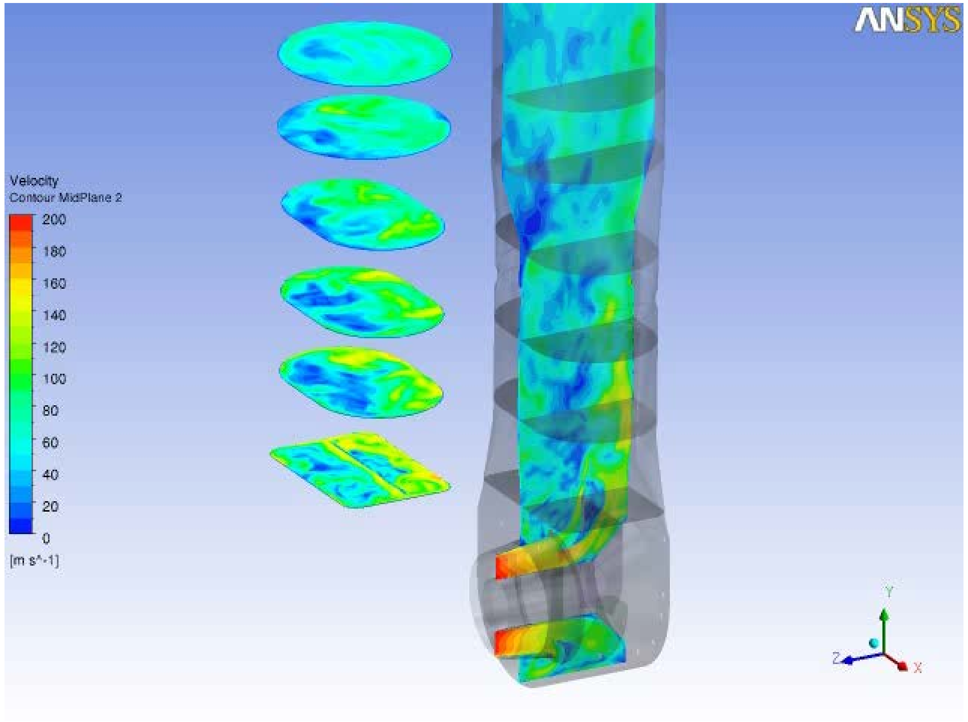
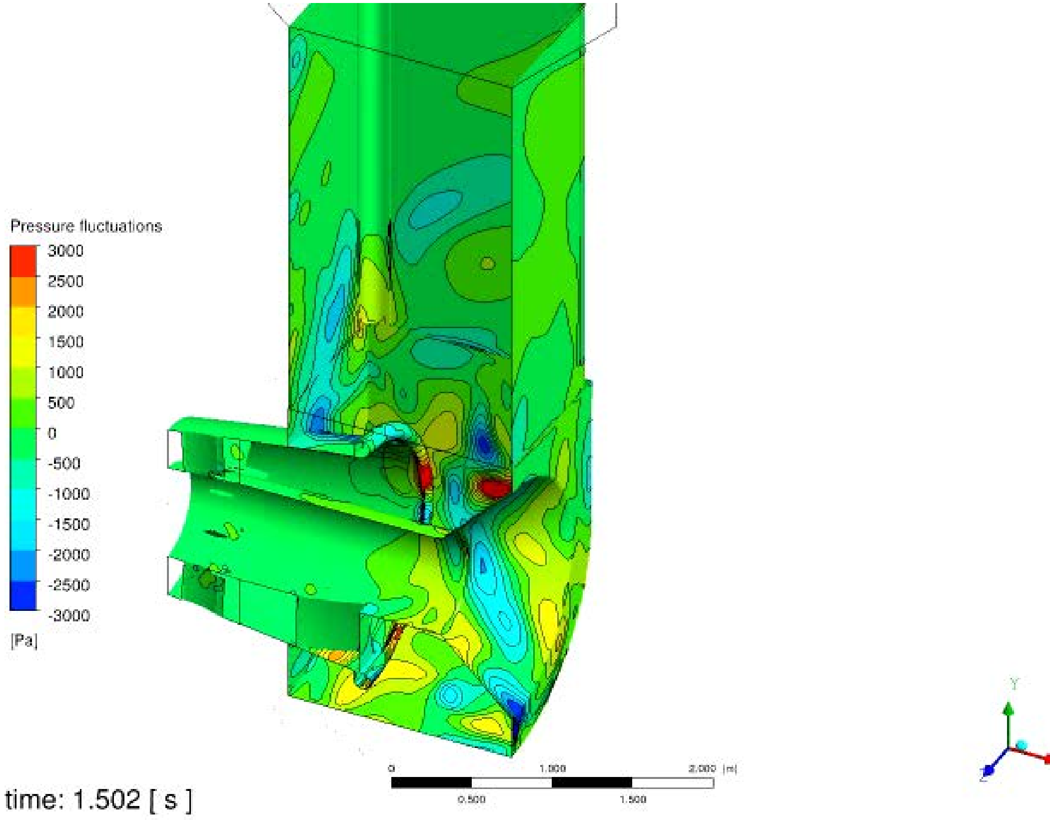
CFD Analysis – The Structural Excitation

- Very marked transient characteristics of flow out of exhaust collector
- Unsteady surface pressures serve as structural excitation







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High Cycle Fatigue (HCF) Exhaust Duct Failures – Caused by Vibrations

- Åsgard B failures in 2005/2006: Platform shut-down due to flow induced vibrations
- Transition – just downstream exhaust collector
- Externally insulated
- Low damping
- Very high velocities close to damaged area
- High pressure fluctuations

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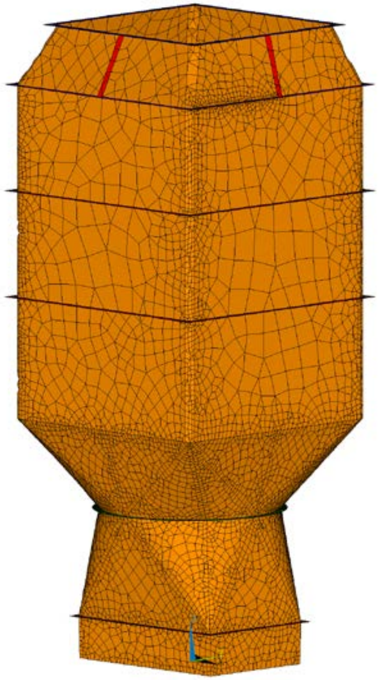
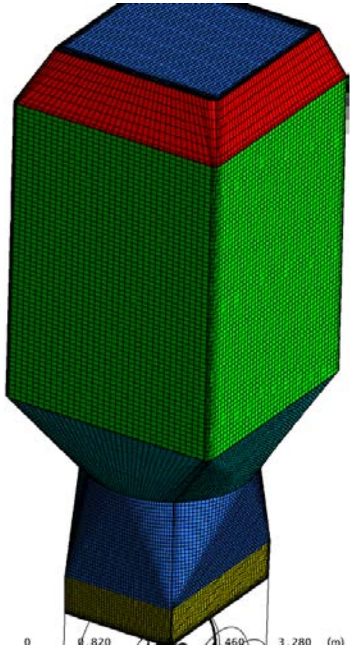
FSI Vibration Analysis Techniques

- Finite Element Analysis (FEA) of exhaust duct to find structural natural frequencies
  - Shell element representations
  - Temperature effects
  - Modal analyses
  - Harmonic analyses
- Unsteady CFD model contains unsteady surface pressures, which is mapped to FEA model
- FSI one-way coupling is used as the structural influence on the flow is not significant (1-3 mm)
- FSI used to evaluate which natural frequencies are critical and design improvements can be guided
- FSI used as input for fatigue assessment, which includes high temperature creep-fatigue effects

FEA surface shell mesh



CFD surface mesh



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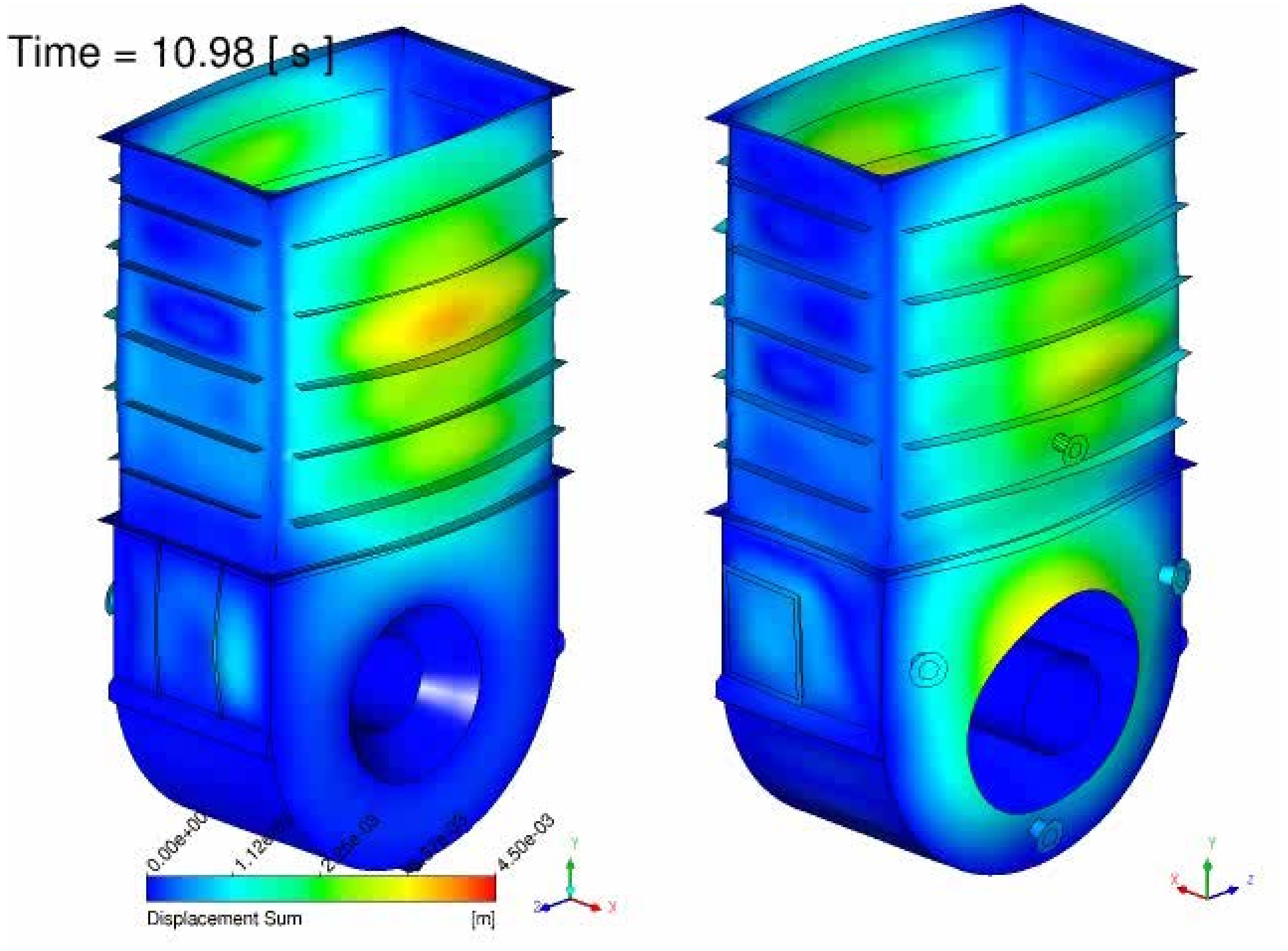
FSI Vibration Analysis Results

- Mode shapes, deformations and stresses are determined



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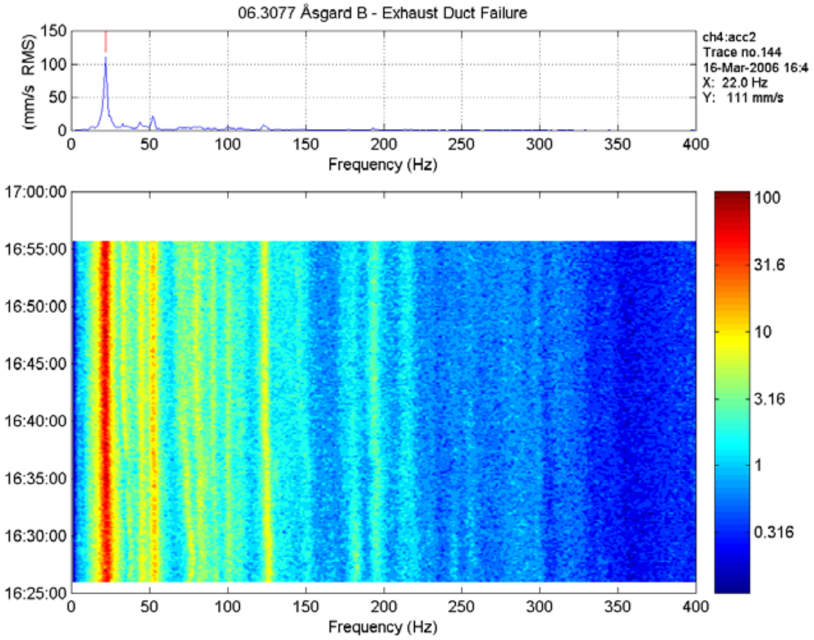
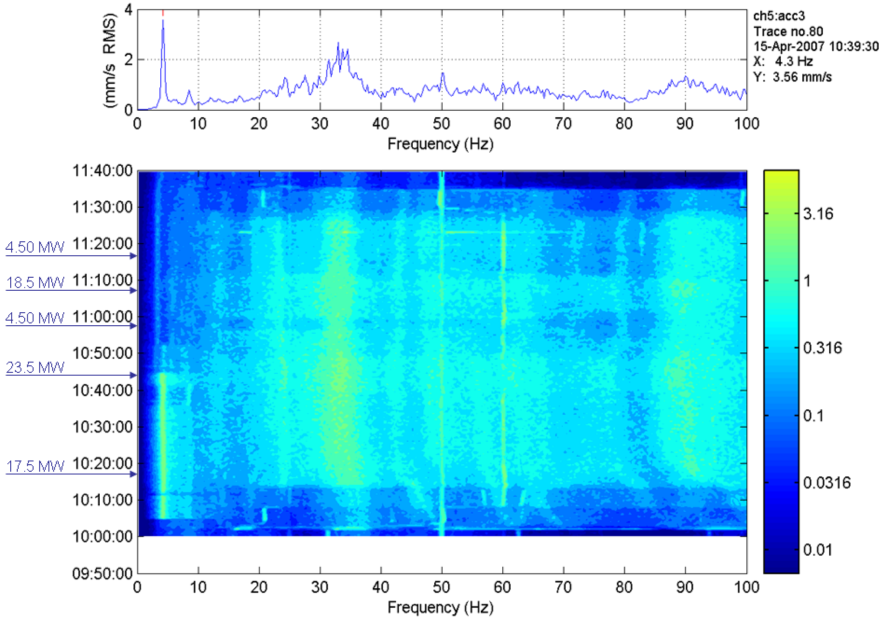
On-Site Vibration Measurements

Original Design



400 Hz, 400 lines, 0 integr., 5 avg., 50% overlap, Hanning, HP 5 Hz, 200 spectra

Final Design



100 Hz, 400 lines, 0 integr., 10 avg., 50% overlap, Hanning, HP 5 Hz, 200 spectra

- Sweep in power: up-down-up-down - note frequency range on plots
- Before approx. 100 mm/s RMS - now approx. 3 mm/s RMS
- Vibration amplitude reduction by a factor of approx. 30 for critical component!
- Total vibration levels reduced by a factor of approx. 5

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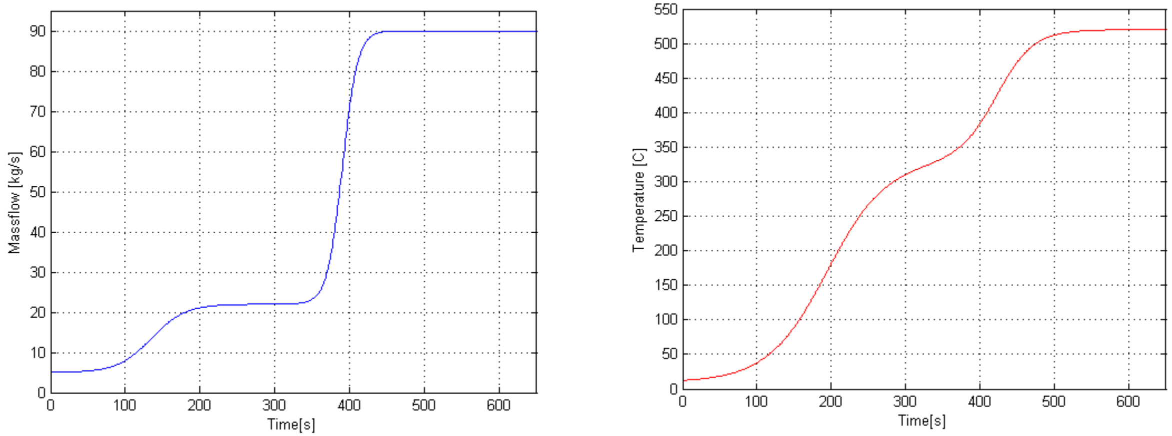
Low Cycle Fatigue (LCF) Exhaust Duct Failures - Caused by Thermal Loads

- During start-up and shut-down of gas turbine very high temperature gradients are present in ducting
- Stresses may exceed material yield levels locally and plastic deformation occurs
- After a relatively low number of cycles cracks may appear

Start-up



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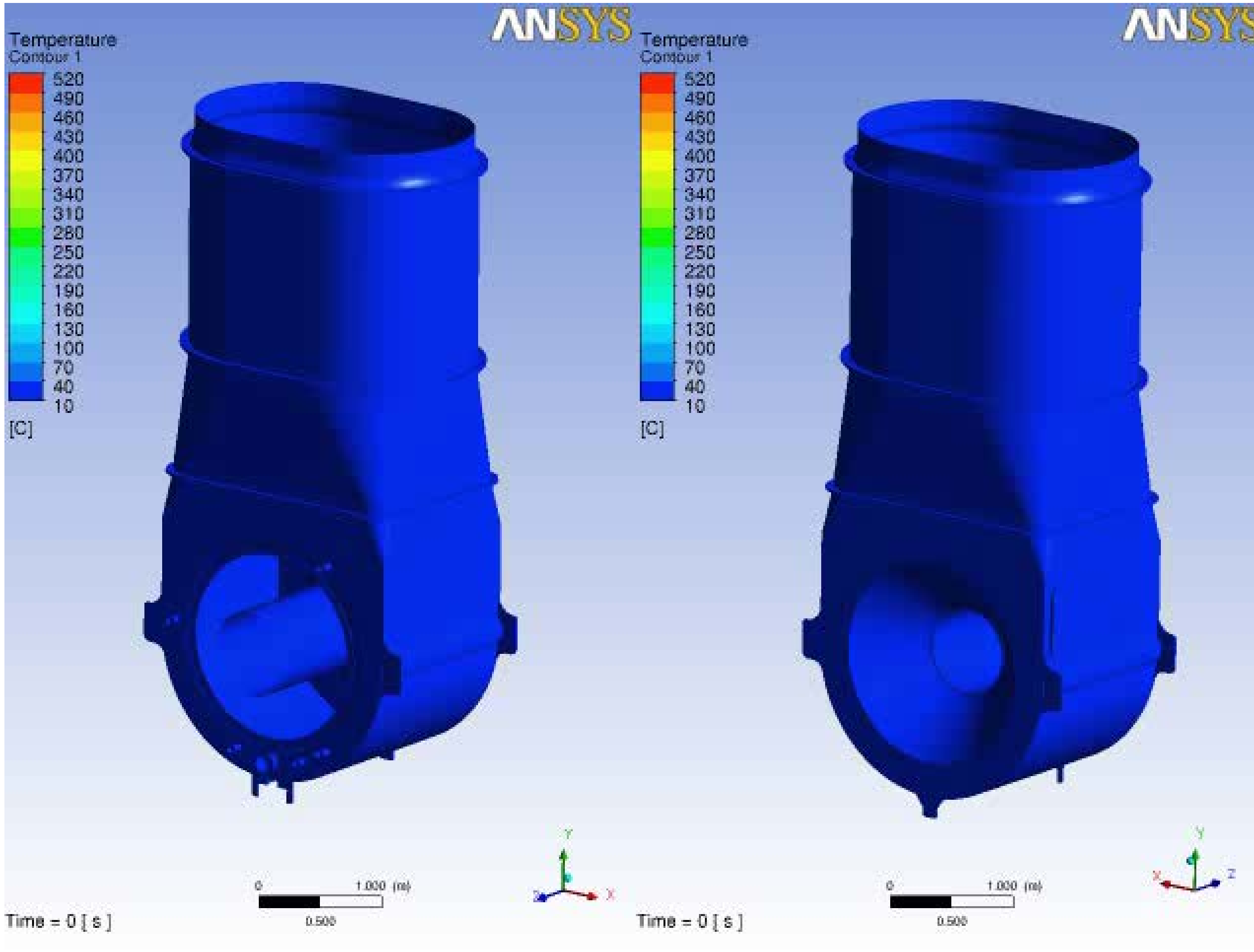
FSI Thermal Analysis Techniques

- Pseudo-transient time-stepping approach used for conjugate heat transfer (CHT) calculations
- Much larger time scales compared to vibrational FSI (now “heat-up” time scales need to be resolved)
- URANS: k-ω SST turbulence model
- Mapping of temperature instead of pressure to FEA model
- Very non-uniform internal convective heat transfer predicted by means of CFD
- Insulation material and outside convective effects included

Temperature of duct structure during start-up



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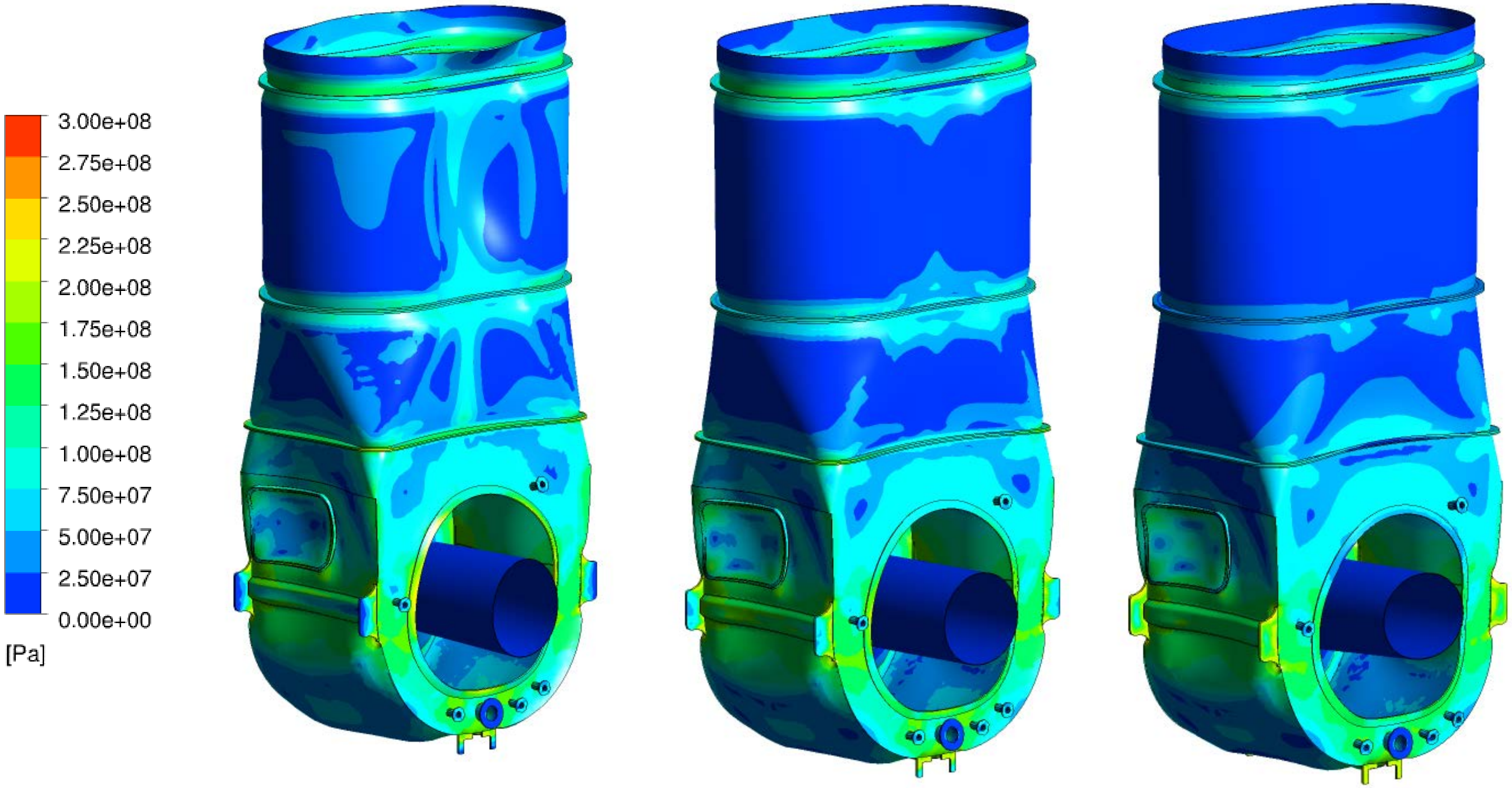
FSI Thermal Analysis Results

- Stress snapshots during start-up
- Stresses may locally exceed the material yield limit



Thank you for your attention!

Questions?

Pipeline Span Vortex-Induced Vibration presentation can be downloaded at: http://www.dansis.dk/default.aspx?id=93

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