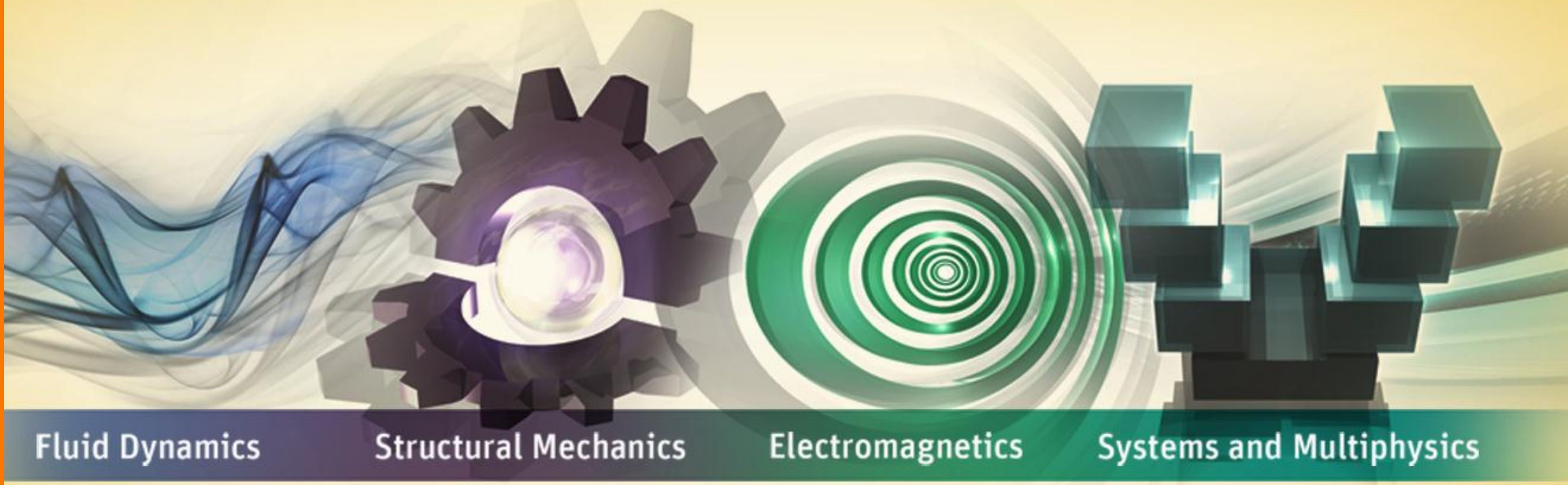
Realize Your Product Promise™

Statistical Analysis of a mistuned Compressor



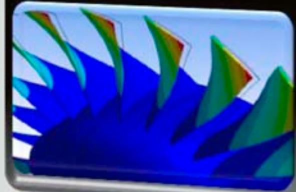
Johannes Einzinger
ANSYS

Outline

What is Mistuning?

Turbo Machinery, FSI-Coupling

Mistuning, Modelling

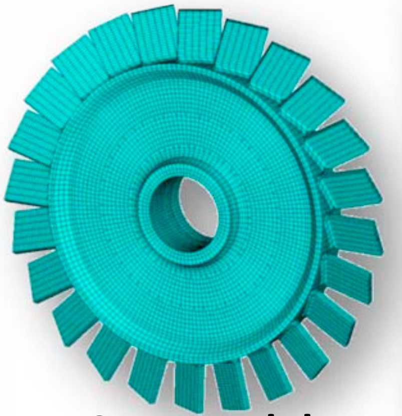


Mistuning, Applications

What is Mistuning?

- Why does Blade x break?
  - Local Production Error?
  - Local Material Error?
  - Local Overload?
  - Local Erosion?
  - …
- Non cyclic System due to
  - Allowed Production Tolerances
  - Small Erosion
- → Mistuned System

Rotor Damage at Blade x



CAD-Model
(=Tuned System)

Real-Model
(=Mistuned)

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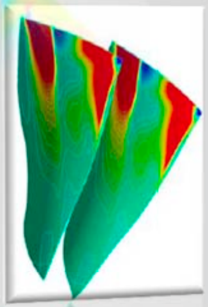
Turbo Machinery, FSI Coupling



Steady CFD
- Aero Dynamic Performance
- Characteristic @ Design Point
- Steady Pressure/Temperature

Pre-Stress Analysis
- Steady/Averaged Mean Stresses
- Steady/Averaged Deformation
- Stress Stiffening

Transient CFD
- Aero Dynamic Performance
- Characteristic @ Off-Design
- Transient Pressure Loads

Modal Analysis
- Eigen Frequencies/Modes
- Resonance?
- Model Order Reduction

Blade Flutter
- Fluid Reaction
- Stability
- Aero Dynamic Damping

Dynamic Analysis
- Transient Stresses
- Fatigue
- Mistuning

Fluid

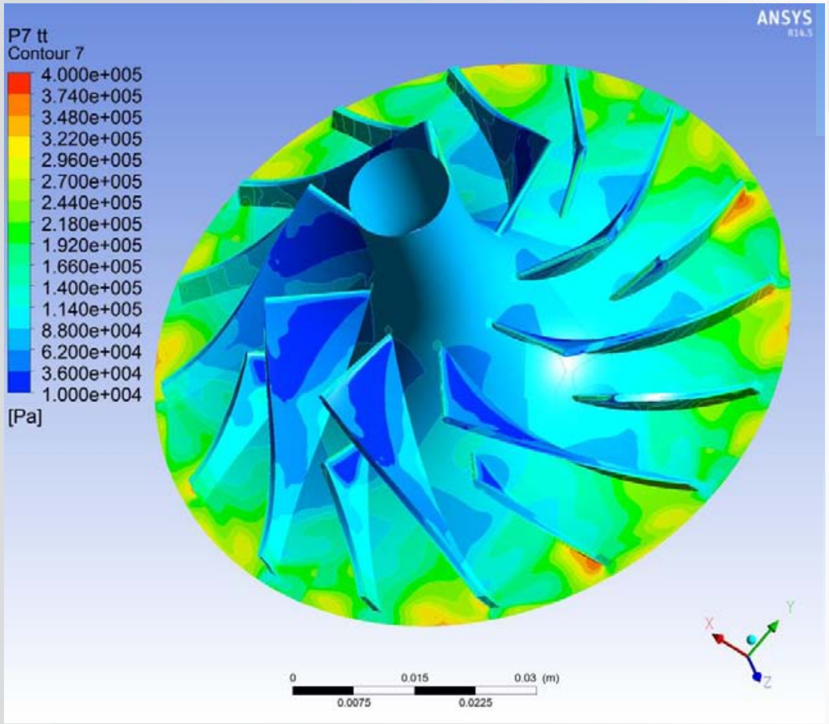
Coupling

Structure

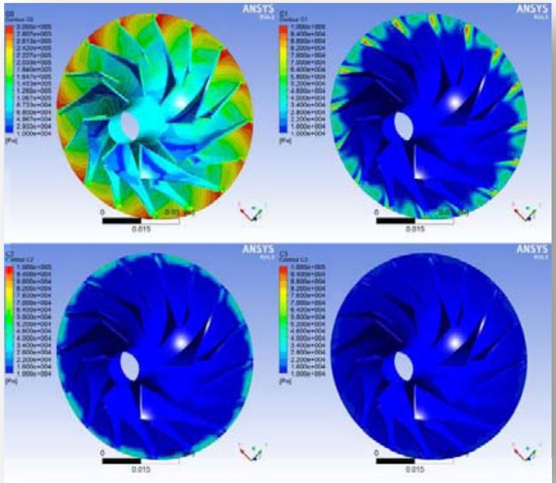
Transient CFD – Dynamic Loading

$$f(t)=\sum_{n=0}^{N} a_n\cdot\cos(n\cdot\omega\cdot t)+b_n\cdot\sin(n\cdot\omega\cdot t)=F(\omega)$$

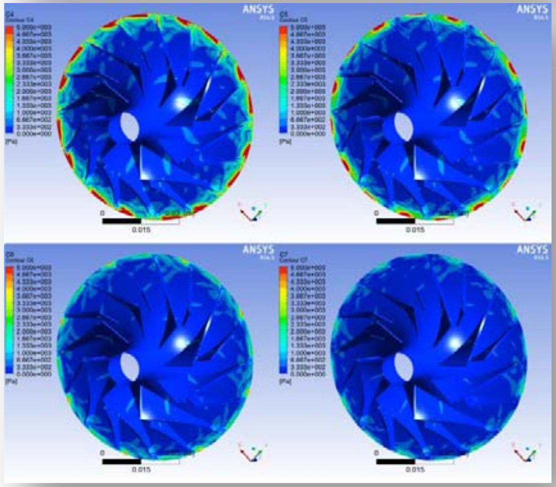
Fourier Transformation



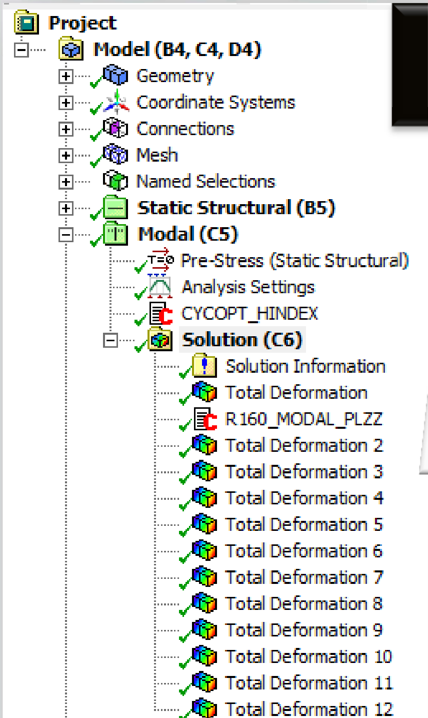
n=0-3
P_{max}= 0.1 [MPa]



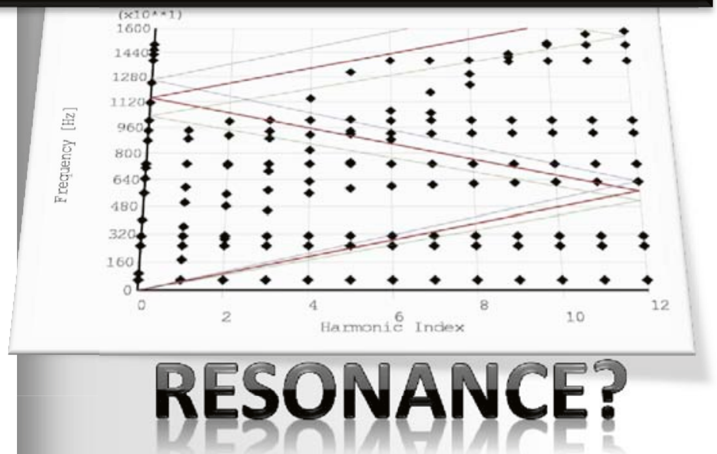
n=4-7
P_{max}= 5000[Pa]



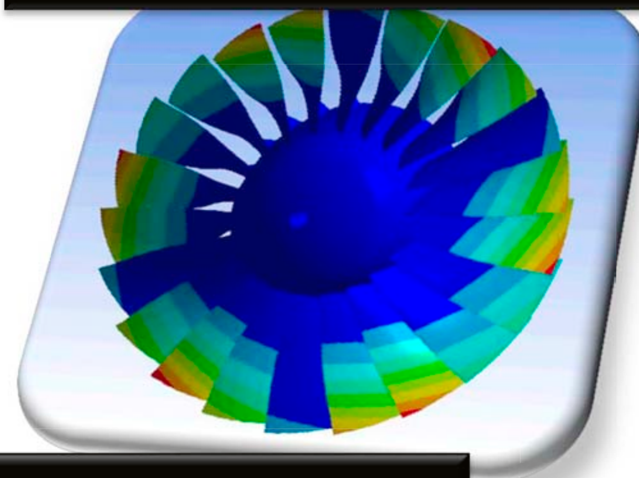
Pre-Stressed Modal Analysis



Eigen Frequencies:

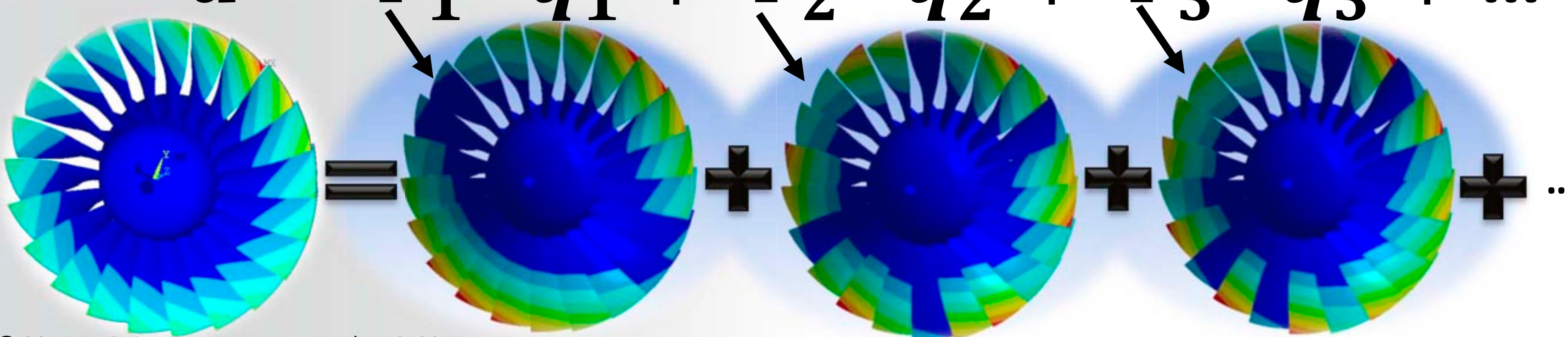


Eigen Modes Φ:

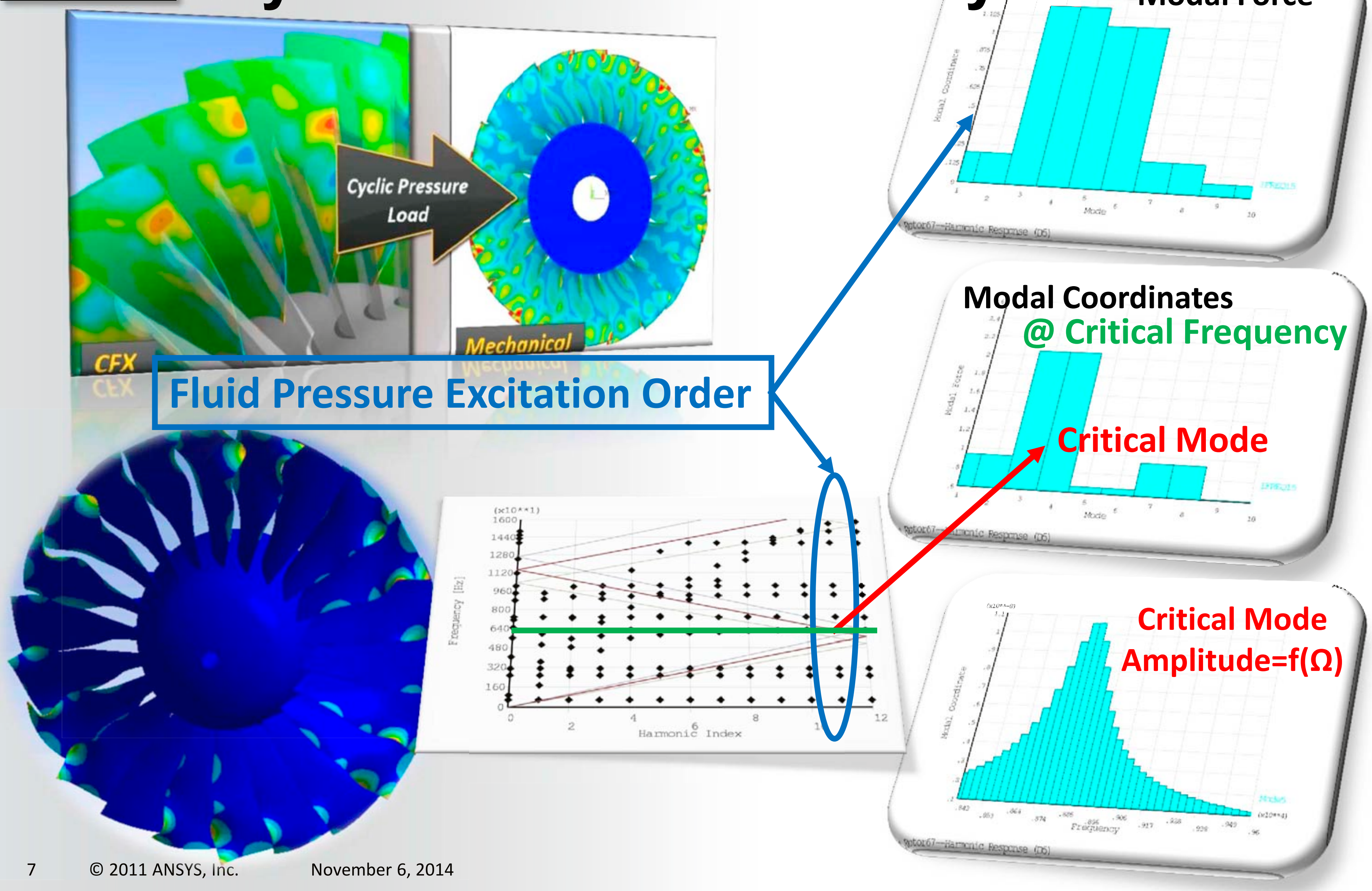


Model Order Reduction:

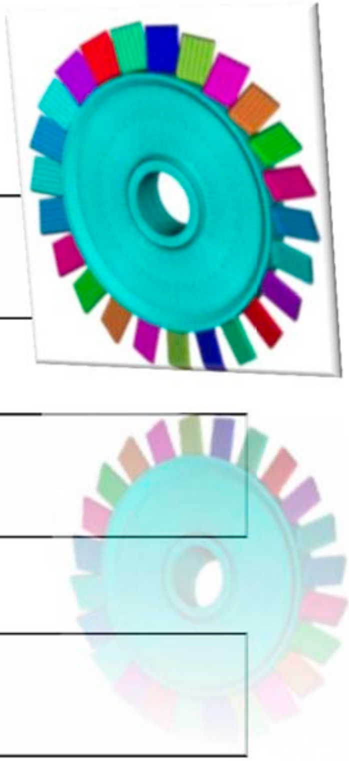
$$\mathbf{u} = \Phi_1 \cdot q_1 + \Phi_2 \cdot q_2 + \Phi_3 \cdot q_3 + \ldots$$



Dynamic Mechanical Analysis



Mistuning, Modelling

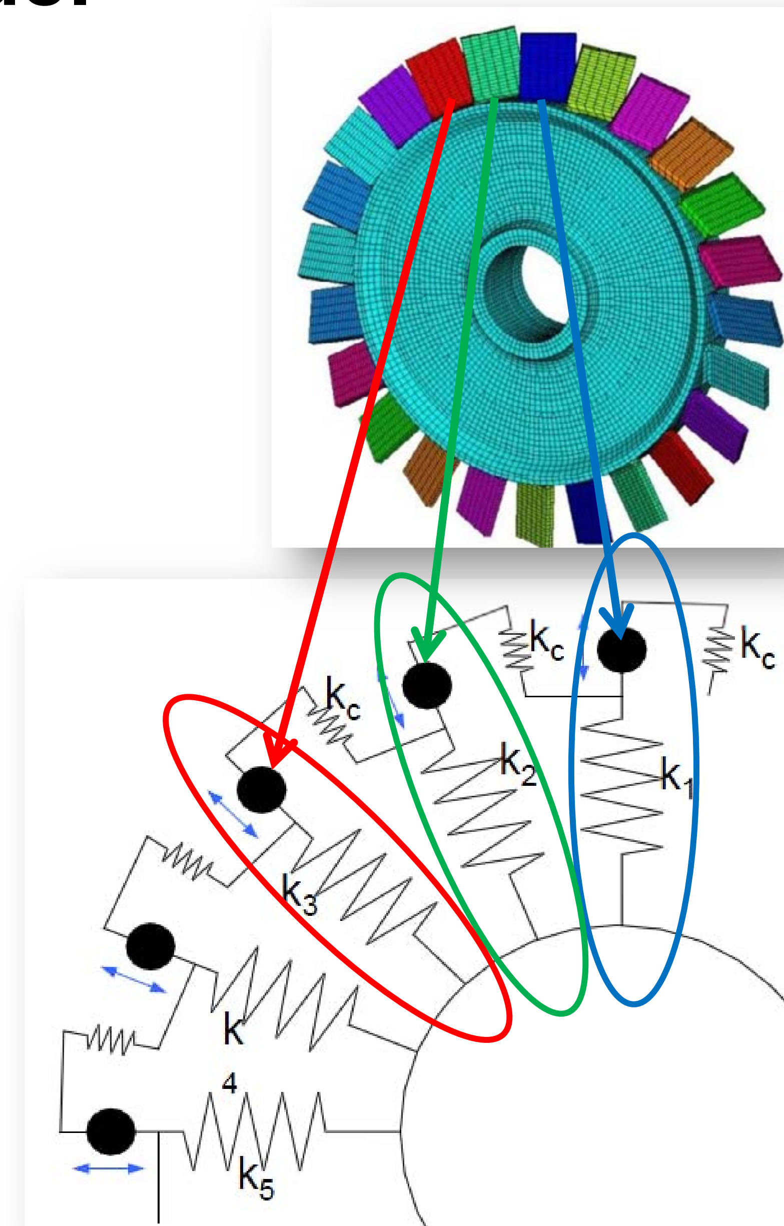


- 1 DOF Minimal Modell
- 2 Sector Modell with Point Mass
- CMS Modell (1 Sector!)
- Full Model with Random Fields

1-DOF Minimal Model

- **Each Blade Oscillation is represented by one mode, i.e. DOF**
- **Parameter: cantilevered blade frequency and coupling stiffness**

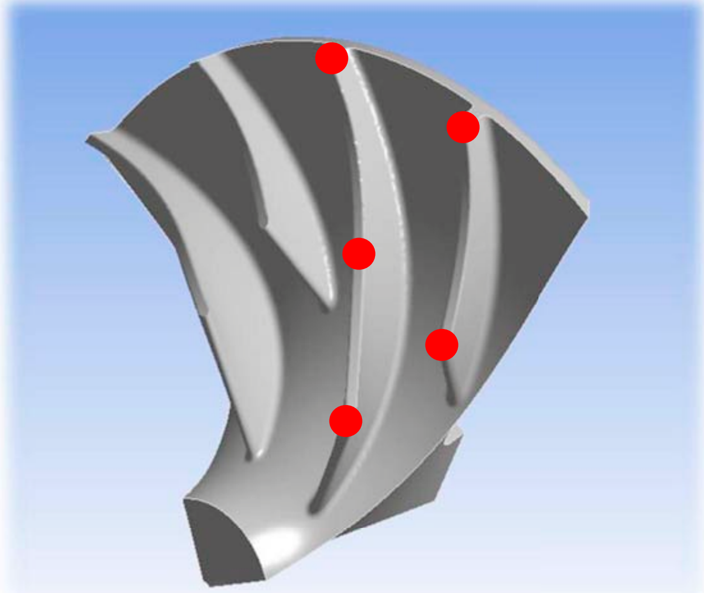
- **Pro:**
  - **efficient due to reduced order model**
- **Con:**
  - **limited in modelling capacities**

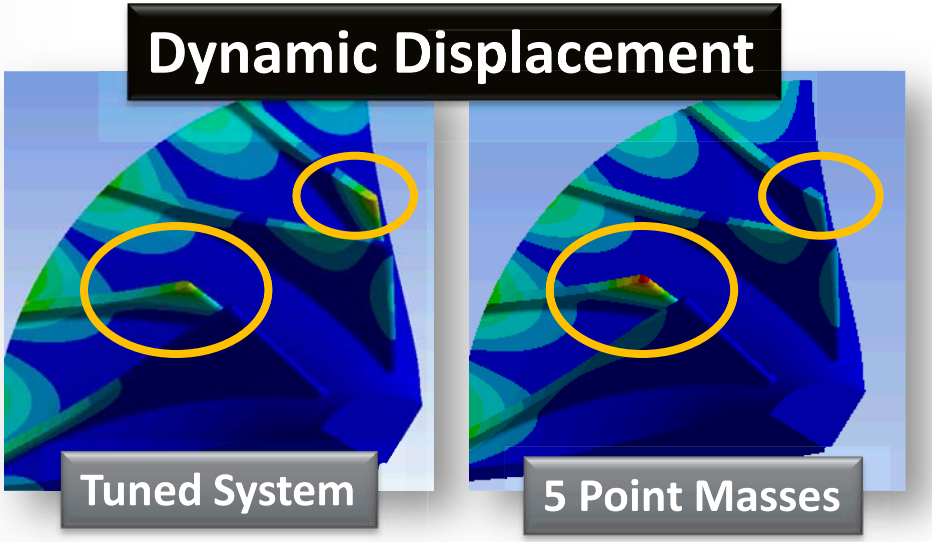


2 Sector Model with Point Mass

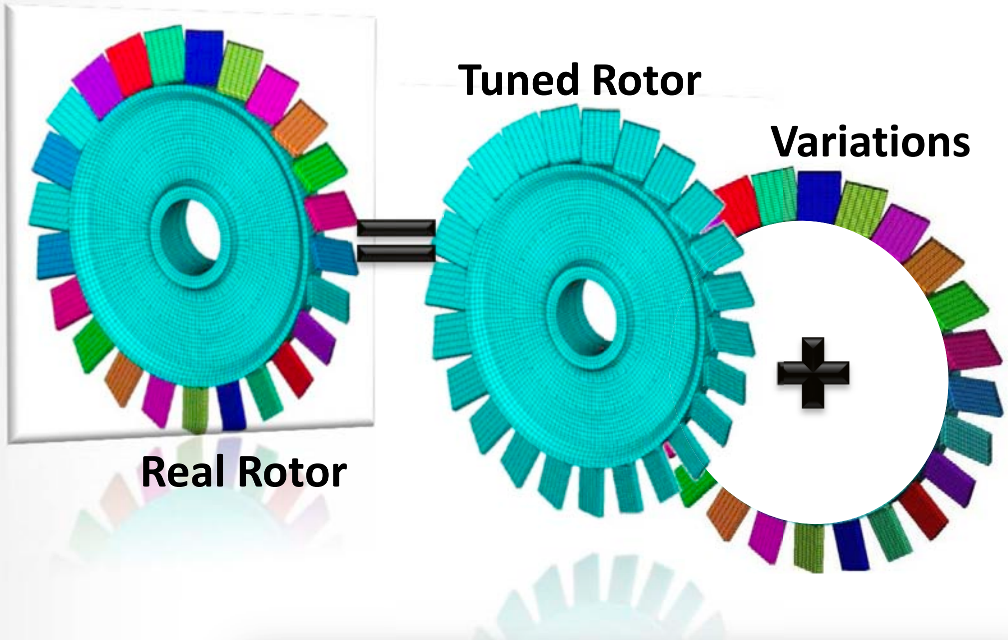
- Cyclic System with 2 sectors
- Additional Point Mass on 2nd Sector → Mistuning

- Pro:
  - easy to apply
- Con:
  - regular pattern implicit included → detuned

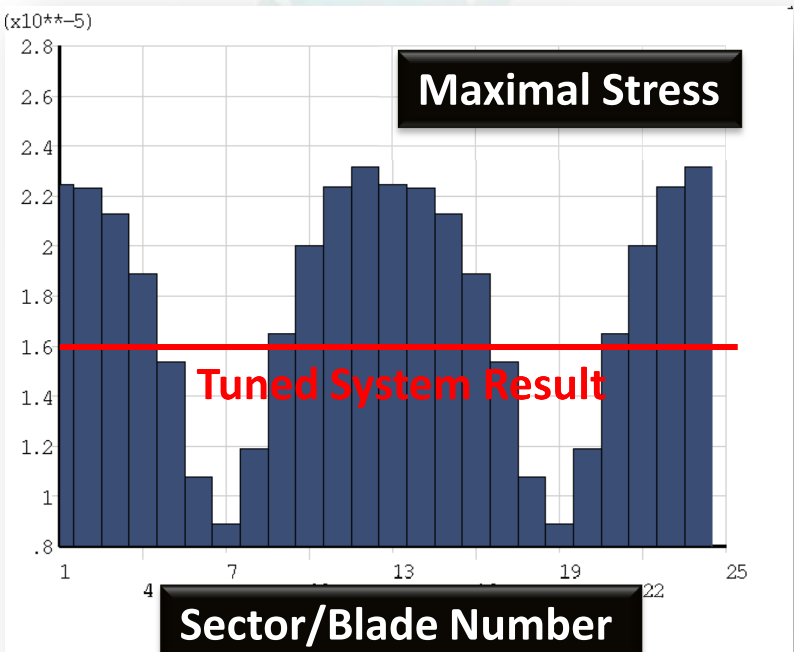




CMS Model



- Cyclic Model + non-cyclic Mistuning
  - Proportional Mistuning
  - Intended Mistuning
  - …
- Different Stress Levels on Sectors/Blades

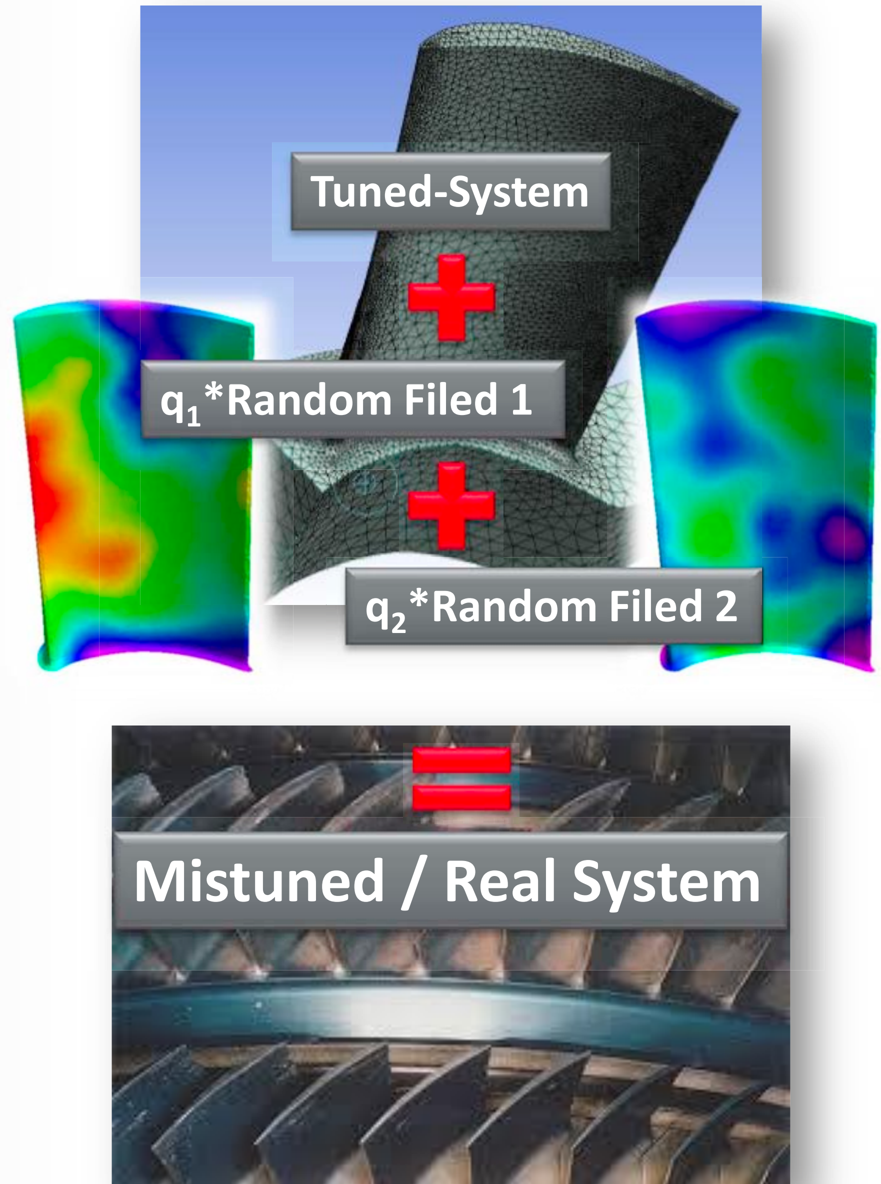


- Pro:
  - efficient: single sector mesh required
- Con:
  - small Mistuning

Full Model with Random Fields

- **Measured / Assumed Variation → Random Fields (=Mode Shapes of Correlation Matrix)**
- **Random Field is morphed on tuned System Mesh**

- **Pro:**
  - **Model for large Mistuning**
  - **efficient handling of statistics**
- **Con:**
  - **computational effort**



Application & Best-Practice

Objective for Meta-Model: Maximal Coefficient of Prognosis

- Reason for small Coefficient of Prognosis:
  - Number Design Points
  - Numerical Error
  - Model Error
  - Multiple Mechanism
- Number of Design Points for Meta-Model depends on:
  - Number of ***important*** parameters
  - Nonlinearity of Response Surface

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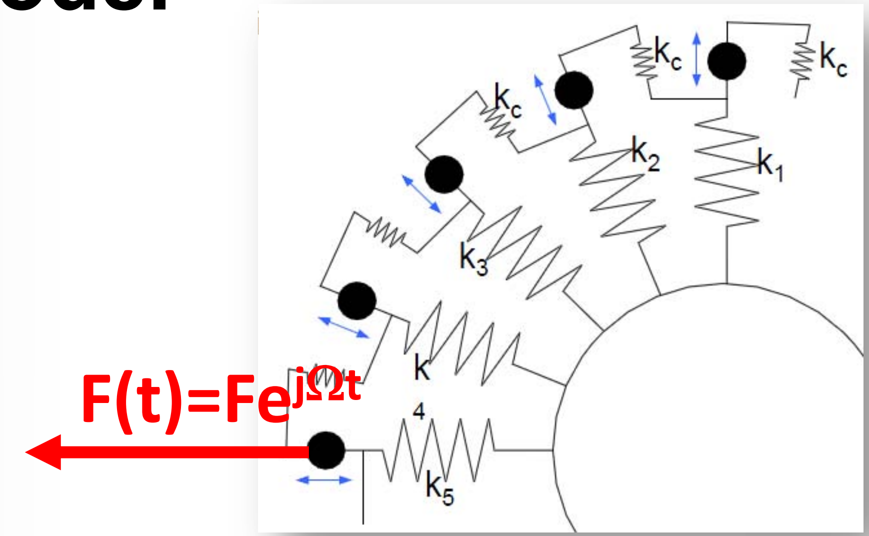
1-DOF Minimal Model

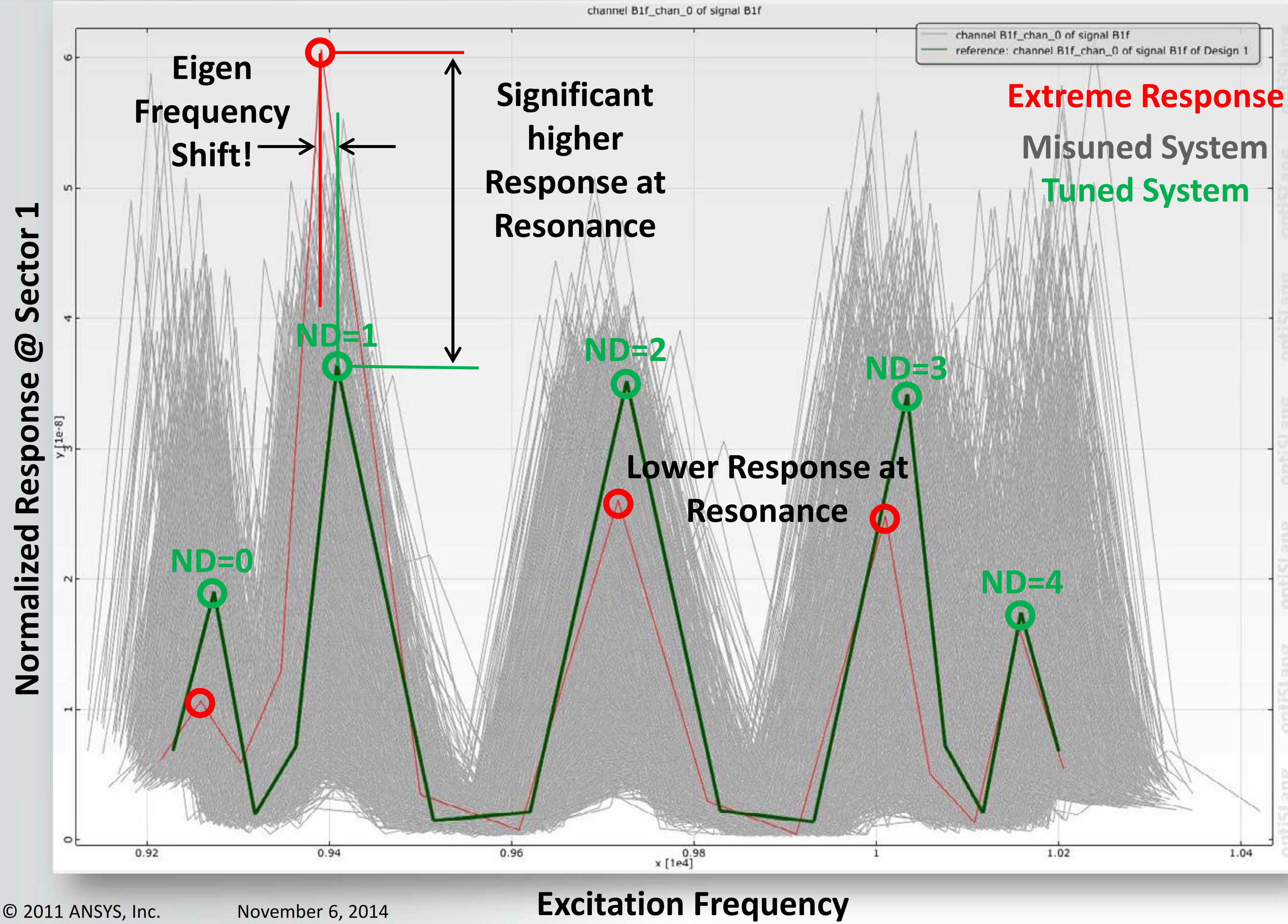
- **8 Sector Model**
  - **16 Input Parameters**
  - **Normal Distribution**
  - **CoV=1%**
- **Simulation:**
  - **Modal Analysis**
  - **Forced Response, Excitation @ 1 Sector**
- **Output:**
  - **5 Eigen Frequencies**
  - **Frequency Sweep:**
    - Signals @ Sectors=f(Ω)
    - Signals for Nodal Diameter @ Eigen Frequency



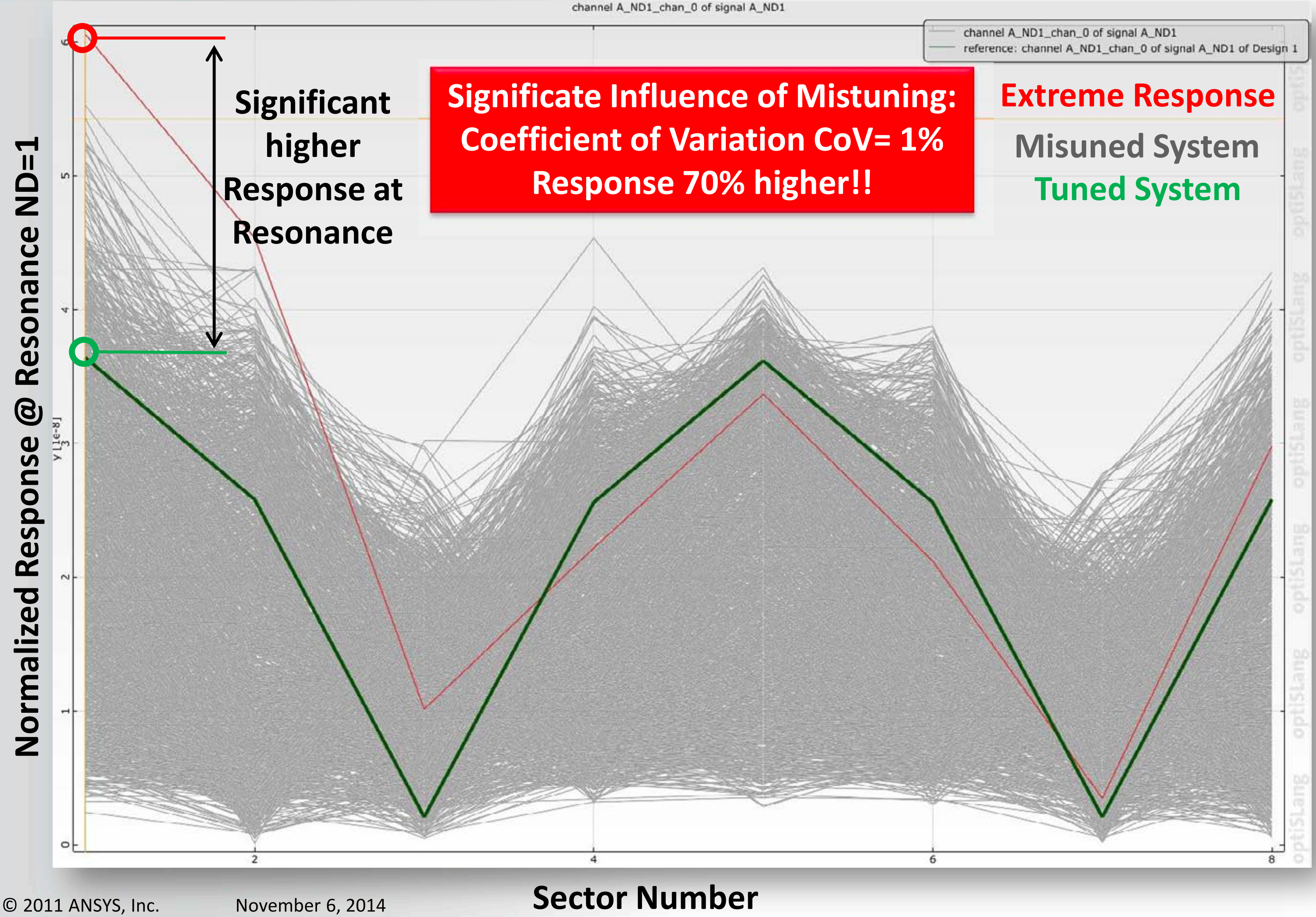
CoP is increasing with Number of Design Points!

CoP [%]	N=200	400	800
Freq. ND=0	96.6	98.7	99.1
Freq. ND=1	75.7	89.5	94.5
Freq. ND=2	81.4	92.6	94.0
Freq. ND=3	79.6	94.2	95.0
Freq. ND=4	88.6	97.6	98.4

1-DOF Minimal Model

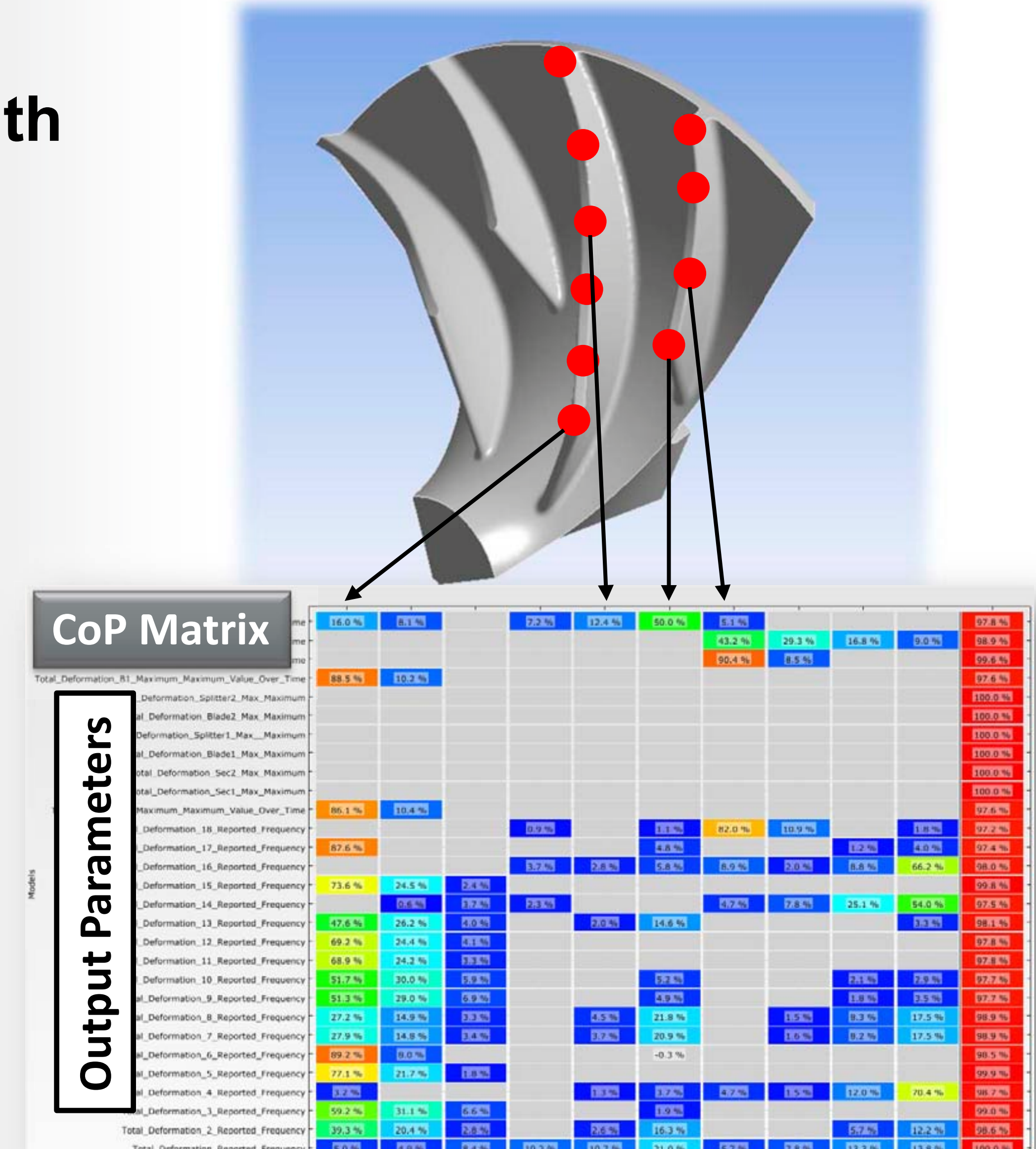


1-DOF Minimal Model



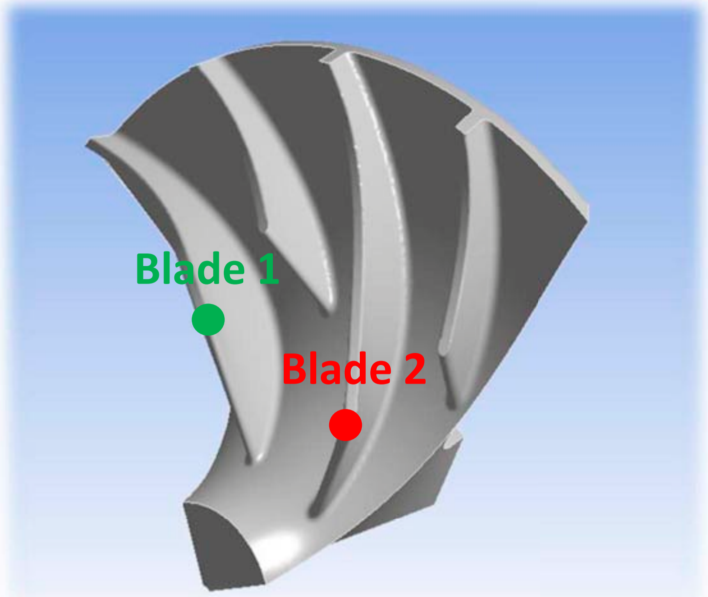
2 Sector Model with Point Mass

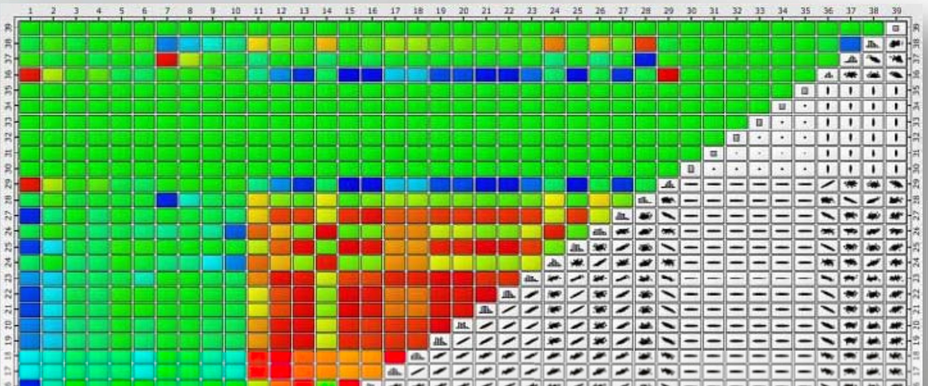
- Radial Compressor with 2x8 Sectors
- 10 Point Masses on even Sector
- Weibull Distribution, CoV 1% Sector Mass
- Excitation with CFD Loads
- Excellent CoP for all Output Variables with 100 Design Points

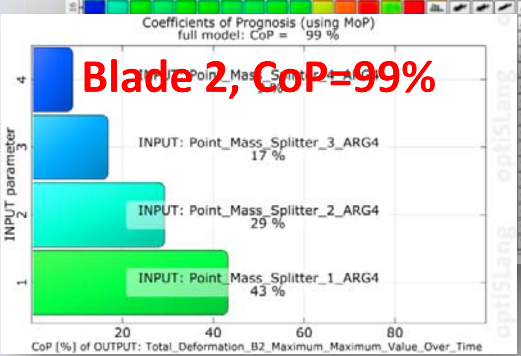


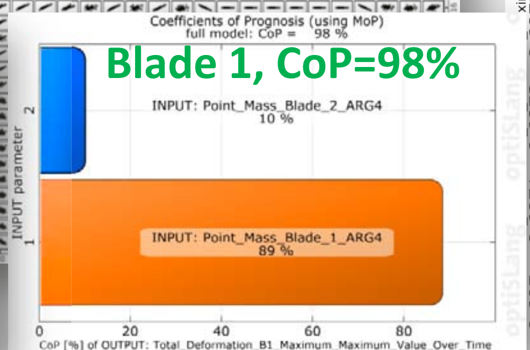
2 Sector Model with Point Mass

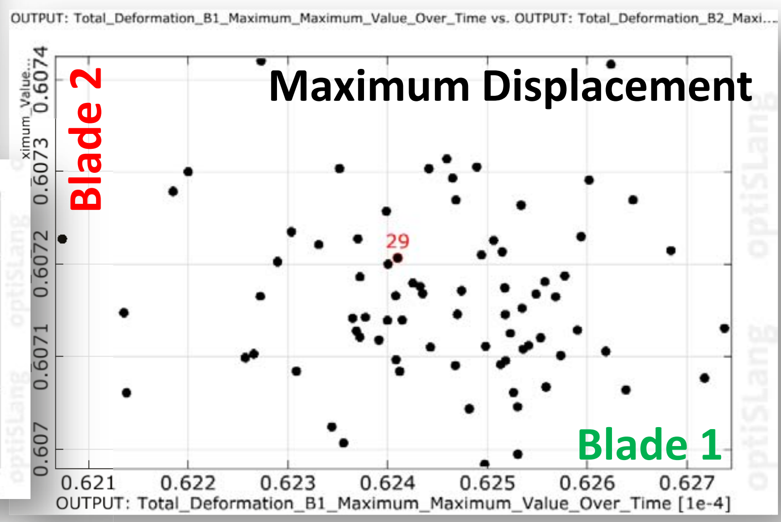
- Disp. Variation ~1% for Blade 1 and 2
- All Input Parameters are important wrt to Output











Summary and Outlook

- **Summary**
  - Mistuning has significant Influence to Bladed-Rotors (and other structures)
  - Efficient Mistuning Models are available

- **Outlook**
  - Application of CMS Model, → Release 16
  - Application of Random Fields

Use Simulation and Statistical Analysis…

…to avoid: