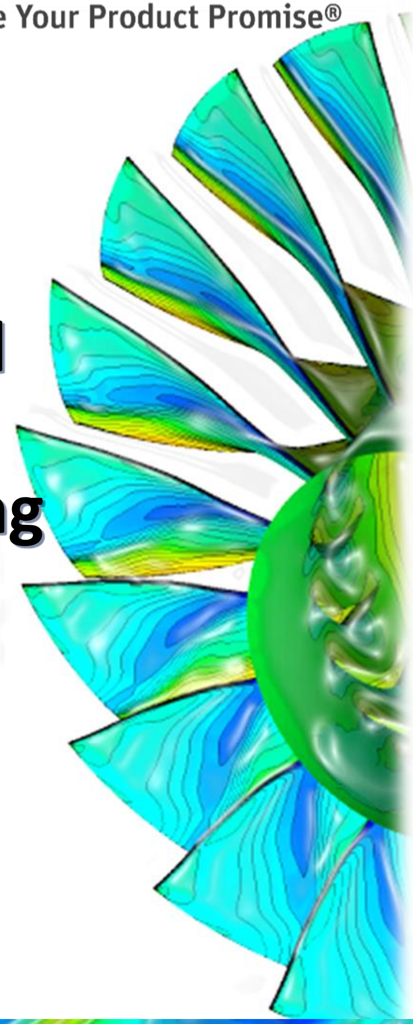
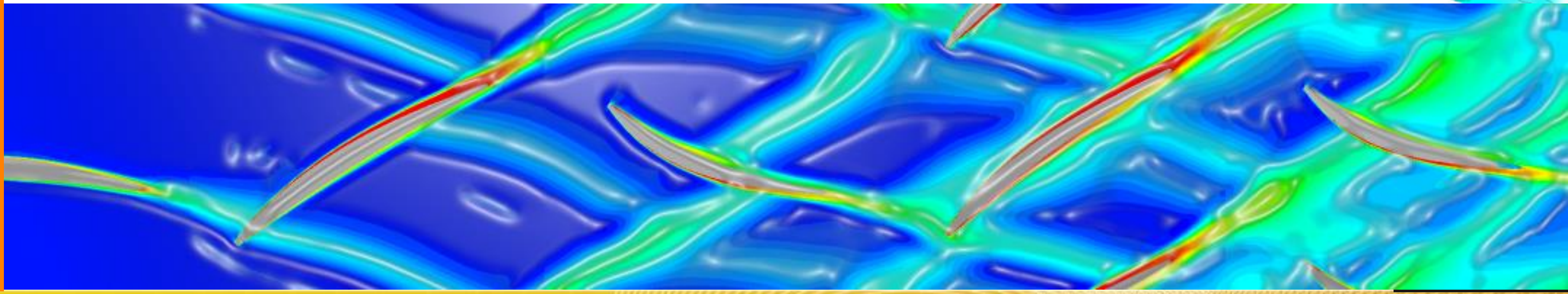


Enhancement regarding the Statistical Analysis of Mistuned Compressor Wheels by Model Order Reduction using the software SoS

Johannes Einzinger

ANSYS



dynardo | presented at the 13th Weimar Optimization and Stochastic Days 2016
Source: www.dynardo.de/en/library

Outline

What is Mistuning?

Aero Mechanic

Review WOST 2015

Apply Best-Practice

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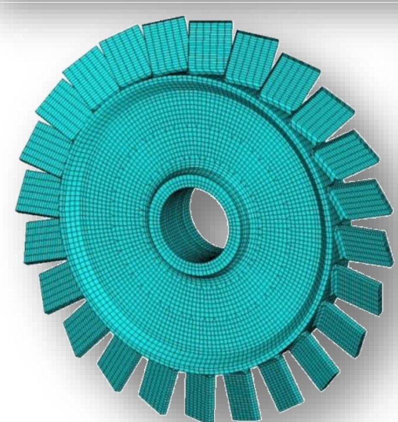
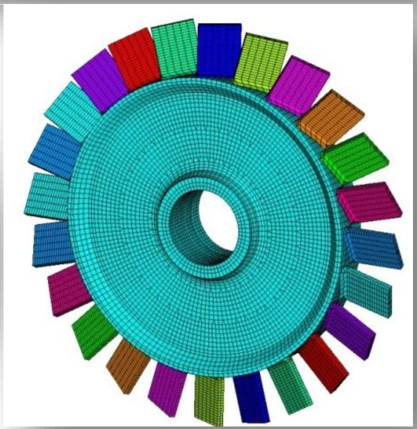
What is Mistuning?

- 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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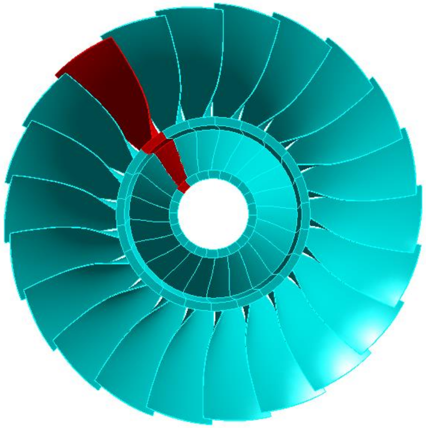
Model Order Reduction



$$\mathbf{P} = \mathbf{I}e^{-j\alpha(i-1)(k-1)}$$

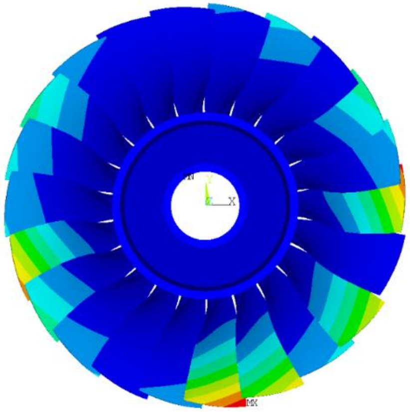
$$\mathbf{x} = \mathbf{P}\mathbf{q}$$

Cyclic Reduction

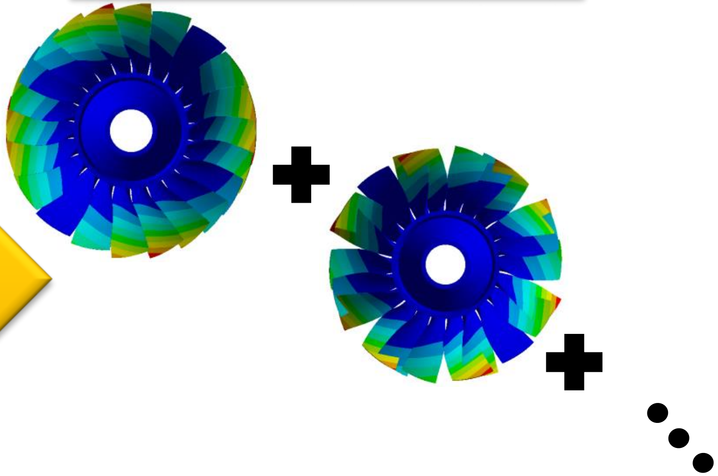
$$\mathbf{P}^{*T}\mathbf{M}\mathbf{P}\ddot{\mathbf{q}} + \mathbf{P}^{*T}\mathbf{C}\mathbf{P}\dot{\mathbf{q}} + \mathbf{P}^{*T}\mathbf{K}\mathbf{P}\mathbf{q} = \mathbf{P}^{*T}\mathbf{F}$$

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{F}$$

Modal Reduction



$$\mathbf{x} = \mathbf{\Phi}\mathbf{q}$$



$$\mathbf{\Phi}^{*T}\mathbf{M}\mathbf{\Phi}\ddot{\mathbf{q}} + \mathbf{\Phi}^{*T}\mathbf{C}\mathbf{\Phi}\dot{\mathbf{q}} + \mathbf{\Phi}^{*T}\mathbf{K}\mathbf{\Phi}\mathbf{q} = \mathbf{\Phi}^{*T}\mathbf{F}$$

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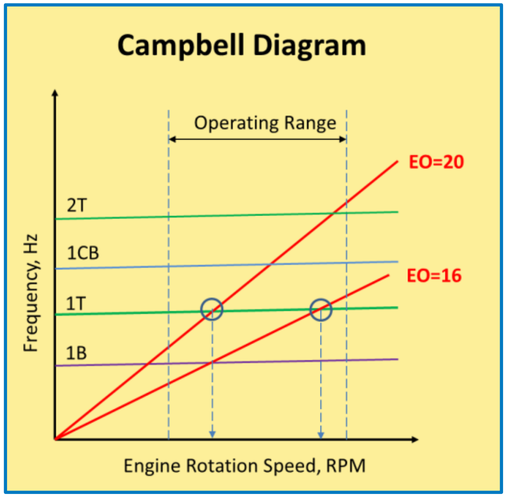
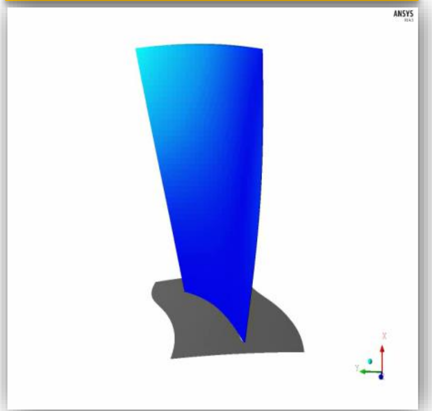
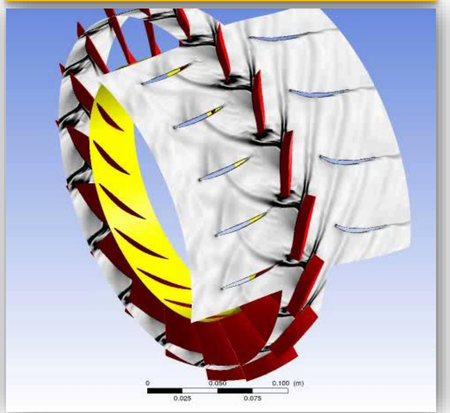
Aero Mechanic - Reduced Oder Model

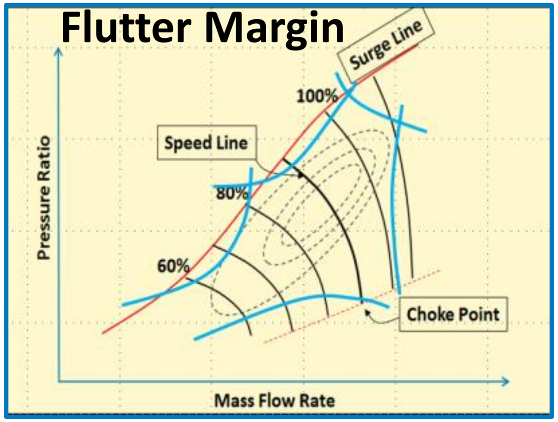


Aerodamping



EO Forcing

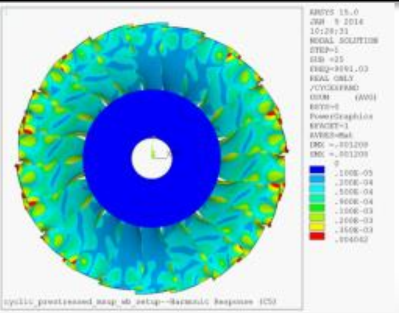




Blade Flutter

$$m\ddot{x}+(c+c_{aero})\dot{x}+(k+k_{aero})x=F(t)$$

Forced Response



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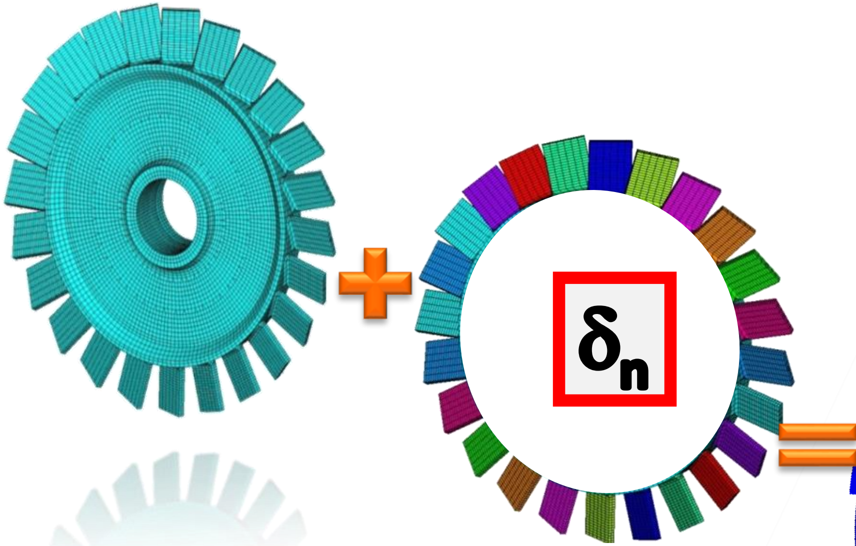
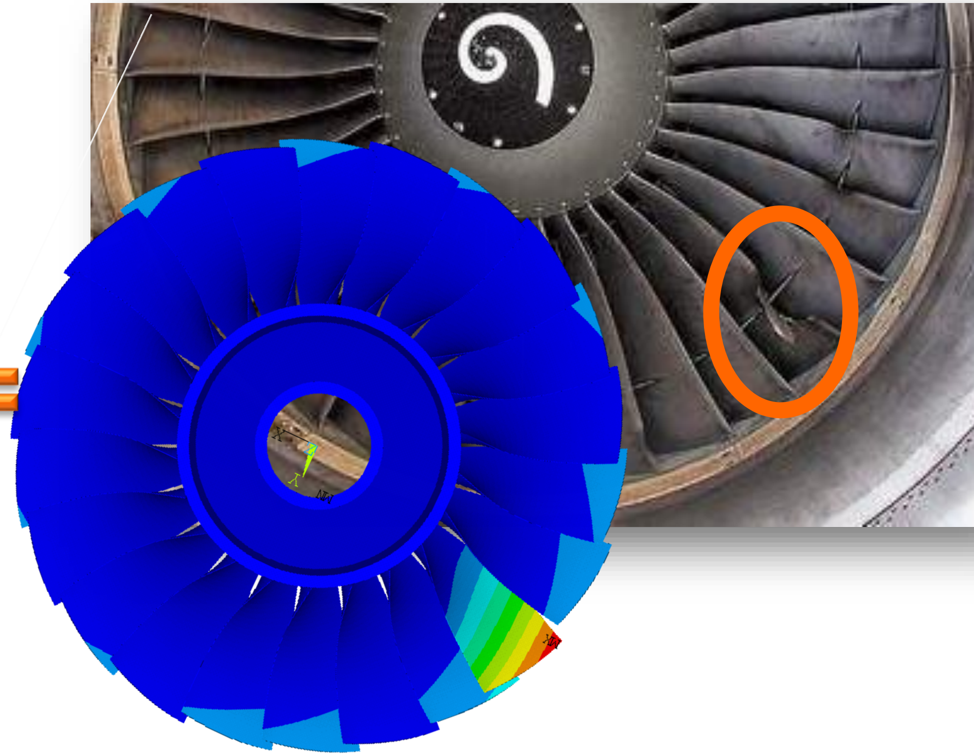
Aero Mechanic - Mistuning





$$\tilde{\mathbf{q}}_{\phi,h} = [\Lambda^B]^{-1} \begin{bmatrix}\phi^B\\ 0\end{bmatrix}^T \mathbf{K}_o\, {}^{\Gamma}\tilde{\Phi}_h$$

Cyclic Modes are approximated by cantilevered Modes→Modal Participation Factors q

$$\left\{-\Omega^2\mathbf{I} + i\Omega\left[\left(\beta+\frac{1}{\Omega^2}g\right)\Lambda^s+\alpha\mathbf{I}\right]+\Lambda^s+\sum_n \mathbf{q_n}^T\delta_n\mathbf{K_o}\mathbf{q_n}+\mathbf{K_a}\right\}\mathbf{a}e^{i\omega t} = \left\{\sum_n F^T_{n,EO}\tilde{\Phi}^T_h\mathbf{F}e^{i\phi(n-1)}\right\}e^{i\omega t}$$

Excitation frequency | Reduced mass | Reduced damping | Reduced stiffness | Misstuning terms | Aero stiffness | Projection to modal space and expansion from cyclic domain | Single sector engine order forcing

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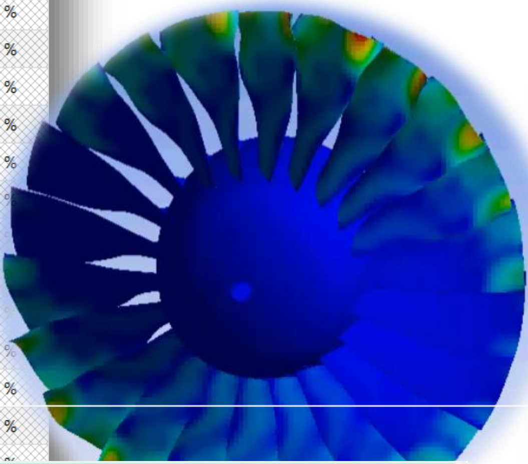
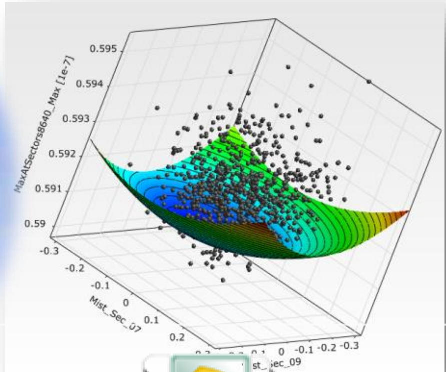
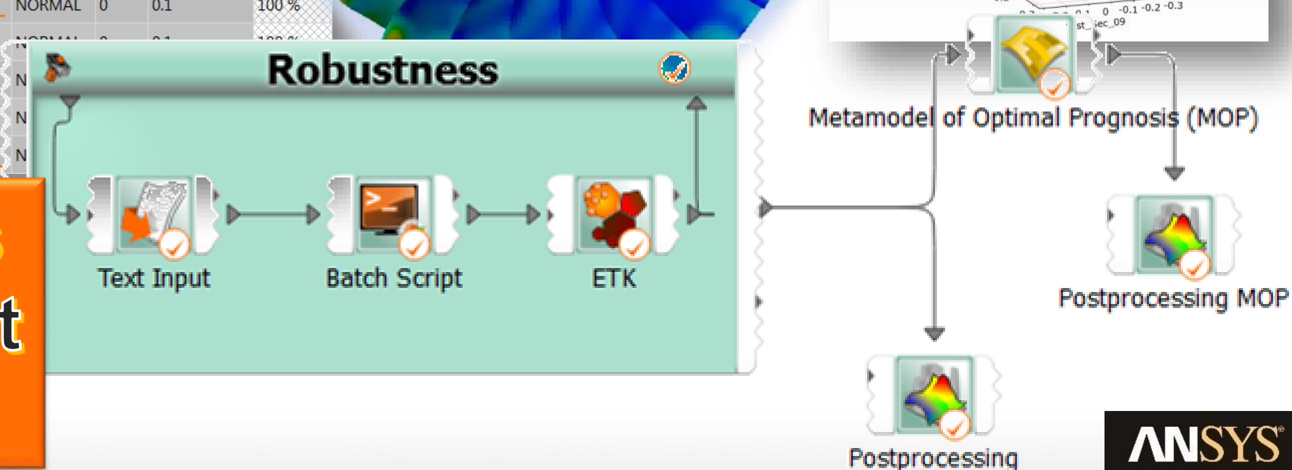
optiSLang Set-Up

- **Reference=Mean Value=0, i.e. Tuned**
- **22 Blades → 22 Random Variables**
- **Standard Deviation=0.1% 1.0% 10% 100%**
- **DoE with 400 and 800 dps**
- **Objective: Variation of Meximal Stress**

	Name	Parameter type	Reference value	Constant	PDF	Type	Mean	Std. Dev	
1	Mist_Sec_01	Stochastic	0			NORMAL	0	0.1	
2	Mist_Sec_02	Stochastic	0			NORMAL	0	0.1	
3	Mist_Sec_03	Stochastic	0			NORMAL	0	0.1	
4	Mist_Sec_04	Stochastic	0			NORMAL	0	0.1	
5	Mist_Sec_05	Stochastic	0			NORMAL	0	0.1	
6	Mist_Sec_06	Stochastic	0			NORMAL	0	0.1	
7	Mist_Sec_07	Stochastic	0			NORMAL	0	0.1	100 %
8	Mist_Sec_08	Stochastic	0			NORMAL	0	0.1	100 %
9	Mist_Sec_09	Stochastic	0			NORMAL	0	0.1	100 %
10	Mist_Sec_10	Stochastic	0			NORMAL	0	0.1	100 %
11	Mist_Sec_11	Stochastic	0			NORMAL	0	0.1	100 %
12	Mist_Sec_12	Stochastic	0			NORMAL	0	0.1	100
13	Mist_Sec_13	Stochastic	0			NORMAL	0	0.1	100
14	Mist_Sec_14	Stochastic	0			NORMAL	0	0.1	100
15	Mist_Sec_15	Stochastic	0			NORMAL	0	0.1	100
16	Mist_Sec_16	Stochastic	0			NORMAL	0	0.1	100
17	Mist_Sec_17	Stochastic	0			NORMAL	0	0.1	100 %
18	Mist_Sec_18	Stochastic	0			NORMAL	0	0.1	100 %
19	Mist_Sec_19	Stochastic	0						
20	Mist_Sec_20	Stochastic	0			N			
21	Mist_Sec_21	Stochastic	0			N			
22	Mist_Sec_22	Stochastic	0			N			







Which Blades have dominant impact???

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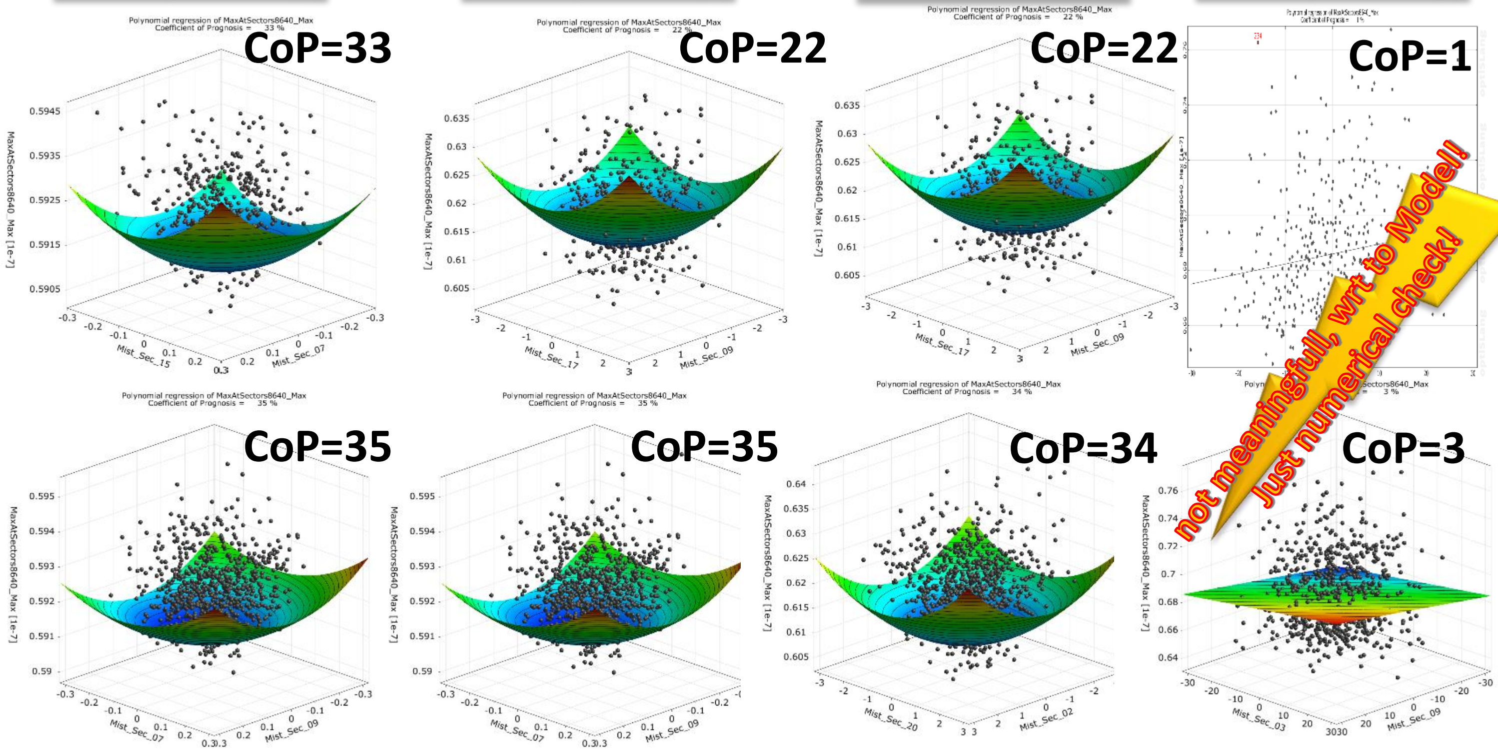
Meta Modell of Optimal Prognosis

Increasing Coefficient of Prognosis

Bad CoP!! WHY??

Std. Dev. δ =0.1%	Std. Dev. δ =1.0%	Std. Dev. δ =10%	Std. Dev. δ =100%



400 Design Points

800 Design Points

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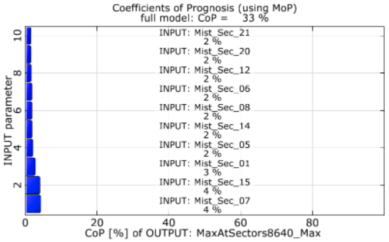
Important Parameters

Increasing Coefficient of Prognosis

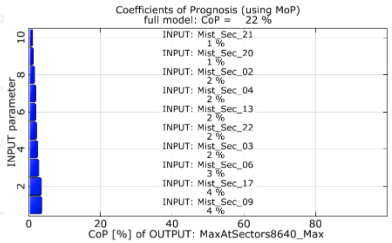
Important Parameters not detected properly!! WHY??

Std. Dev. δ =0.1%	Std. Dev. δ =1.0%	Std. Dev. δ =10%	Std. Dev. δ =100%

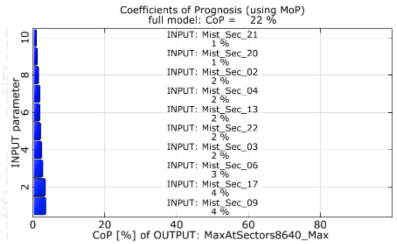
CoP=33



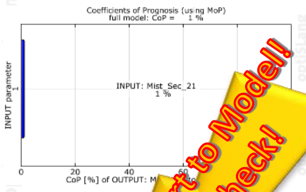
CoP=22



CoP=22



CoP=1

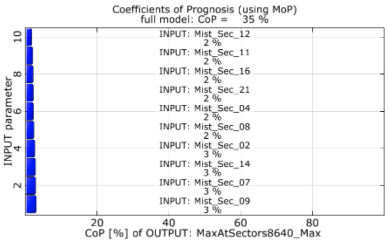


not meaningfull, wrt to Model!
Just numerical check!

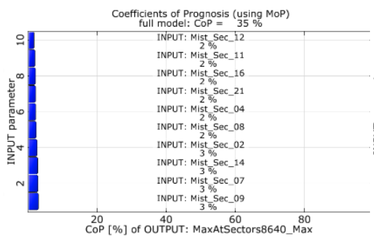
400 Design Points

800 Design Points

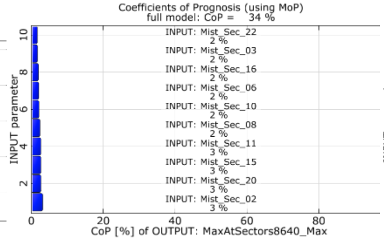
CoP=35



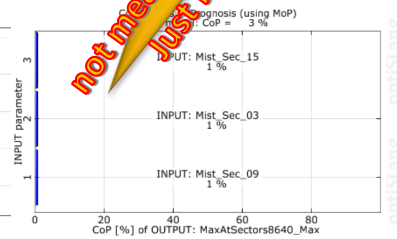
CoP=35



CoP=34



CoP=3



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Apply Best-Practice Guide Lines

Number of Design Points for Meta-Model depends on:

- Number of *important* Parameters
- Nonlinearity of Response Surface

Objective for Meta-Model: Maximal Coefficient of Prognosis

Reason for small Coefficient of Prognosis:

- Parameterization Input (TWC vs. discrete)
- Parameterization Output (Scalar, Signal, Field)
- Number Design Points
- Number of Input Parameter

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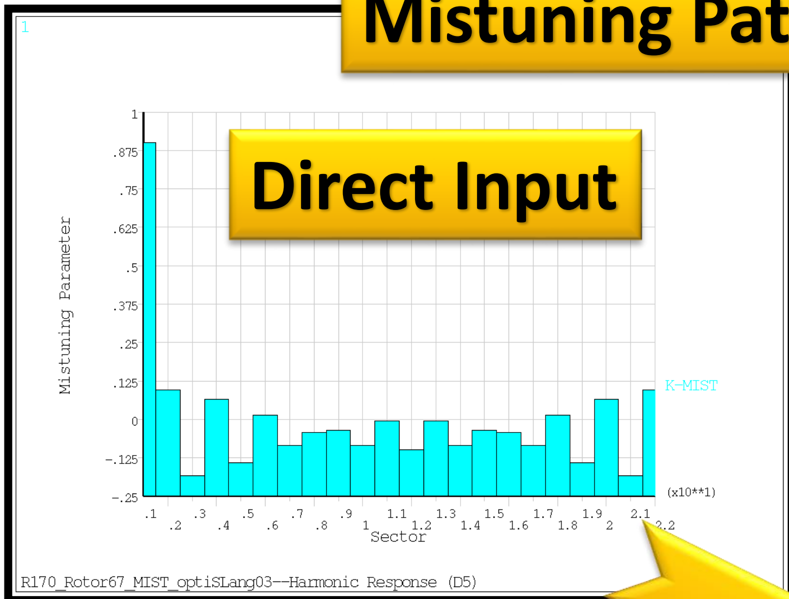
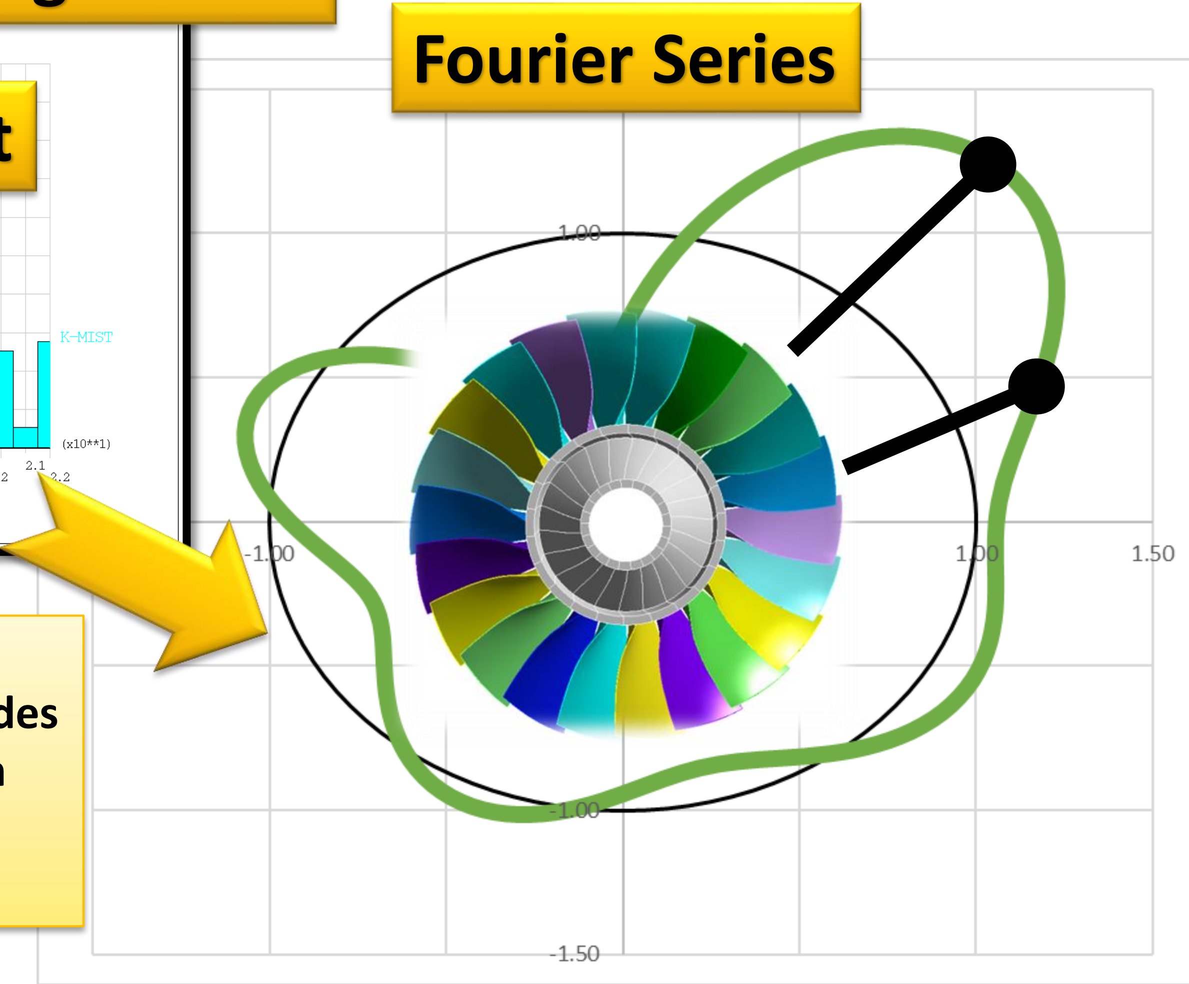
Parameterization – Input

Mistuning Patter=





+Fourier Sieries:

- **Independent of #Blades**
- **Parameter Reduction**
- **High Flexibility**
- **100% accurate**

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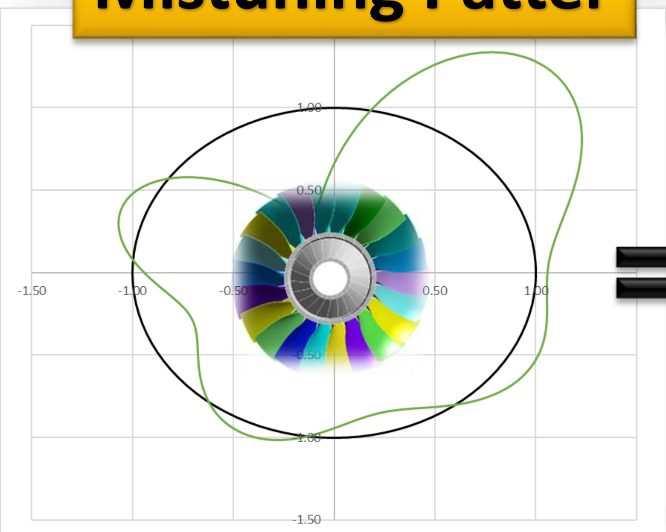
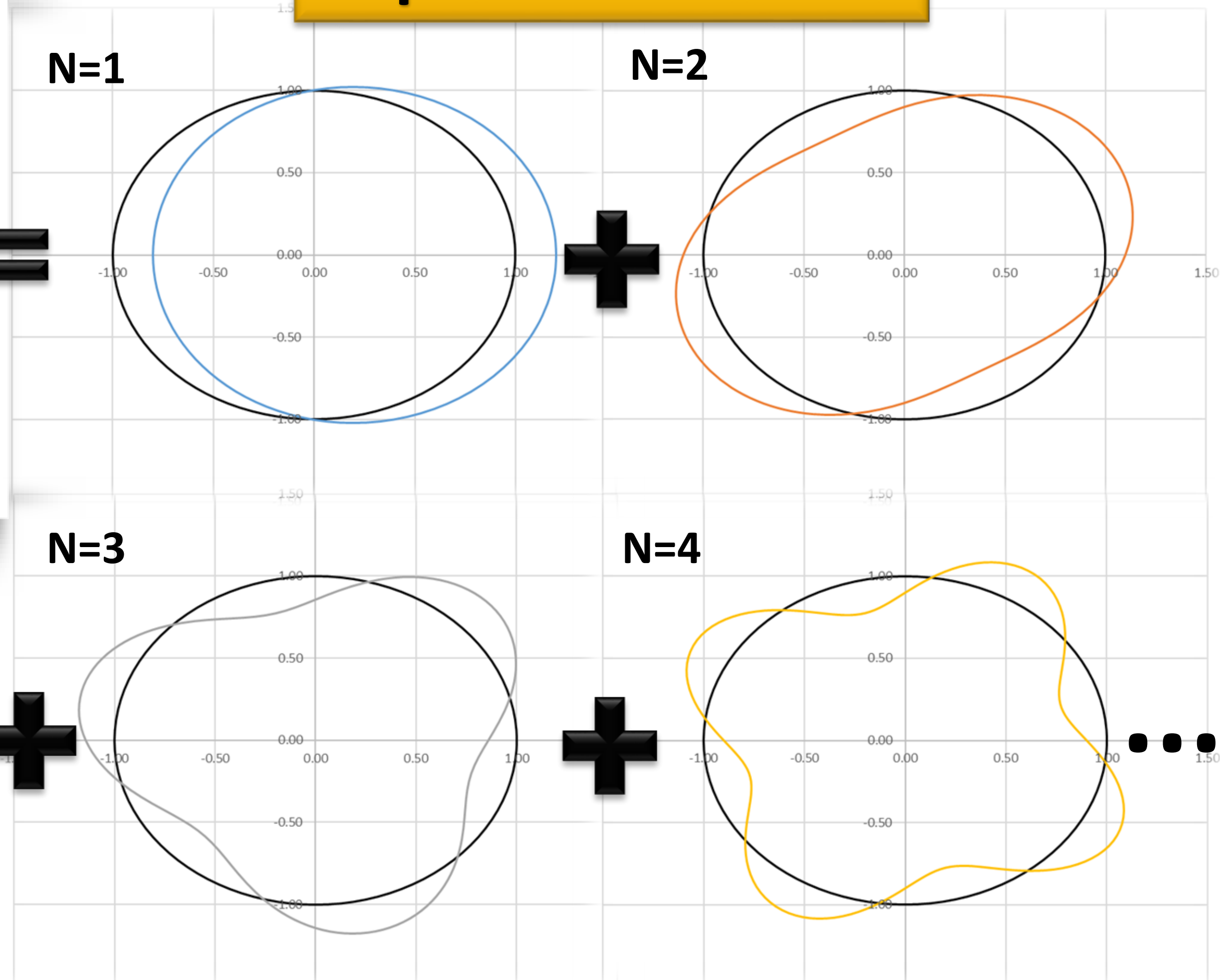
Parameterization – Input as Fourier Series

Mistuning Patter



Imperfection Wave



Parameters per Imp-Wave:

- **Amplitude**
- **Phase Position:**
  - **N=1: 0-360° → [0-1]**
  - **N=2: 0-180° → [0-1]**
  - **N=3: 0-120° → [0-1]**
  - **…**

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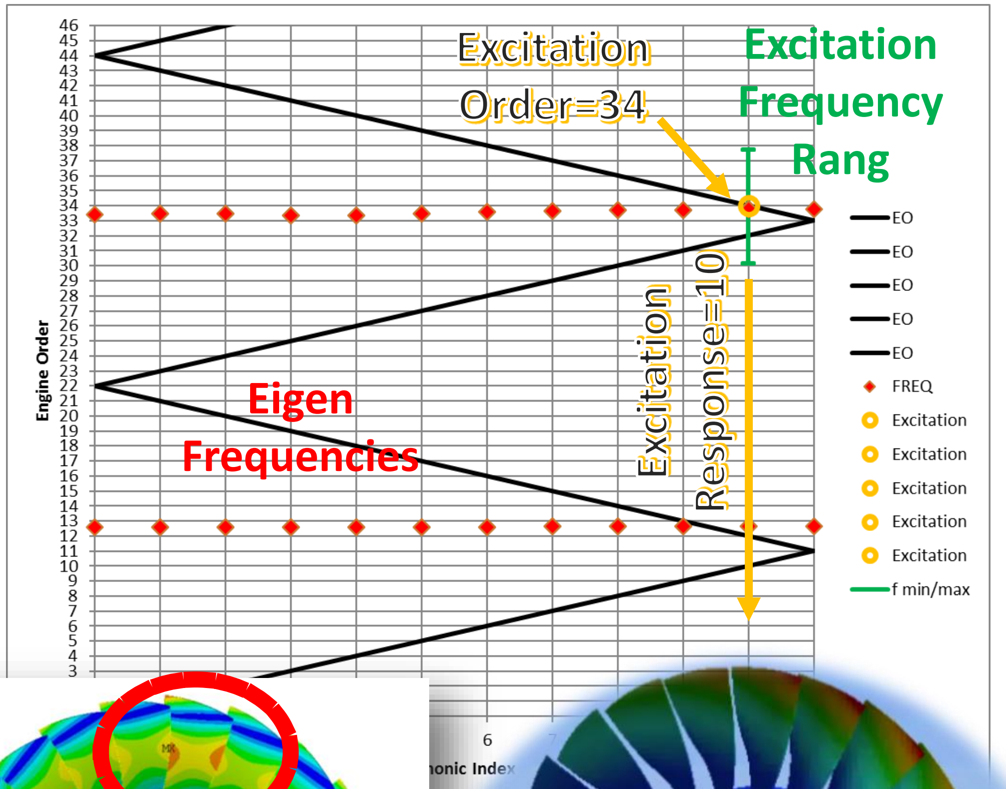
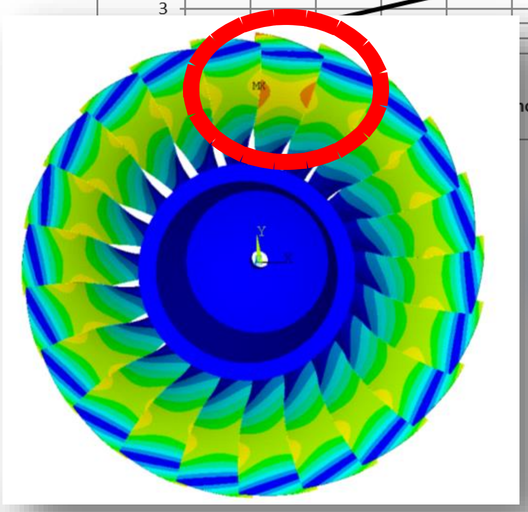
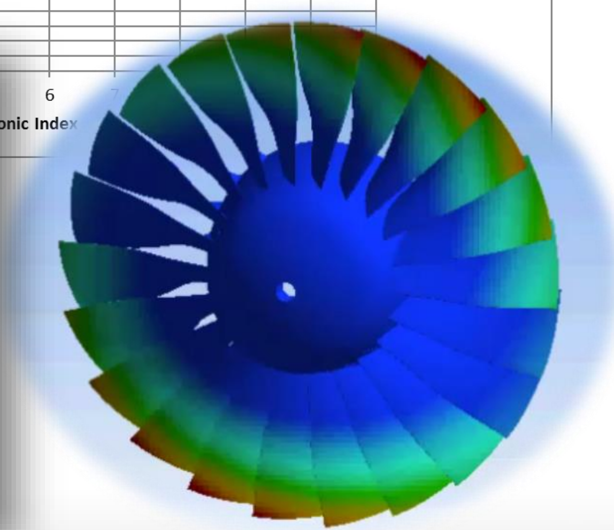
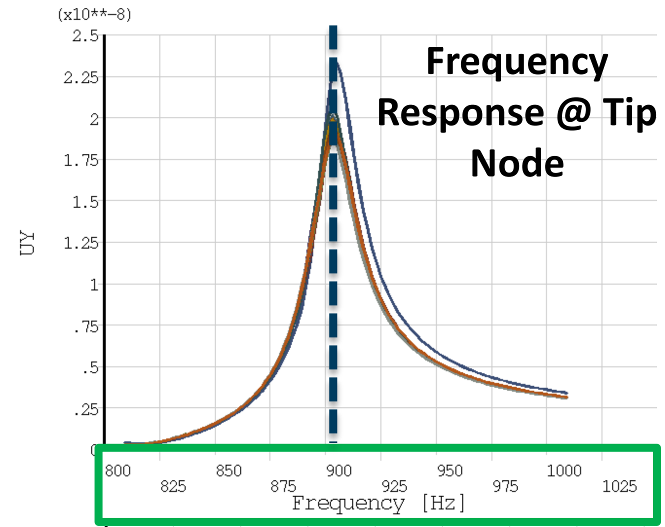
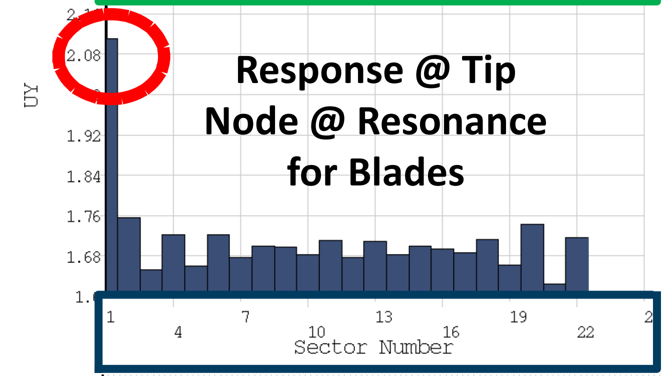
Simulation – Results

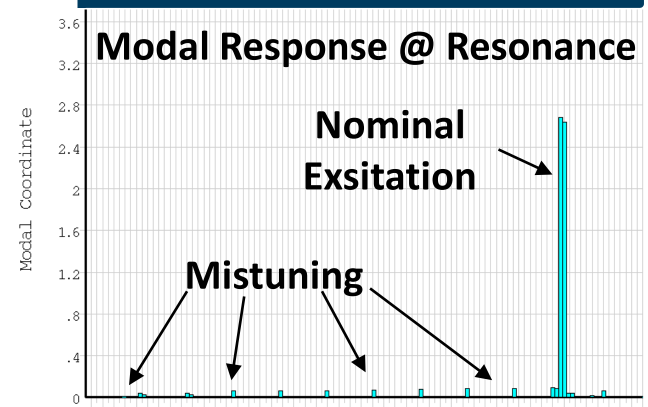












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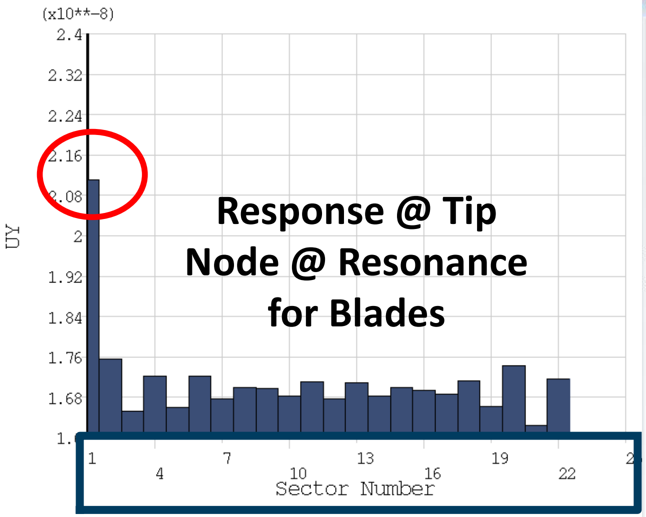
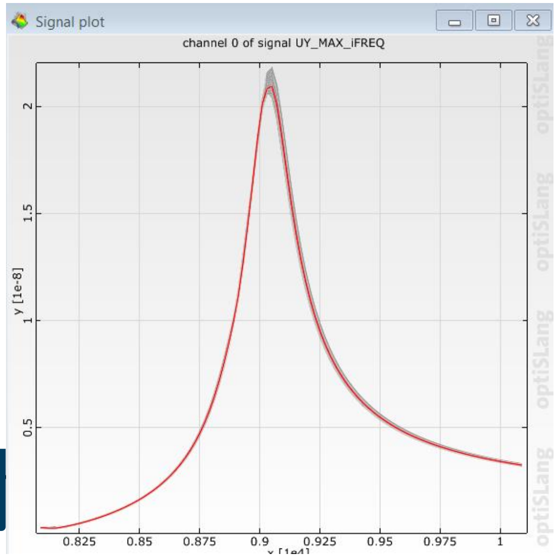
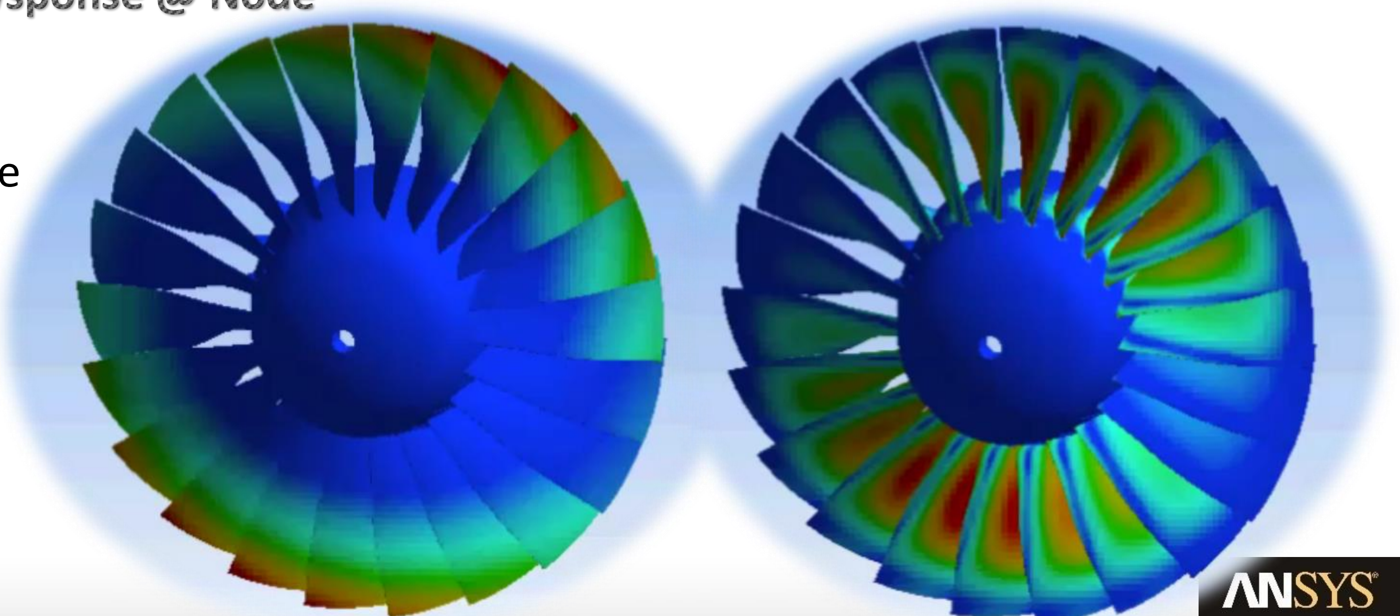
Parameterization – Output

- Scalar
  - Global Maximum
  - Local Maximum @ Blades
- Signal
  - Local Maximum @ Blades
  - Frequency Rewsponse @ Node
- Field → SoS
  - Value @ Surface







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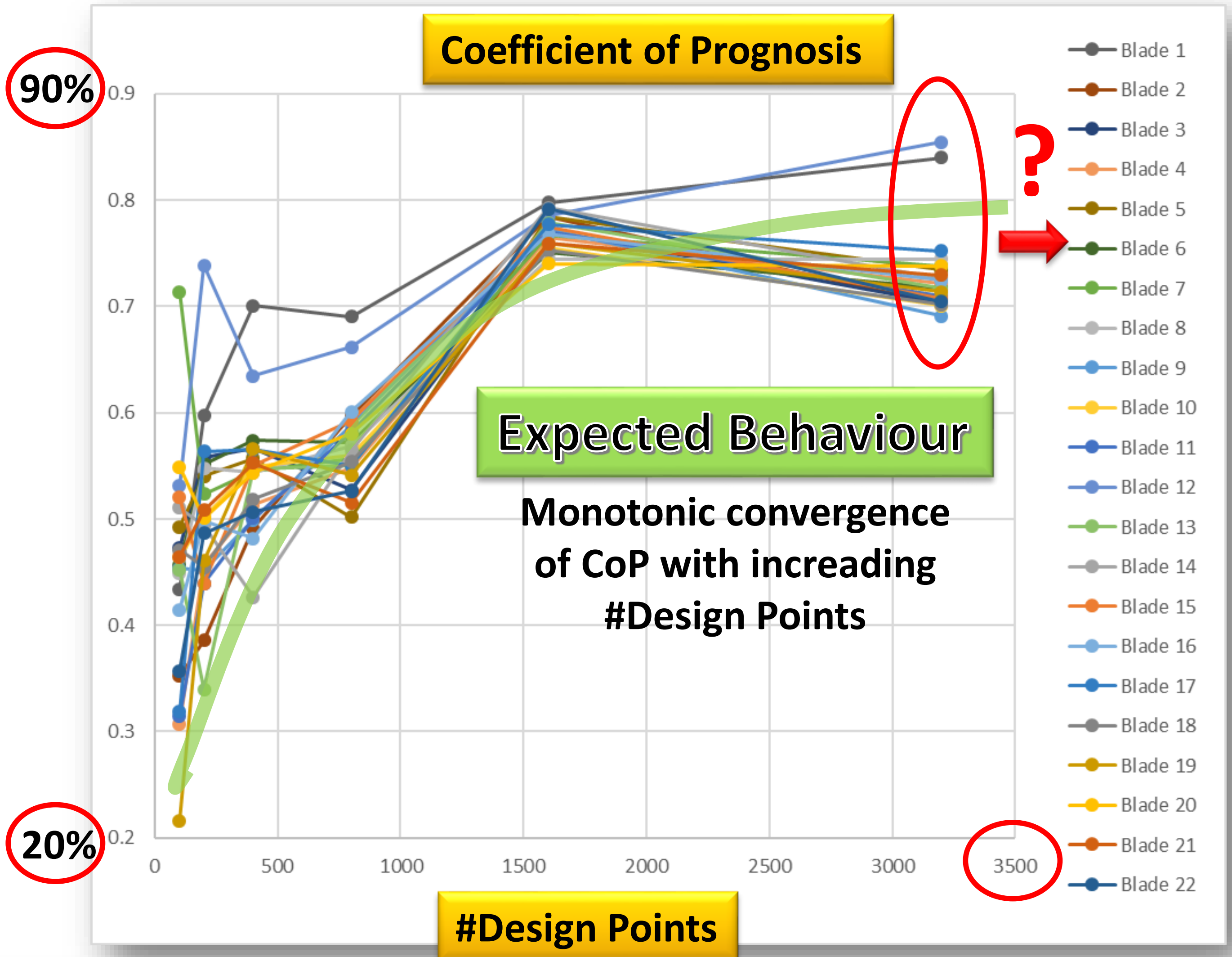
Investigation: Number of Design Points



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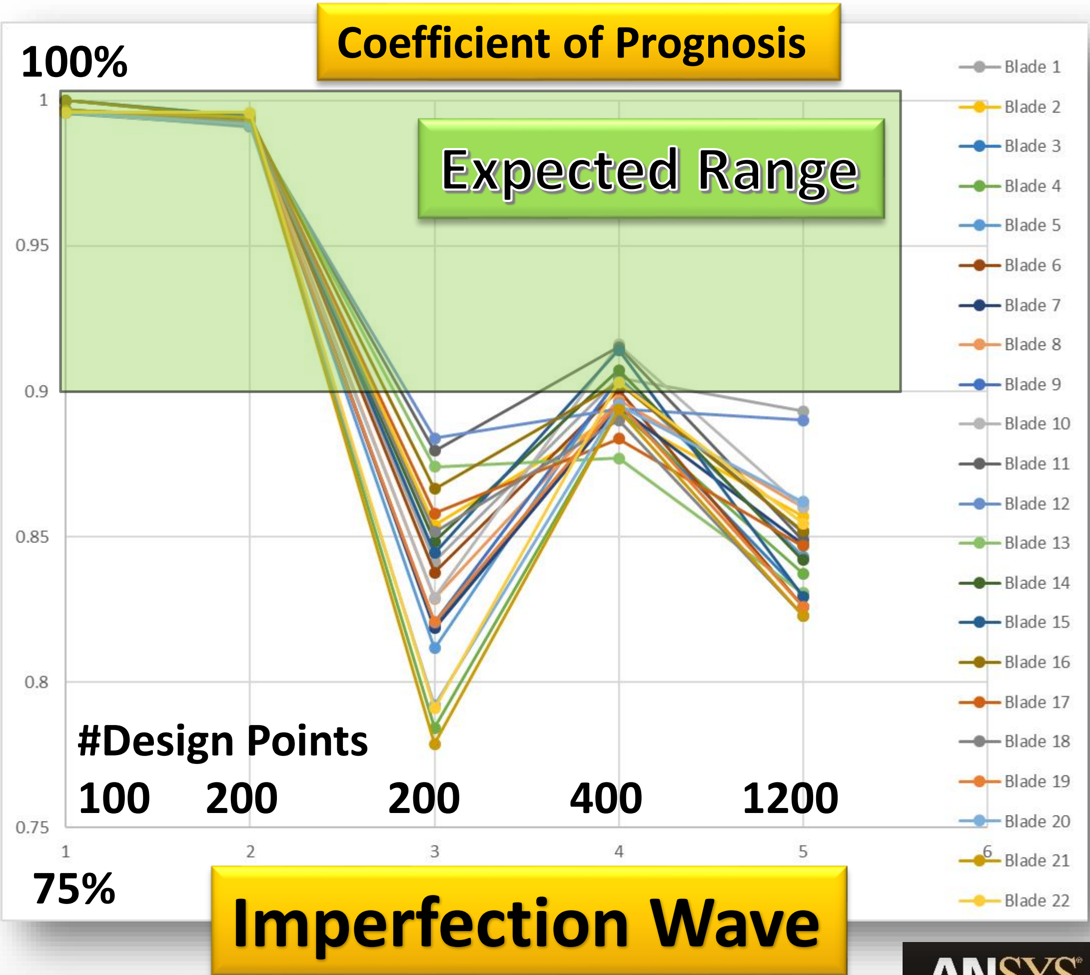
Investigation: Number of Input Parameters

- **Parameter Reduciton**
- **CoP wrt:**
  - **#Imperfection Waves**
    - **Amplitudes**
    - **Phase**
  - **#Design Points**
    - **Increased with Imp. Waves**



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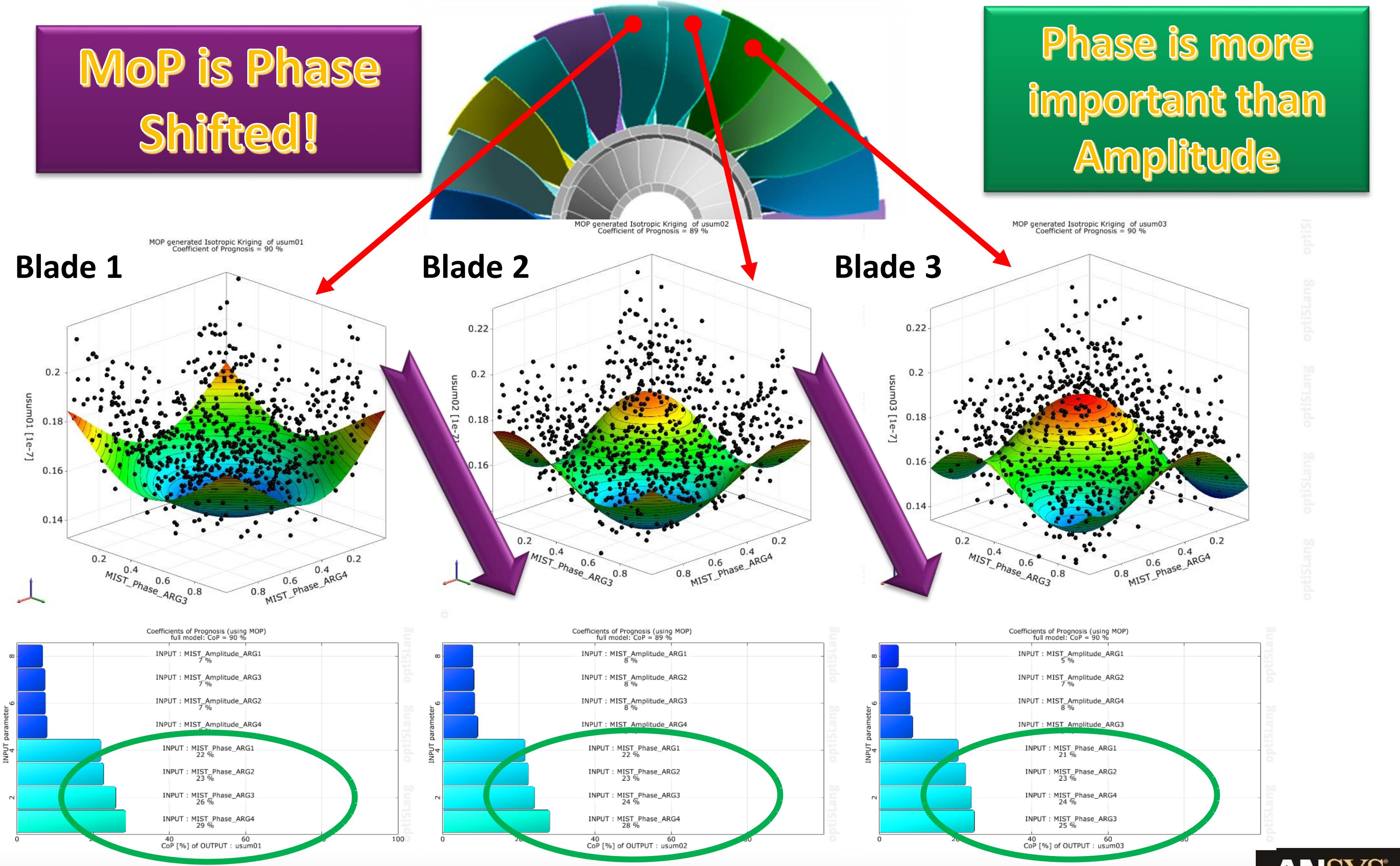
Parameter Impact & Response Surface



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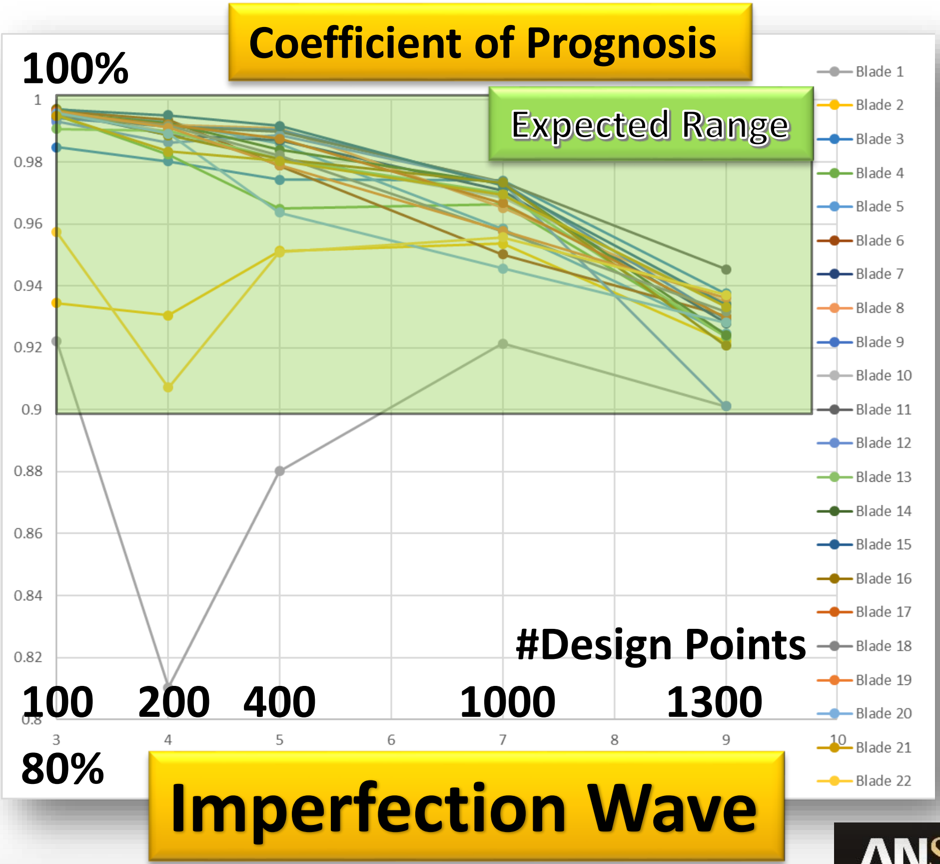
Investigation: Number of Input Parameters

- **Parameter Reduciton**
- **CoP wrt:**
  - #Imperfection Waves
    - Phase
  - #Design Points
    - Increased with Imp. Waves



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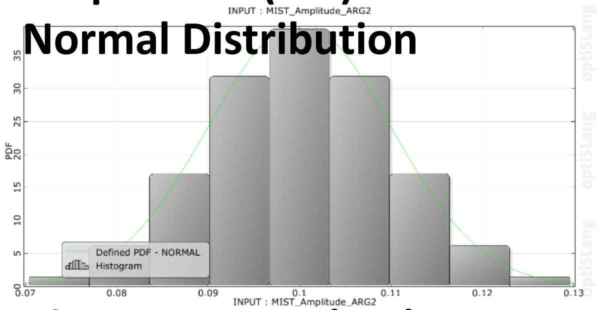
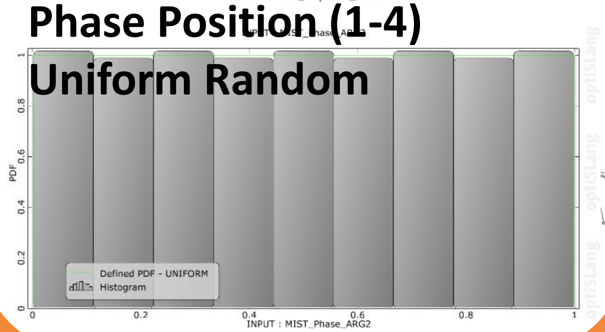
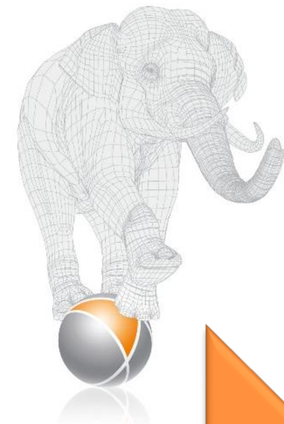
Robustness Evalution

Amplitudes (1-4)
Normal Distribution

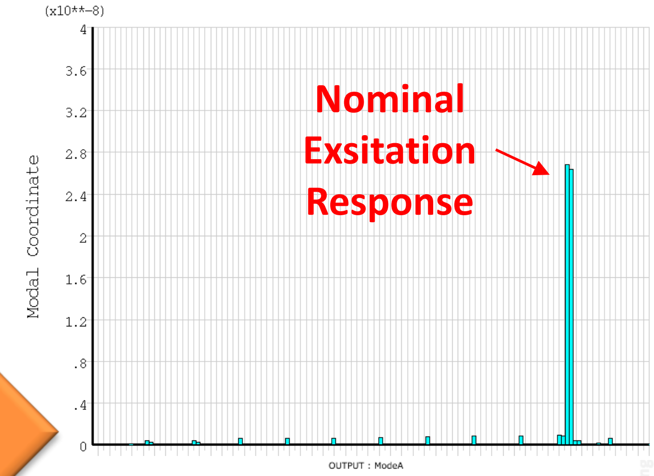


Phase Position (1-4)
Uniform Random

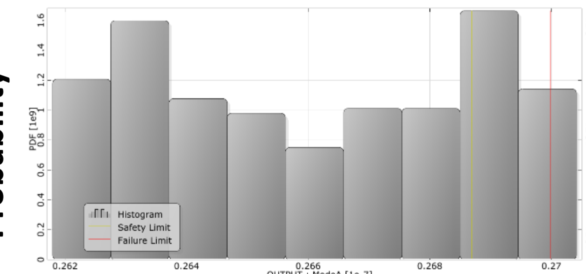




2x4 Parameter, 100 Design Points

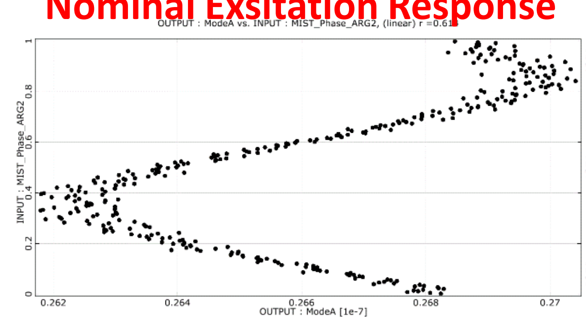


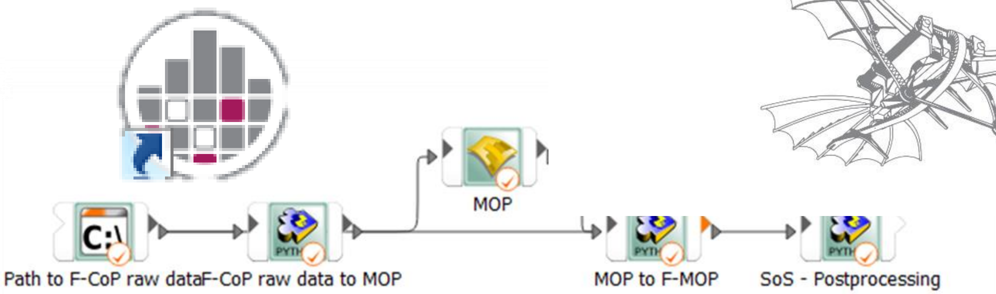
Probability



Nominal Exsitation Response

Imperfection Phase 2





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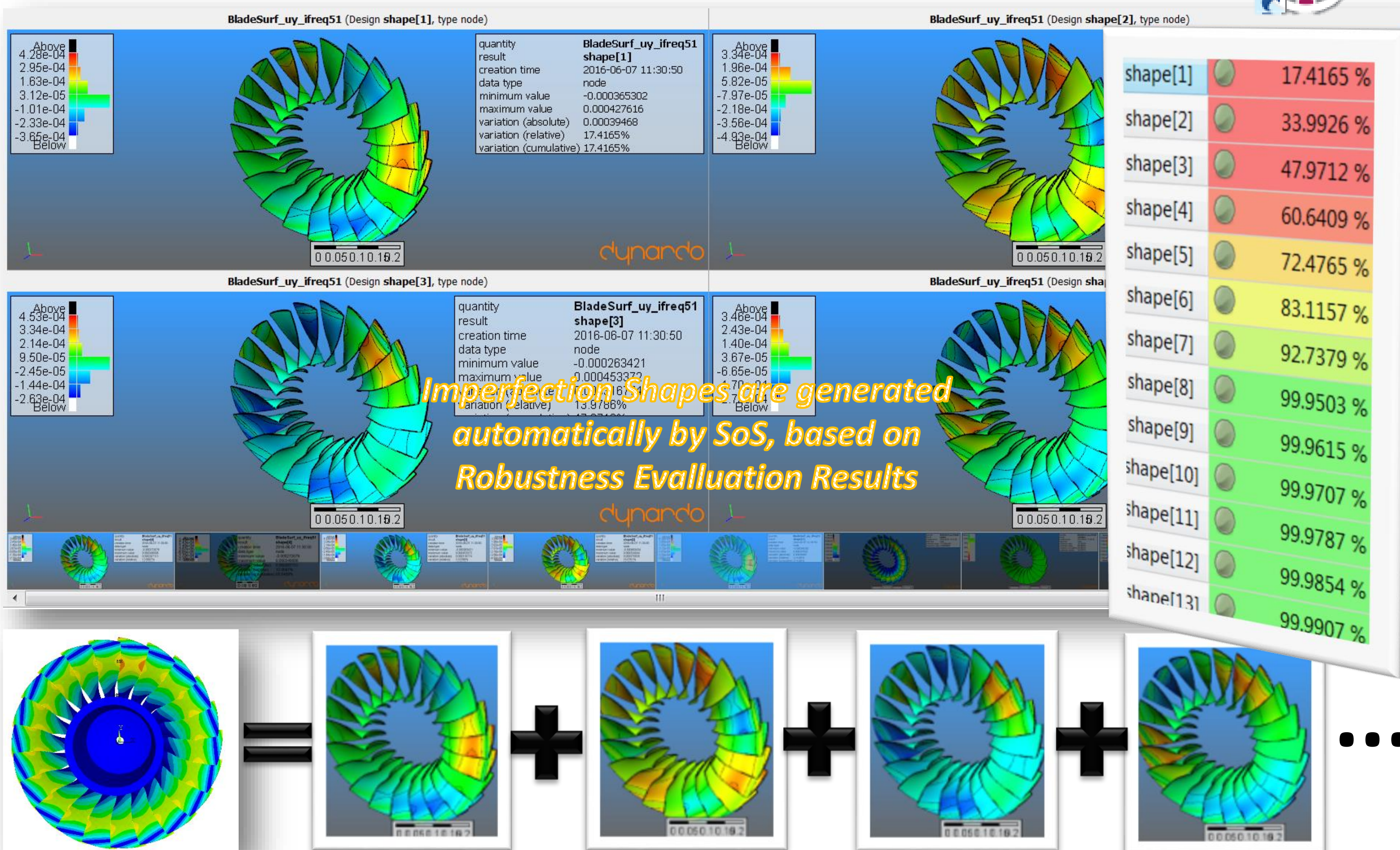
Imperfection Shapes - Statistic on Structures



Reconstruction of single Design Point by Imperfection Shapes

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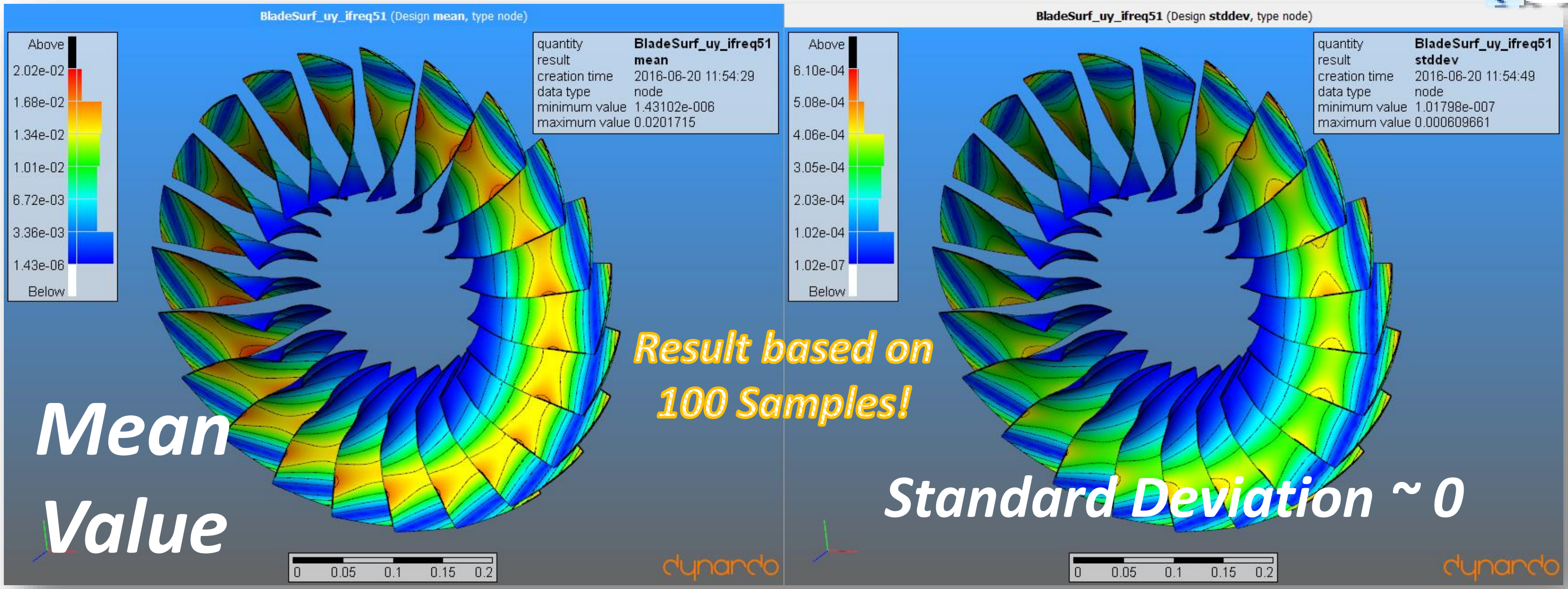
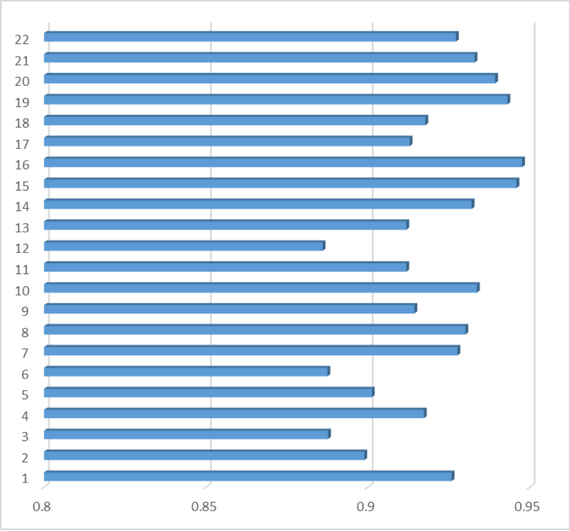
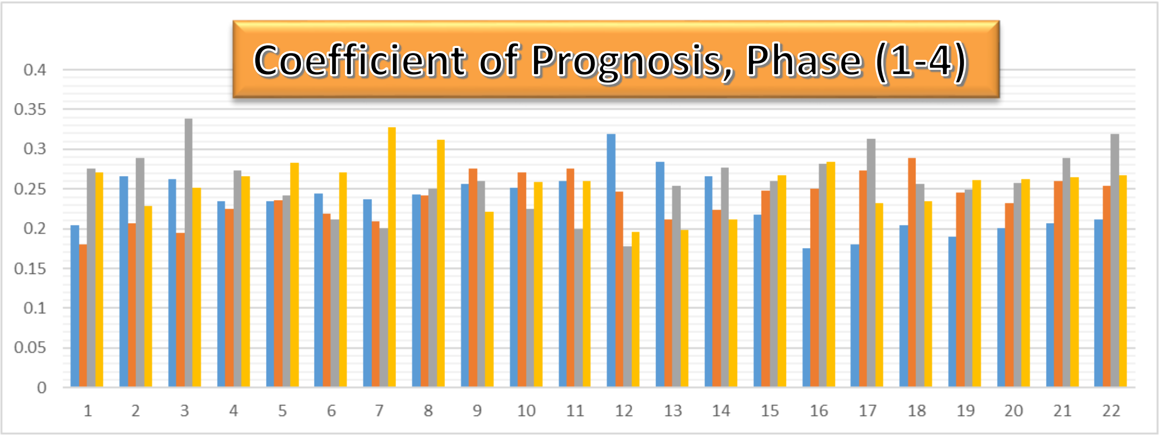
Final Result with Statistic on Structures



Coefficient of Prognosis, Total





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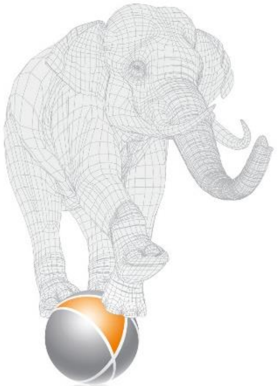
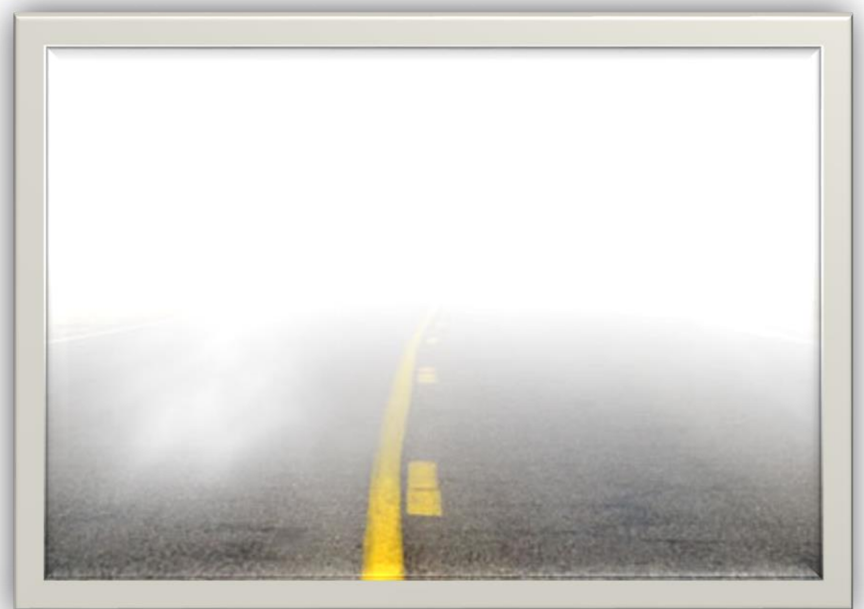
Summary



Process:

- Full automatic
- Reliable - Physics and Numerics
- Efficient - fast Simulation



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Number of Design Points for Meta-Model depends on:

- Number of ***important*** Parameters
- Nonlinearity of Response Surface

Beat-Practice Analysis:

- Parameterization Input
- Parameterization Output (Scalar, Signal, Field)
- Numerical Error
- Number of Design Points
- Number of Input Parameter
- Systematic Error

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