AEROSPACE TECHNOLOGY CONGRESS 2019 (FT2019)

INTENTIONAL MISTUNING EFFECTS ON THE FORCED RESPONSE OF A COMPRESSOR BLISK

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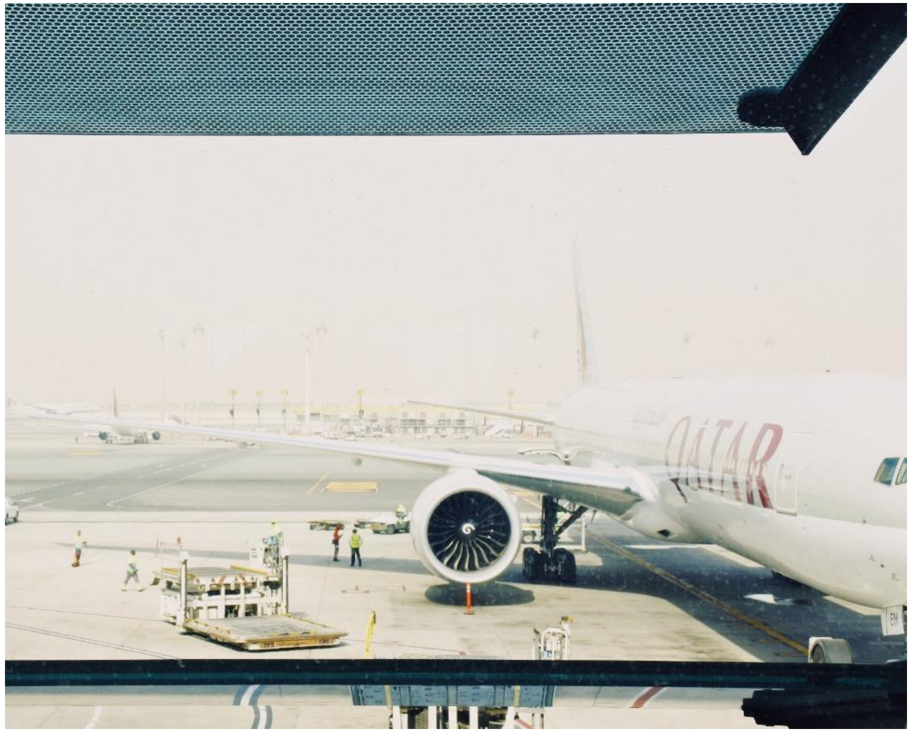
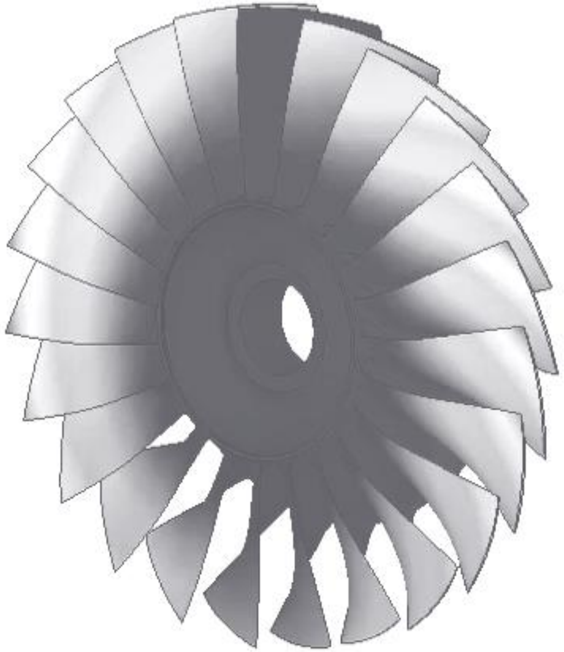
Motivation

- Blades inside a gas turbine are subjected to vibrate



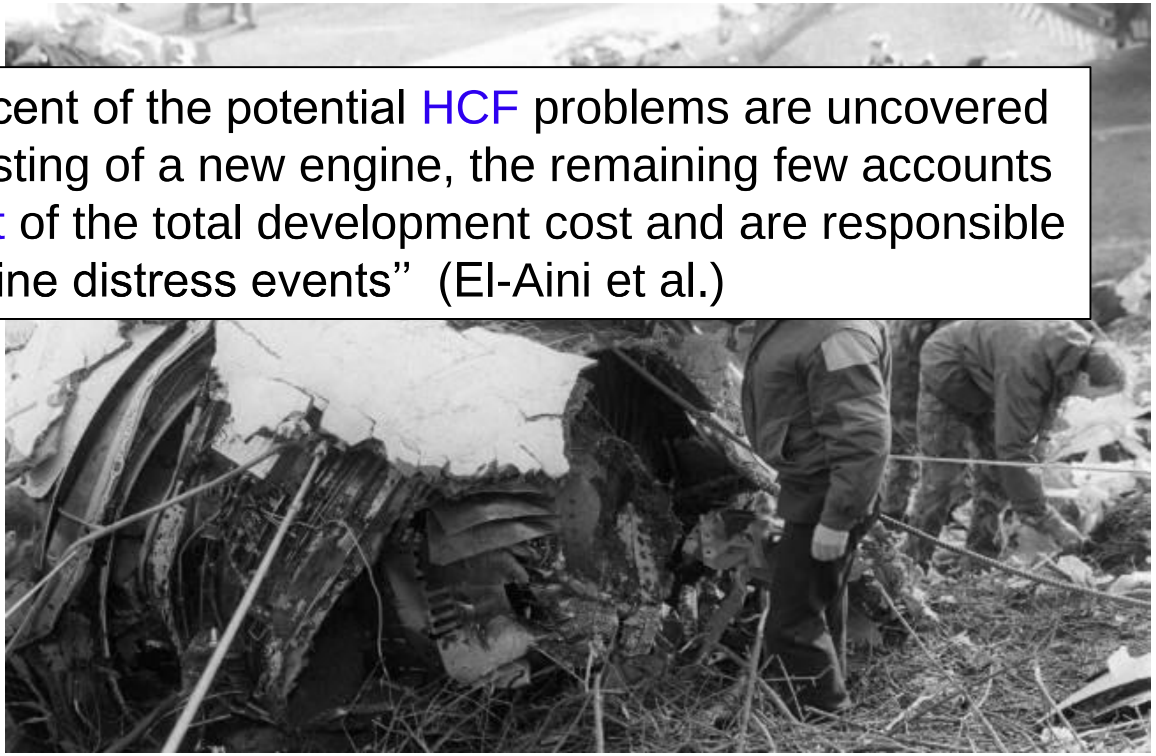
Ref: unsplash.com



Current designs involves thinner and more complex blades

Motivation

- Vibrations → High Cycle Fatigue (HCF) → Failure

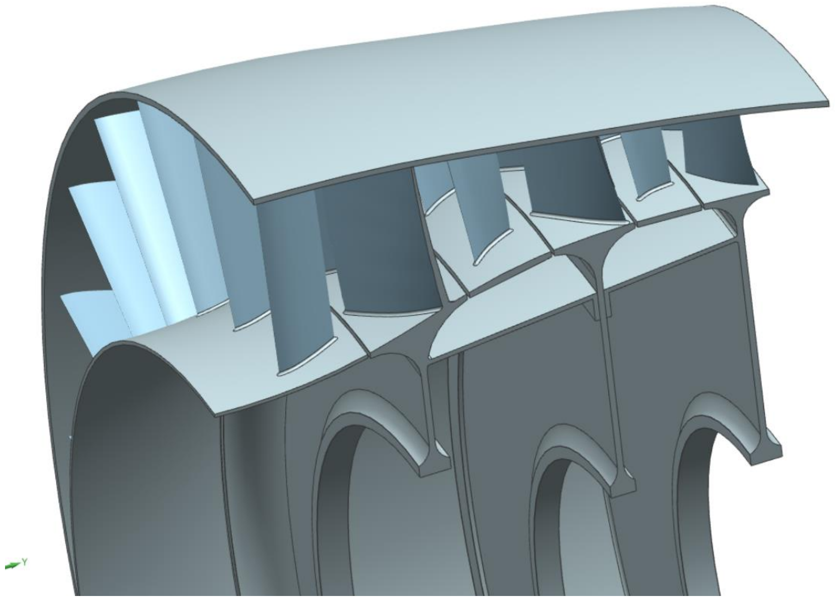



“ while over ninety percent of the potential HCF problems are uncovered during development testing of a new engine, the remaining few accounts for nearly thirty percent of the total development cost and are responsible for over 25% of all engine distress events” (El-Aini et al.)

Ref: https://flashbak.com/the-kegworth-air-disaster-the-story-in-photos-7956/

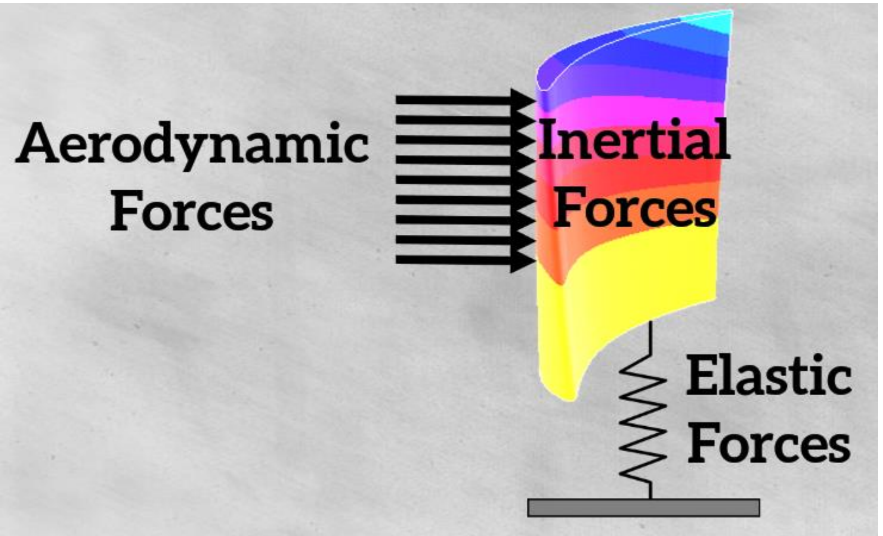
Presentation Outline

- Background
- Objective
- Approach
  - AROMA Tool
  - Test object
- Results
- Conclusions
- Future work



Background

- Forced Response (Aeroelastic phenomenon)



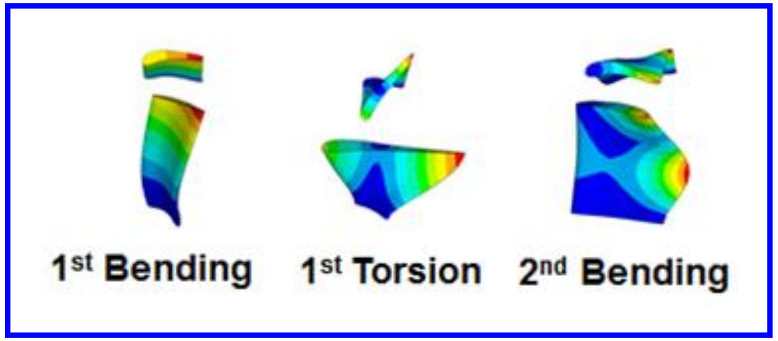
$$[M_{STRUC}\omega^2 + C_{STRUC}\omega i + K_{STRUC}]\{\hat{x}\} = \{\hat{F}_{AERO}\}$$

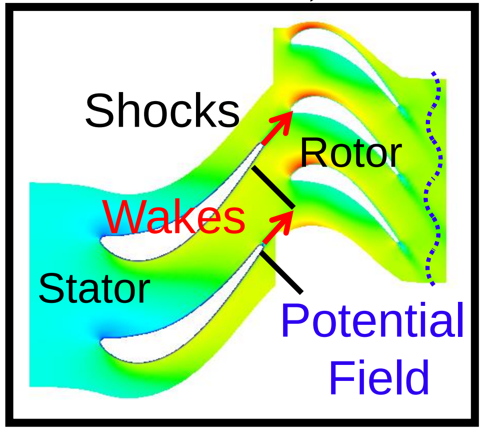
Background

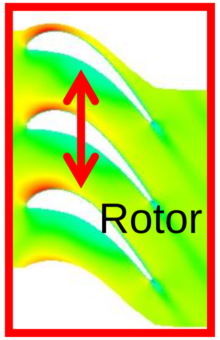
- Forced Response (Aeroelastic phenomenon)

$$[M_{STRUC}\omega^2 + C_{STRUC}\omega i + K_{STRUC}]\{\hat{x}\} = \{\hat{F}_{AERO}\}$$

$$\underbrace{[M_{STRUC}\omega^2 + C_{STRUC}\omega i + K_{STRUC}]}\{\hat{x}\} = \{\hat{F}_{EXC}\}+\{\hat{F}_{COUPLED}(\hat{x})\}$$







Background

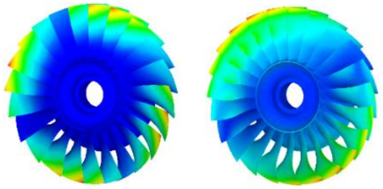
- Forced Response (Aeroelastic phenomenon)

$$[M_{STRUC}\omega^2 + C_{STRUC}\omega i + K_{STRUC}]\{\hat{x}\} = \{\hat{F}_{EXC}\}+\{\hat{F}_{COUPLED}(\hat{x})\}$$

$$\downarrow$$

$$[M_{STRUC}\omega^2 + (C_{STRUC}+C_{AERO})\omega i + (K_{STRUC}+K_{AERO})]\{\hat{x}\} = \{\hat{F}_{EXC}\}$$

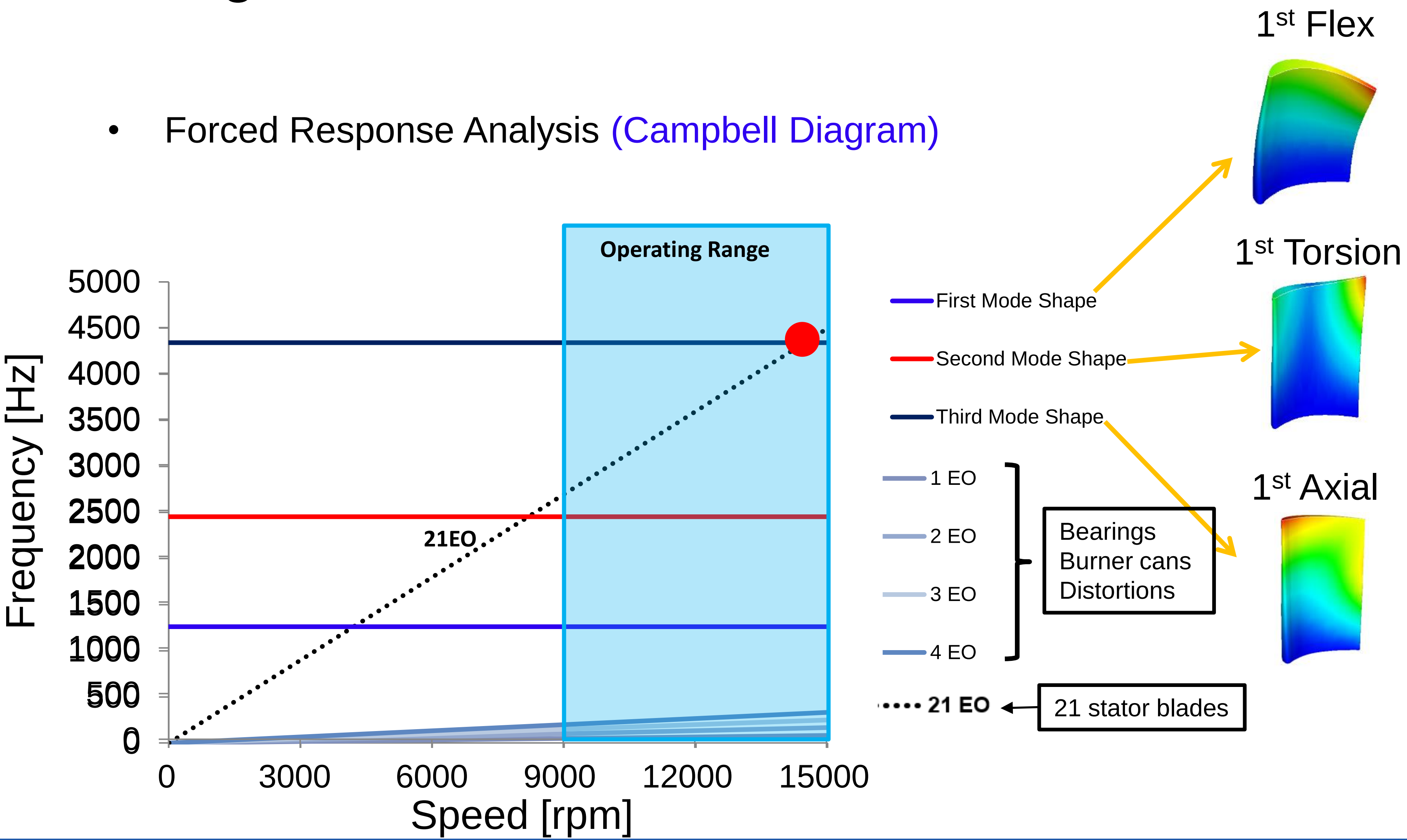
Forced response



High Cycle Fatigue (HCF)

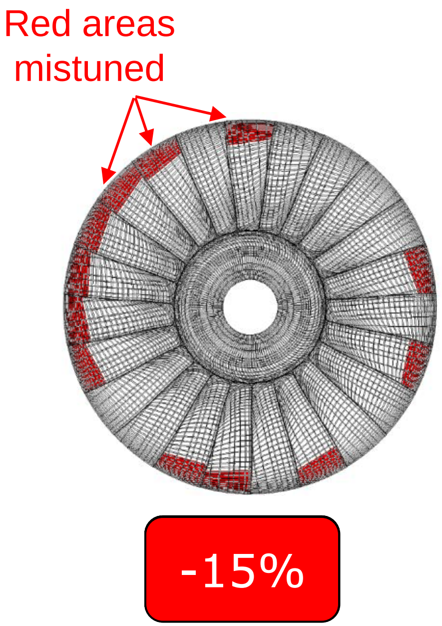
Background

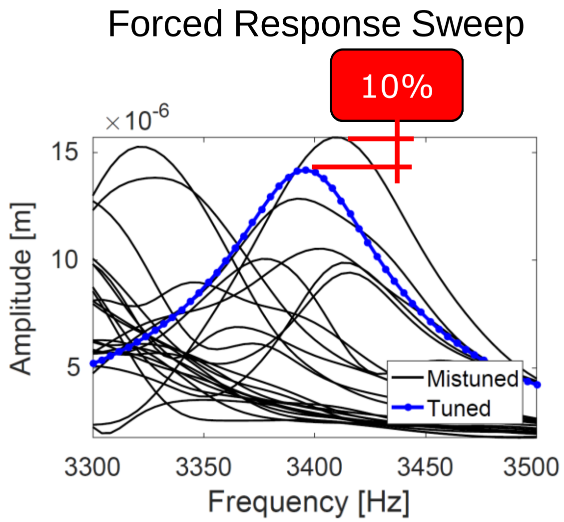
- Forced Response Analysis (Campbell Diagram)

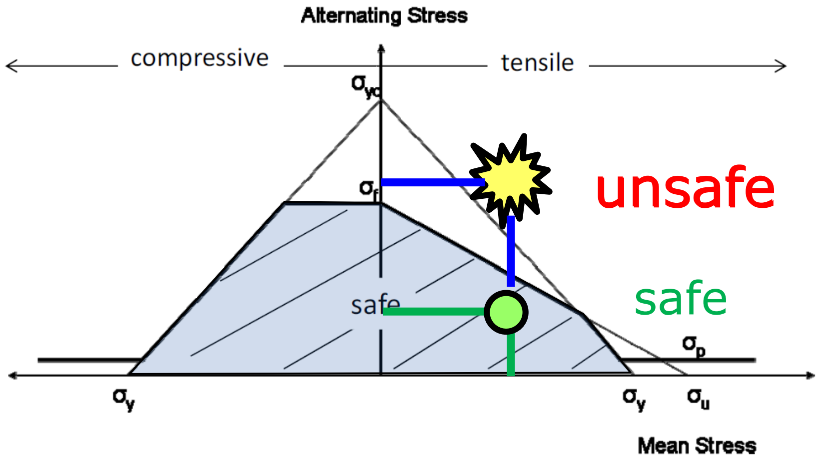


Background

- Forced Response Analysis (Haigh Diagram)



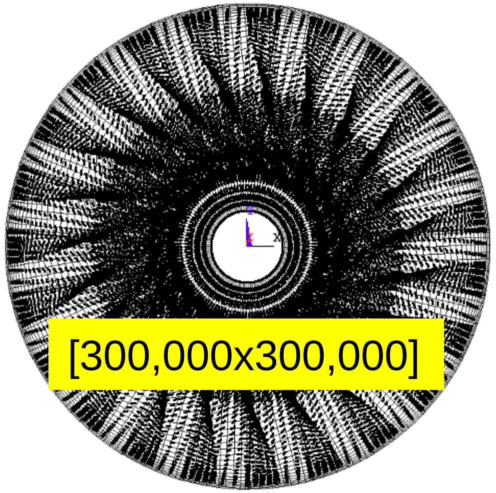




Background

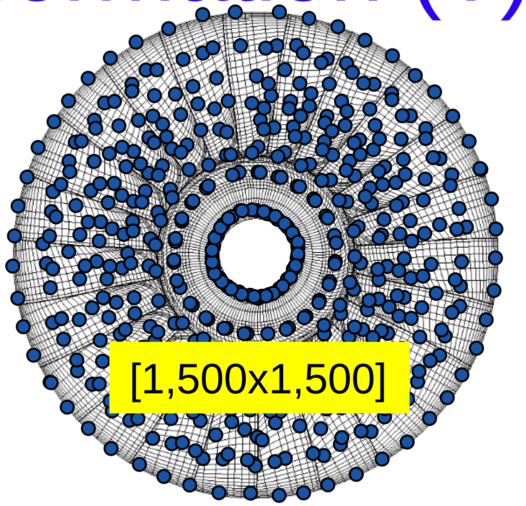
- In order to solve forced response analyses with mistuning Reduced Order Models are needed.

It is all about the Transformation (T)



Actual
Model

Apply
T



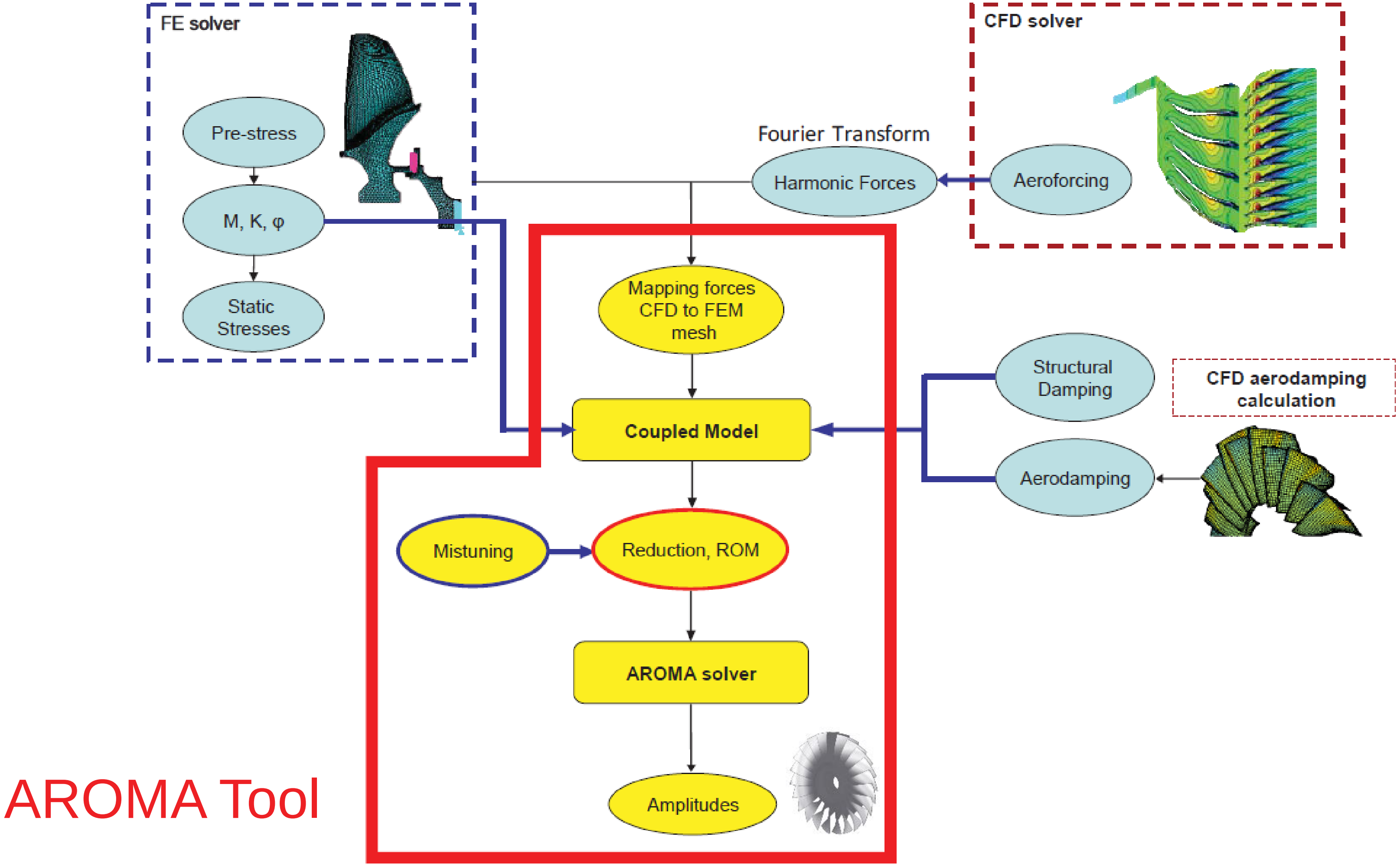
ROM
Less DoF

35 minutes ← Forced Response Sweep → 5 sec (400x faster)

Objective

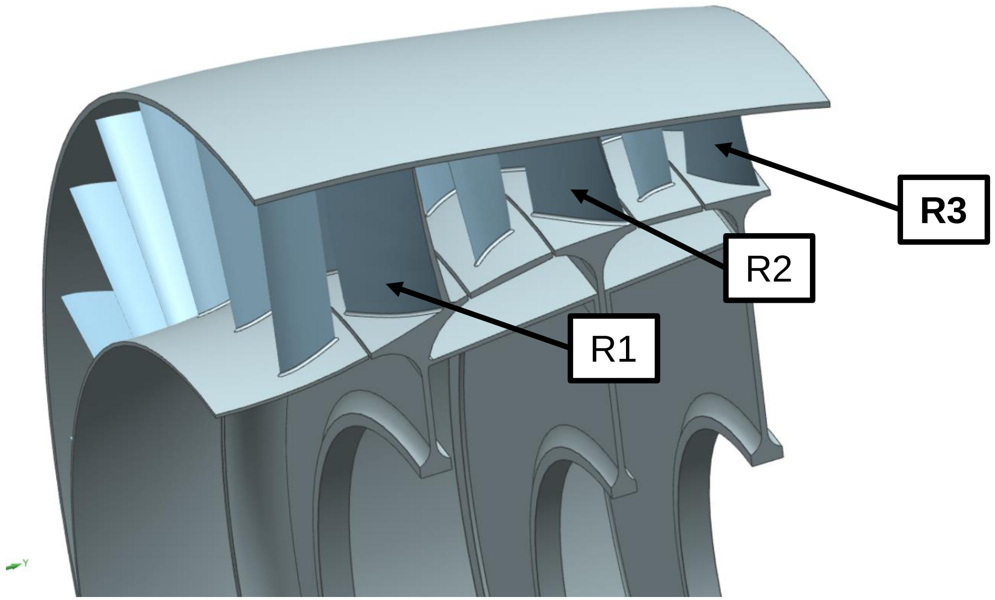
- Perform a mistuned forced response analysis of a rear stage rotor of a modern 3-stage high-speed booster compressor using the aeromechanical tool AROMA, and the commercial software (ANSYS) .
  - Run an aerodynamic steady simulation to obtain the steady forces.
  - Run an aerodynamic transient simulation to obtain the unsteady forces.
  - Evaluate the different methods to solve for intentional mistuning and to address probabilistic mistuning.
  - Use intentional mistuning strategies onto the compressor blisk in attempt to find an optimum pattern yielding reduced vibration amplitudes.

Approach-AROMA



Approach-Test object

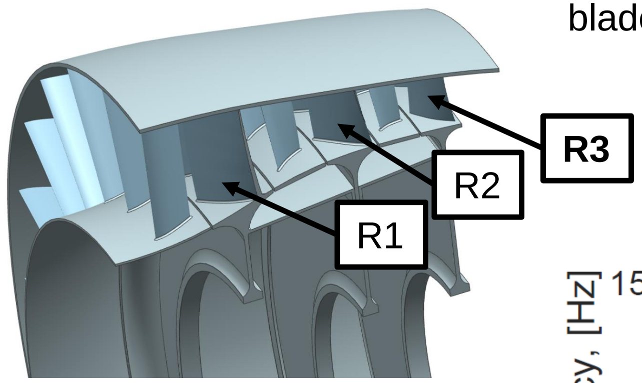
- The rotor 3 (**R3**) has the following characteristics:
  - Material used is titanium (Ti64)
  - Speed of 7454rpm (top-of-climb)



3-stage high-speed
booster

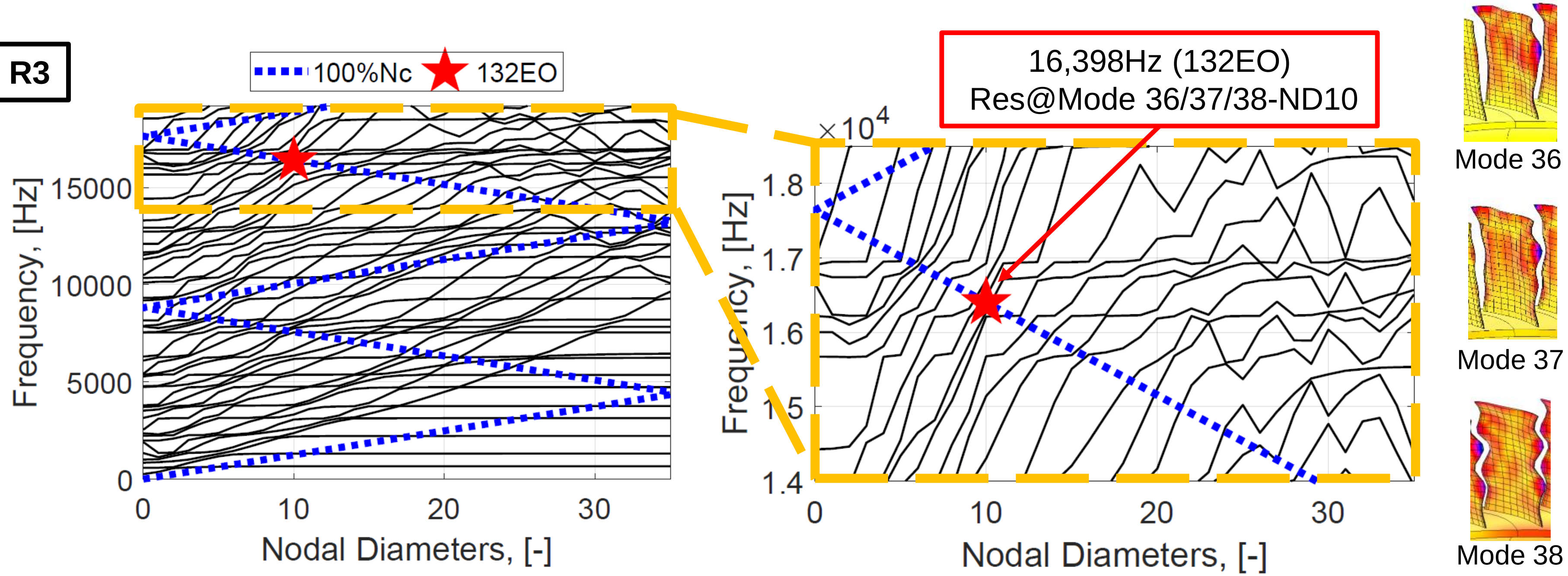
Results-Operating point (rotor 3)

- Resonance @7454 rpm occurs at Mode 36/37/38-ND10 due to the 132 blade count upstream.
- The approach has been limited to only study the 132EO case.



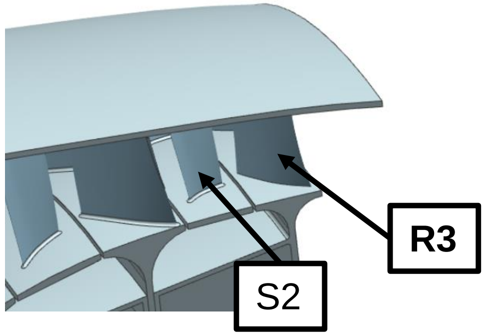
Compressor blade count

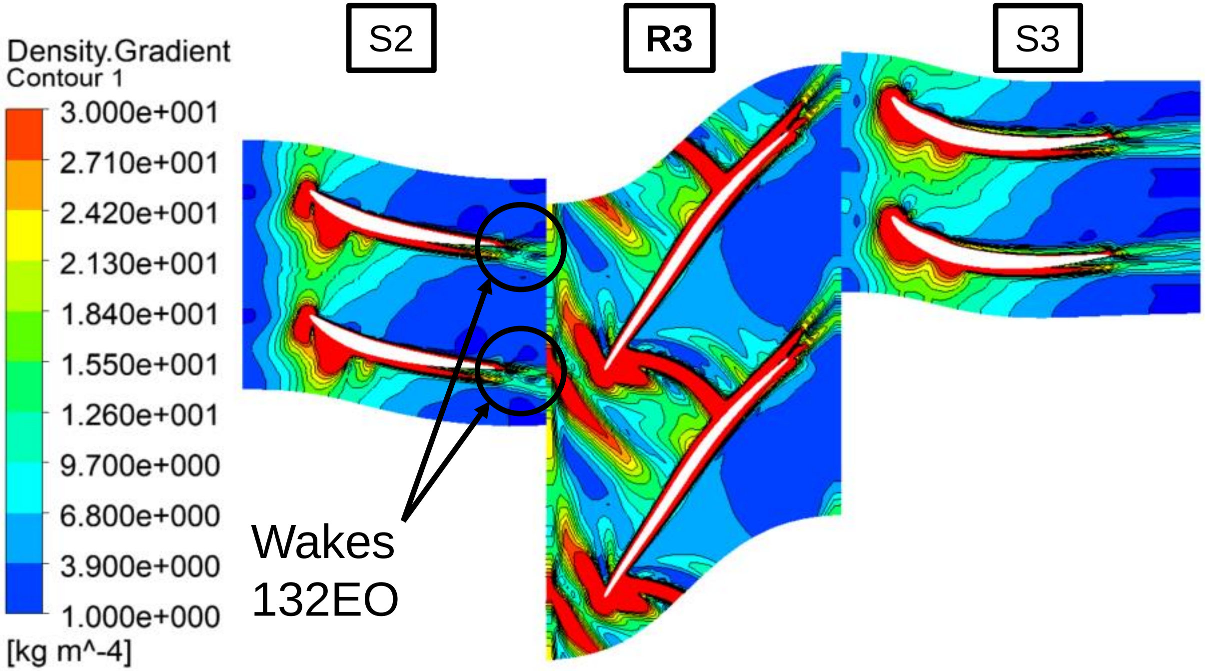
VIGV	R1	S1	R2	S2	R3
41	37	108	48	132	71



Results-Aerodynamic excitation predictions
CFD steady-state analysis

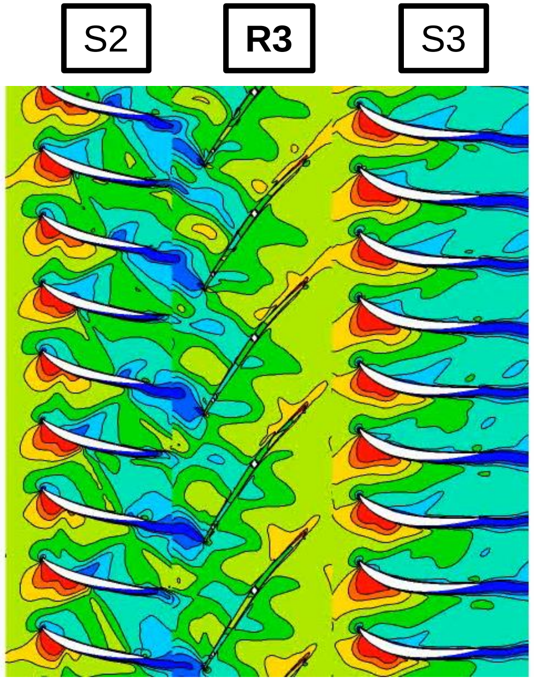
- Results show the 132EO from the upstream wakes
- Speed: 7454rpm
- Turbulence Model: SST

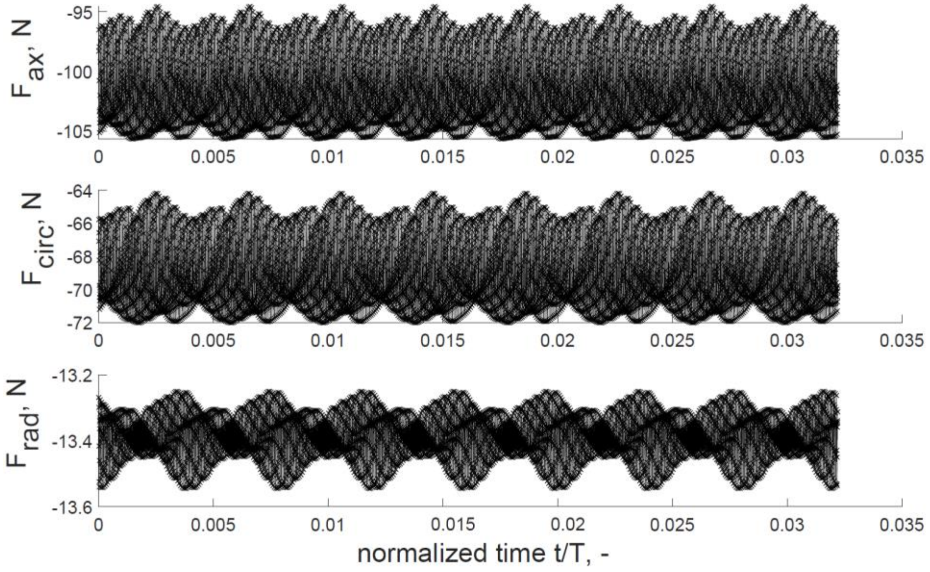




Results-Aerodynamic excitation predictions CFD transient analysis

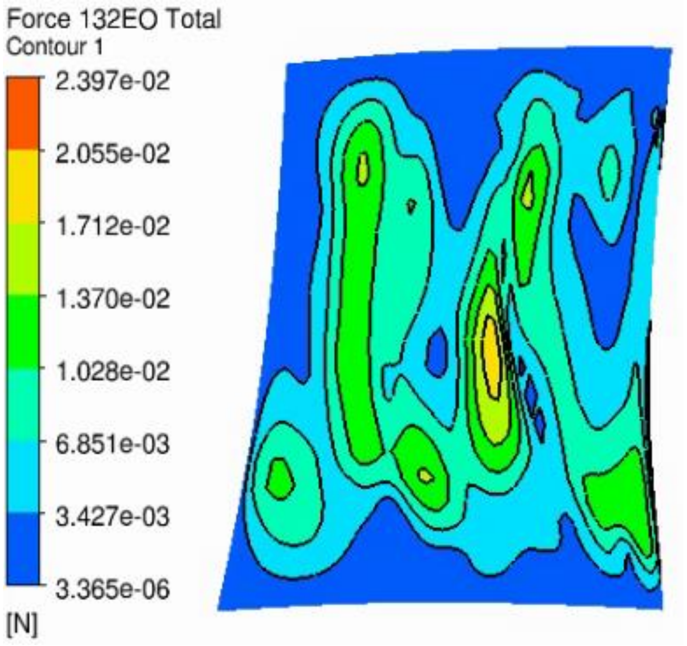
- The time-transformation method from CFX has been applied using a configuration of two S2,one R3 and two S3 blades.
- The analysis run for 3 complete revolutions.



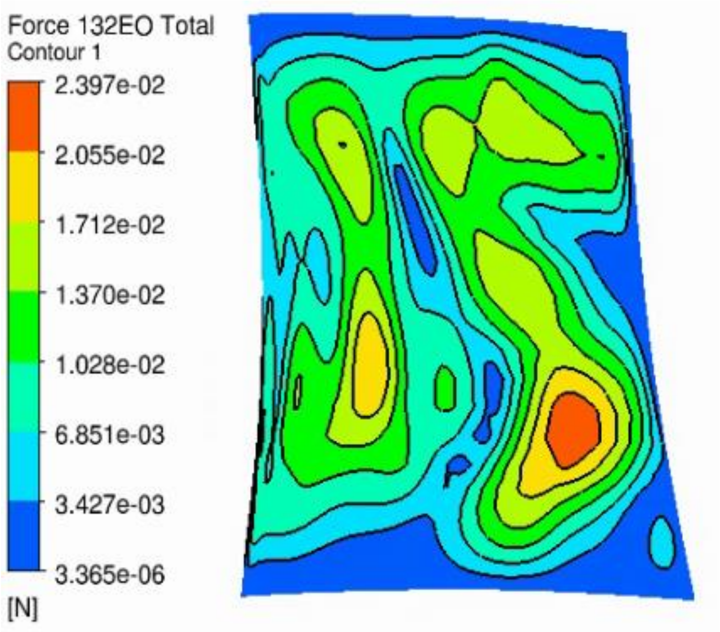


Results-Aerodynamic excitation predictions
CFD transient analysis

- Unsteady forces distribution (harmonic content) for the 132EO excitation



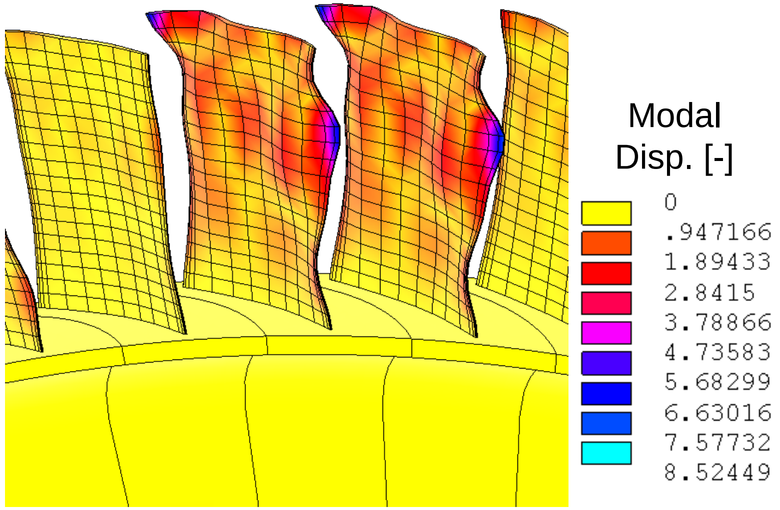
Suction Side



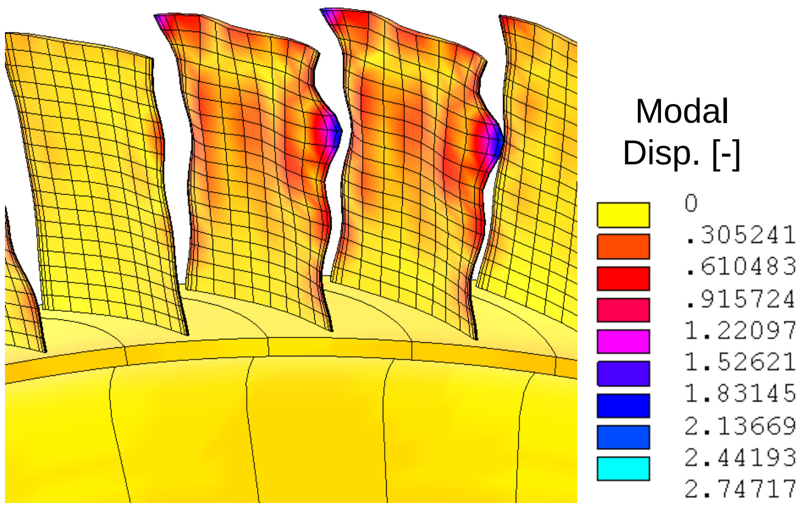
Pressure Side

Results-Structural dynamics
Modal analysis

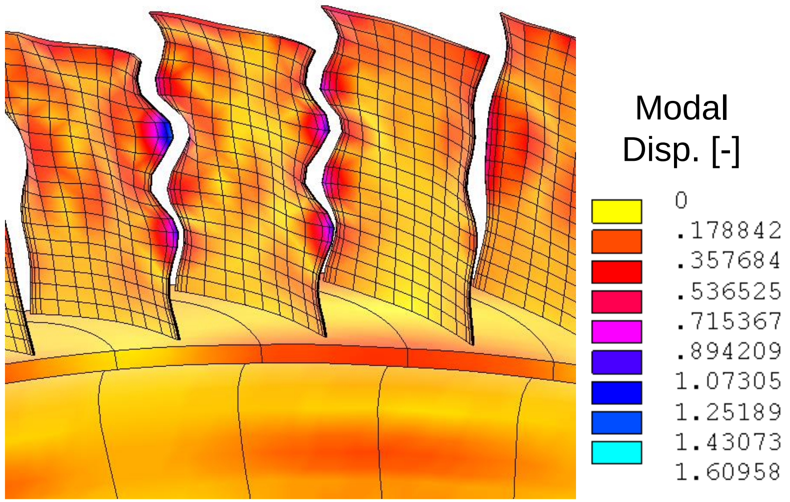
- For the tuned case, several modes participate close to the resonance frequency
- The blade modes are similar, but the disk's strain energy for Mode 37 and Mode 38 is higher than for Mode 36



Mode 36 @ND10 (16212Hz)



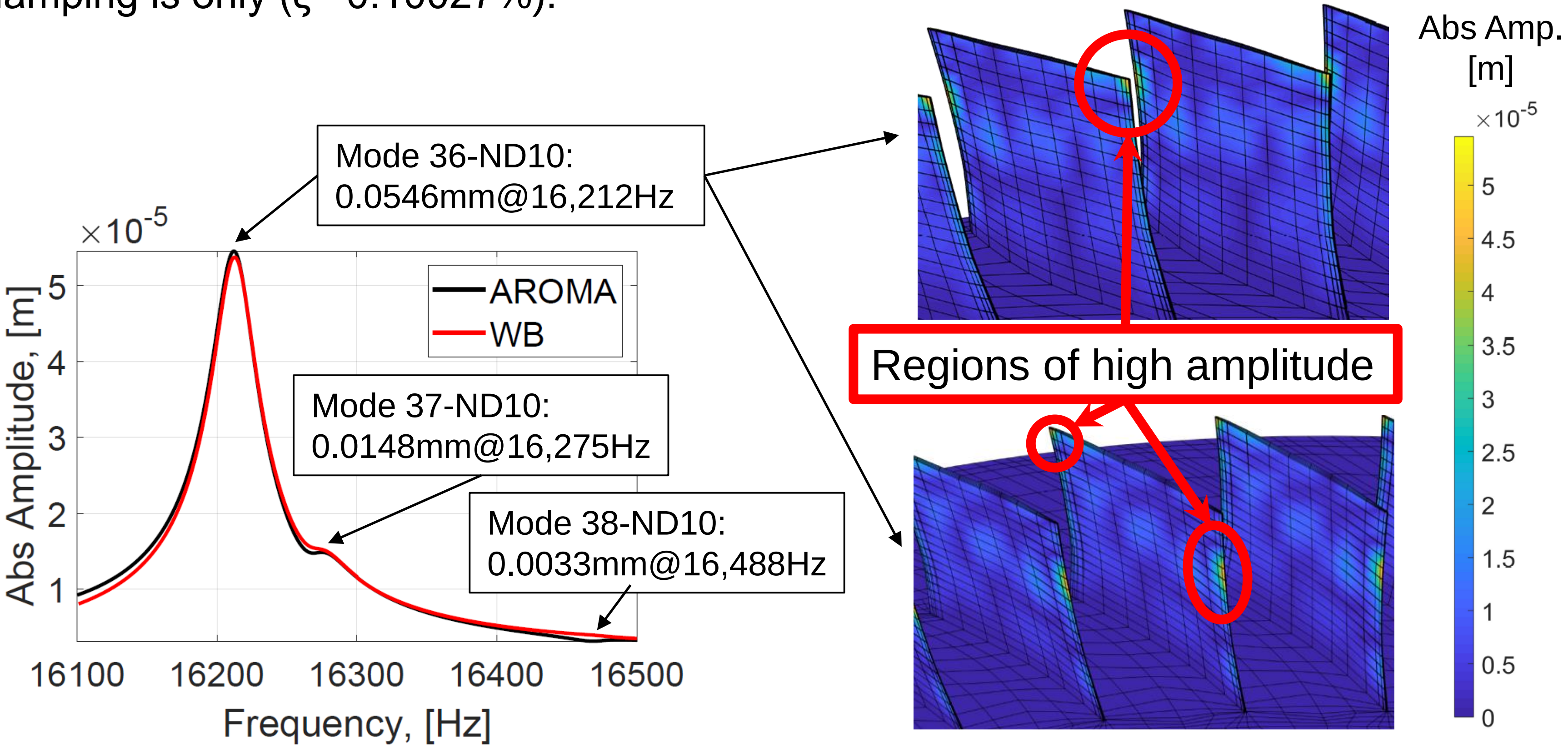
Mode 37 @ND10 (16272Hz)



Mode 38 @ND10 (16473Hz)

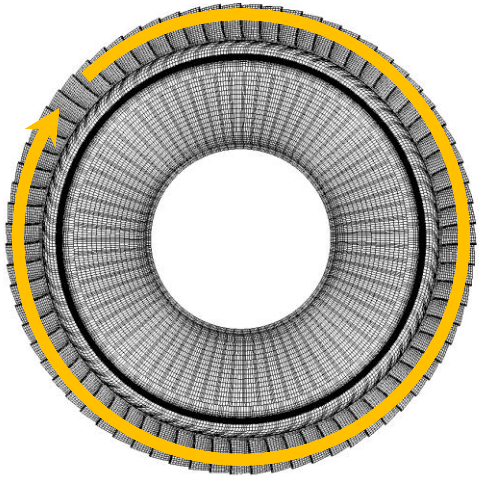
Results-Forced Response Analysis
Tuned Blisk (rotor3)

- The response is due to the 132EO FTWM, all the blades share a max amplitude of 0.0546mm.
- Total damping is only (ζ= 0.10027%).



Results-Forced Response Analysis

Mistuning



Mistuning

Intentional

-control the response
-suppress flutter

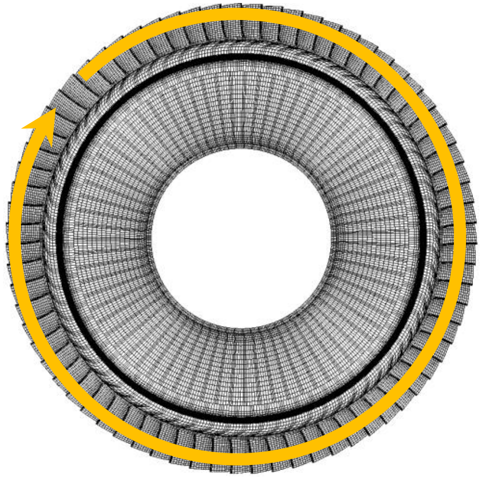
Probabilistic

-manufacturing tolerances
-foreign object damaged
-deterioration

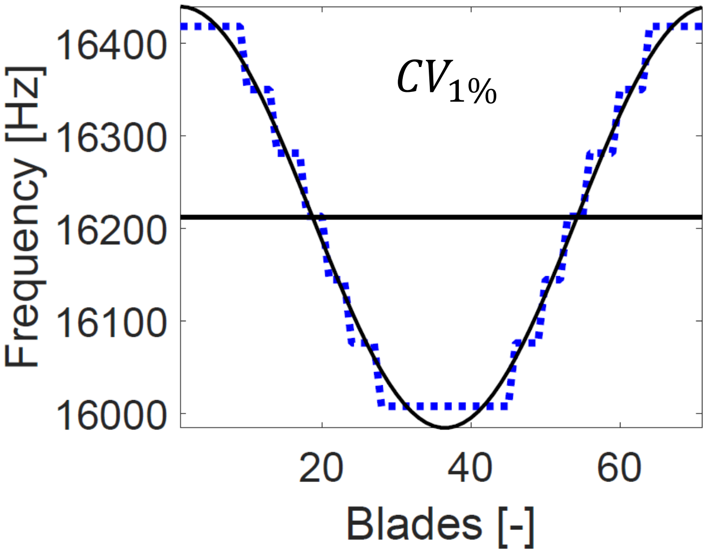
Results-Forced Response Analysis
Intentional Mistuned Blisk (rotor3)

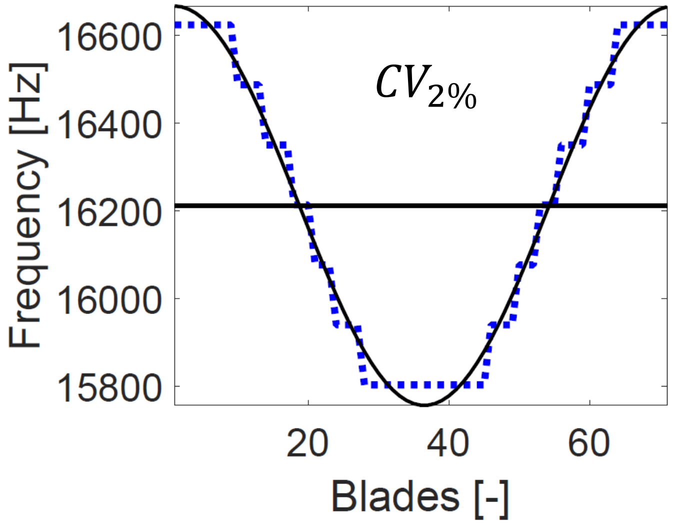
- $Coefficient\ of\ Variation\ (CV) = 1\text{-}10\%$.
- μ_{freq} =16212Hz.

Change the stiffness until achieving $CV_{1\%}$



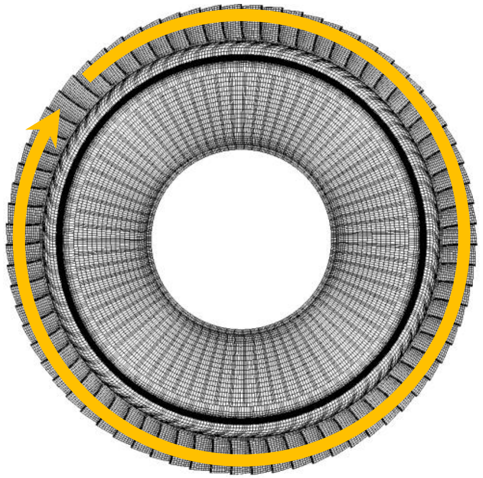
$$CV_{1\%} = \frac{\sigma}{\mu} = \frac{\sqrt{\frac{1}{71-1}\sum_{i=1}^{71}(f_i - \bar{f})^2}}{(\sum_{i=1}^{71} f_i)/71} \approx 0.01$$

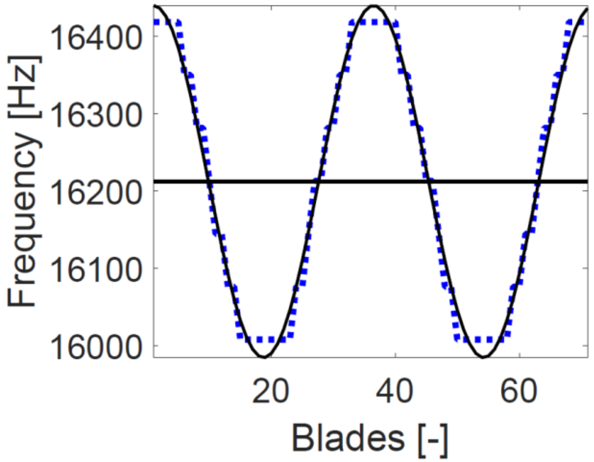


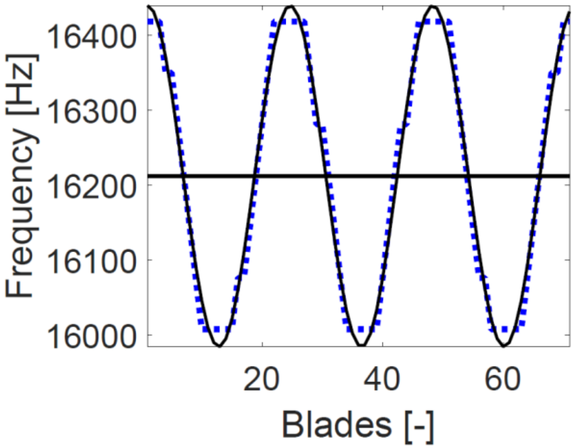


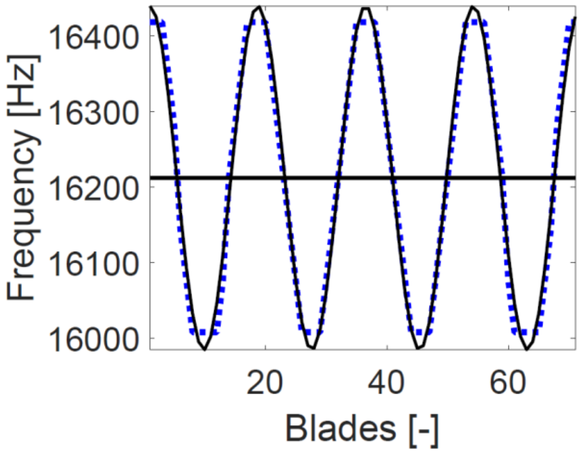
Results-Forced Response Analysis
Intentional Mistuned Blisk (rotor3)

- $Different\ variations\ (patterns)$



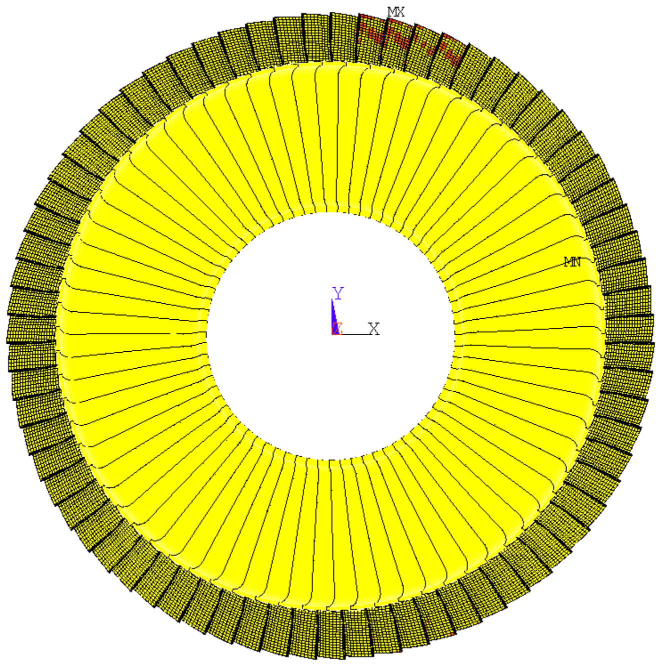


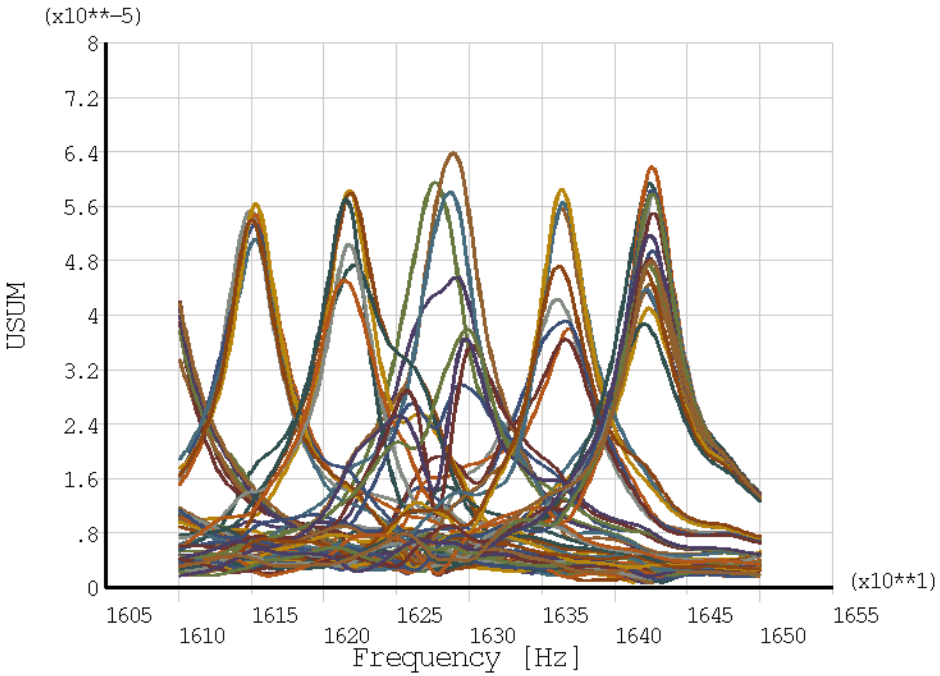


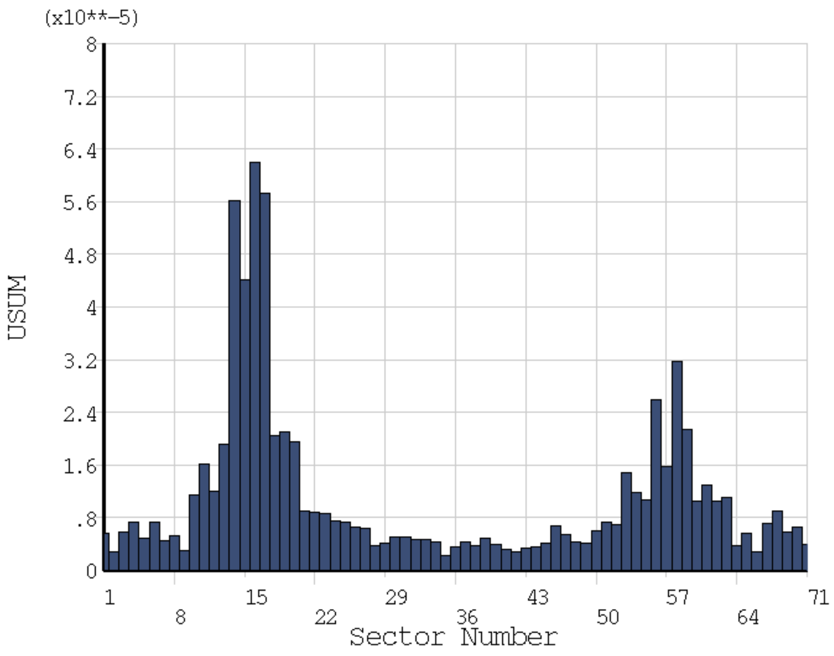


Results-Forced Response Analysis
Intentional Mistuned Blisk (rotor3)

- $Coefficient\ of\ Variation\ (CV) = 1\%$.
- μ_{freq} =16212Hz.

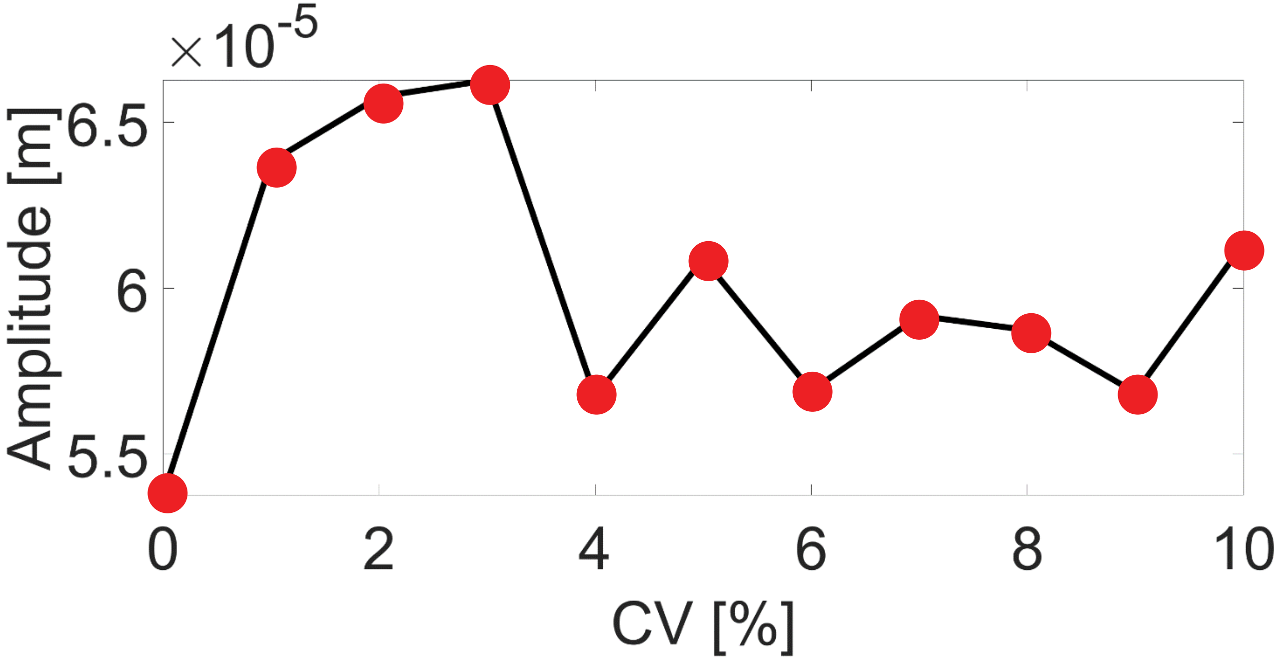


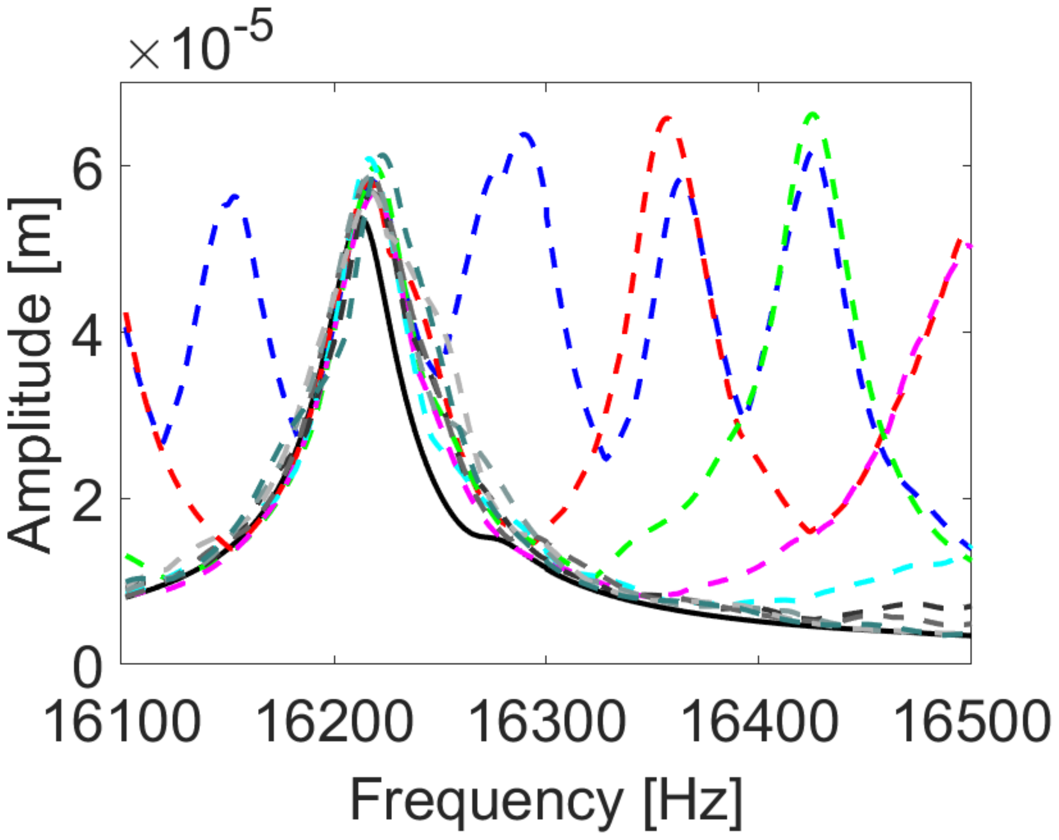




Results-Forced Response Analysis
Intentional Mistuned Blisk (rotor3)

- $Coefficient\ of\ Variation\ (CV) =$ 1-10%.
- μ_{freq} =16212Hz.
- Using 1 harmonic



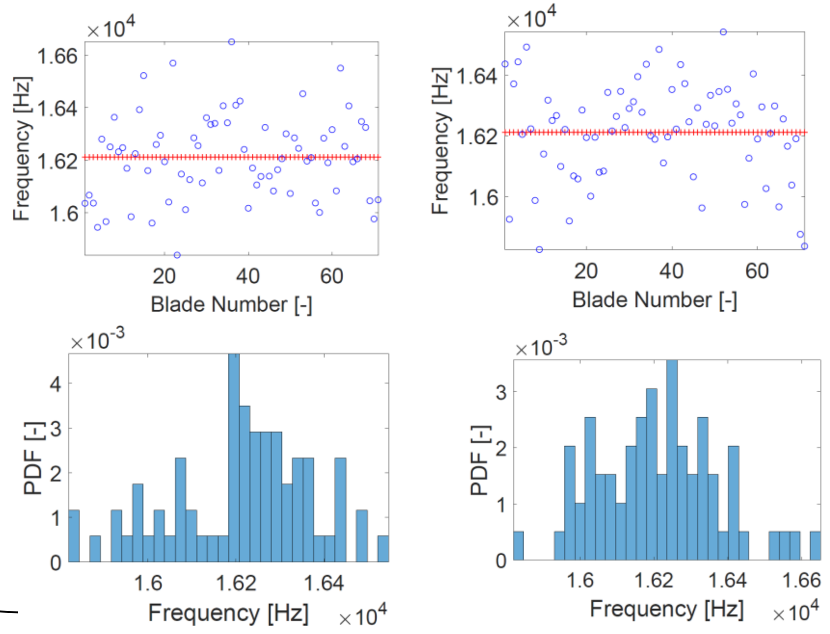


Results-Forced Response Analysis
Random Mistuned Blisk (rotor3)

- Monte-Carlo requires around 1000 random mistuned cases.
- Weibull requires only 50 random mistuned cases.
- $Coefficient\ of\ Variation\ (CV)$ =0-3%.

Mistuned Case #1 Mistuned Case #2 Mistuned Case #50

μ_{freq} = 16212Hz
CV = 1%



Conclusions

- A methodology has been created to run the tuned forced response analysis, by using ANSYS Workbench and AROMA.

- The steady-state and unsteady aerodynamic predictions for R3 have been achieved.

- A tuned forced response analysis for rotor 3 has been performed for Mode 36, 37, and 38 using AROMA and ANSYS Workbench.

- ROMs have their own benefits and drawbacks, where a one-fits-all approach is not possible. However, they can be individualized for specific cases based on their characteristics.

- The maximum vibrational amplitude is considered low, but a stress evaluation can be considered to assess if it leads to High Cycle Fatigue.

- An optimum intentional mistuning pattern has been found yielding reduced vibration amplitudes.

Future work

- Run the random simulations in ANSYS Workbench and AROMA and compare their results.

- To continue assessing the fatigue life of the blisk (rotor 3) with probabilistic and deterministic mistuning.

Acknowledgments

VINNOVA

GKN AEROSPACE

THANK YOU

QUESTIONS?