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

Current designs involve 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.)

Presentation Outline

• Background
• Objective
• Approach
  – AROMA Tool
  – Test object
• Results
• Conclusions
• Future work
Background

- **Forced Response** (Aeroelastic phenomenon)

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

- Forced Response (Aeroelastic phenomenon)

\[
\begin{aligned}
\left[ M_{\text{STRUC}} \omega^2 + C_{\text{STRUC}} \omega i + K_{\text{STRUC}} \right] \{ \hat{x} \} &= \{ \hat{F}_{\text{AERO}} \} \\
\downarrow

\left[ M_{\text{STRUC}} \omega^2 + C_{\text{STRUC}} \omega i + K_{\text{STRUC}} \right] \{ \hat{x} \} &= \{ \hat{F}_{\text{EXC}} \} + \{ \hat{F}_{\text{COUPLED}} (\hat{x}) \}
\end{aligned}
\]
Background

- **Forced Response** (Aeroelastic phenomenon)

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

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

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)**

![Diagram showing transformation process]

- Actual Model: $[300,000 \times 300,000]$
- ROM: $[1,500 \times 1,500]$
- Apply $T$

35 minutes $\rightarrow$ Forced Response Sweep $\rightarrow$ 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

AROMA Tool
• The rotor 3 (R3) has the following characteristics:
  – Material used is titanium (Ti64)
  – Speed of 7454rpm (top-of-climb)
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.

<table>
<thead>
<tr>
<th>VIGV</th>
<th>R1</th>
<th>S1</th>
<th>R2</th>
<th>S2</th>
<th>R3</th>
</tr>
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<tbody>
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<td>41</td>
<td>37</td>
<td>108</td>
<td>48</td>
<td>132</td>
<td>71</td>
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</tbody>
</table>

Compressor blade count

- 16,398Hz (132EO)
- Res@Mode 36/37/38-ND10
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
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
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 (\(\zeta = 0.10027\%\)).

### Mode 36-ND10:
- Frequency: 16,212Hz
- Amplitude: 0.0546mm

### Mode 37-ND10:
- Frequency: 16,275Hz
- Amplitude: 0.0148mm

### Mode 38-ND10:
- Frequency: 16,488Hz
- Amplitude: 0.0033mm

Regions of high amplitude
Results-Forced Response Analysis

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 ($CV$) = 1-10%.
- $\mu_{freq}$ = 16212 Hz.

\[ CV_{1\%} = \frac{\mu}{\sigma} = \sqrt{\frac{1}{71-1} \sum_{i=1}^{71} (f_i - \bar{f})^2} \approx 0.01 \]
Results-Forced Response Analysis

Intentional Mistuned Blisk (rotor3)

- Different variations (patterns)
Results-Forced Response Analysis

Intentional Mistuned Blisk (rotor3)

- Coefficient of Variation ($CV = 1\%$).
- $\mu_{freq} = 16212\text{Hz}$. 
Results-Forced Response Analysis

Intentional Mistuned Blisk (rotor3)

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

\[
\mu_{freq} = 16212\text{Hz} \\
CV = 1\%
\]
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
THANK YOU
QUESTIONS?