Modal Analysis of a turbocharger shaft

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Agenda

1. Introduction
2. Shaft reverse engineering
3. Modal simulations
4. Modal testing
5. Results
   a) Compressor: splitter blades
   b) Compressor: main blades
   c) Rotor assembly
   d) Turbine
6. Conclusions
1. Introduction

CIFRE PhD program (Industrial PhD)
“Contribution to the modelling and measurement of vibroacoustic phenomena in an automotive turbocharger and its failure prediction”

Acoustic measurements in compressor ducts

Intensity measurements for acoustic power estimation

Failure simulation and reproduction for methods testing.

Vibrations signal treatment for failure detection

RMS analysis, Empirical Mode Decomposition, Wavelet Decomposition, …
2. Shaft reverse engineering

1. CAD design needed for FE simulations

2. Compressor and turbine milling performed for 3D scan
2. Shaft reverse engineering

1. 3D scan to obtain precise geometries of single blades

2. CAD reconstruction of the compressor wheel (turbine in progress)
2. Shaft reverse engineering

1. Reconstruction result
3. Modal simulations

1. Axisymmetric compressor
2. Separation of the analysis on main blades and splitter blades.
3. Convergence study to optimize the FEM mesh size and reduce computing time

Itt. 1: Mesh size 5mm, local size 0.6 mm

Itt. 6: Mesh size 0.8 mm, local size 0.1 mm

1\textsuperscript{st} natural frequency splitter blade

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12280</td>
</tr>
<tr>
<td>2</td>
<td>12300</td>
</tr>
<tr>
<td>3</td>
<td>12320</td>
</tr>
<tr>
<td>4</td>
<td>12340</td>
</tr>
<tr>
<td>5</td>
<td>12360</td>
</tr>
<tr>
<td>6</td>
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<tr>
<td></td>
<td>12440</td>
</tr>
<tr>
<td></td>
<td>12460</td>
</tr>
</tbody>
</table>
3. Modal simulations: rotational speed influence

1. Pre stress due to rotational speed
2. The stiffness of the structure increases
3. The natural frequencies get higher as the rotational speed increases
4. Modal testing

1. Modal analysis of the whole shaft was performed:
   a) Excitation with impact hammer or piezoelectric shaker.
   b) Clamping at turbine end of the shaft.
   c) Compressor wheel mounted in position.
   d) Vibration measurements with a 3D laser vibrometer.

2. Modal simulations were performed with CATIA and ANSYS.

3. Results and theory/experimentation comparison are presented on the next slides.

*Test rig*

Piezoelectric shaker
5. Results: compressor splitter blades

1. Whole structure excitation with a piezoelectric shaker: Swept sine from 10kHz to 64kHz

2. Meshing of the desired zone of the compressor and definition of the measurement points performed by the 3D laser vibrometer

<table>
<thead>
<tr>
<th>Mode</th>
<th>Computed Frequency</th>
<th>Measured Frequency</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12314</td>
<td>12055</td>
<td>2.1%</td>
</tr>
<tr>
<td>2</td>
<td>24971</td>
<td>23875</td>
<td>4.4%</td>
</tr>
<tr>
<td>3</td>
<td>28663</td>
<td>28755</td>
<td>0.3%</td>
</tr>
<tr>
<td>4</td>
<td>40734</td>
<td>41042</td>
<td>0.8%</td>
</tr>
<tr>
<td>5</td>
<td>46605</td>
<td>44340</td>
<td>4.9%</td>
</tr>
<tr>
<td>6</td>
<td>54494</td>
<td>54767</td>
<td>0.5%</td>
</tr>
</tbody>
</table>

Piezoelectric excitation

Table of frequencies

Frequencies

Vibrometer mesh

FE analysis of the splitter blade
5. Results: compressor splitter blades

Mode 1

Mode 2

Mode 3

Computed mode shapes

Measured mode shapes
5. Results: compressor main blades

1. Whole structure excitation with a piezoelectric shaker: Swept sine from 10kHz to 64kHz
2. Meshing of the desired zone of the compressor and definition of the measurement points performed by the 3D laser vibrometer

<table>
<thead>
<tr>
<th>Mode</th>
<th>Computed Frequency</th>
<th>Measured Frequency</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10686</td>
<td>10957</td>
<td>2.5</td>
</tr>
<tr>
<td>2</td>
<td>22813</td>
<td>21107</td>
<td>7.5</td>
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<tr>
<td>3</td>
<td>29619</td>
<td>31590</td>
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</tr>
<tr>
<td>4</td>
<td>37315</td>
<td>38020</td>
<td>1.9</td>
</tr>
</tbody>
</table>
5. Results: compressor main blades

Mode 1
- Computed mode shapes: $f_{1s} = 10686$ Hz
- Measured mode shapes: $f_{1e} = 10957$ Hz

Mode 2
- Computed mode shapes: $f_{2s} = 22813$ Hz
- Measured mode shapes: $f_{2e} = 21107$ Hz

Mode 3
- Computed mode shapes: $f_{3s} = 29619$ Hz
- Measured mode shapes: $f_{3e} = 31590$ Hz
5. Results: Rotor assembly

1. Whole rotor assembly excitation with an impact hammer, controlled by a coil so the excitation can be perfectly repeatable.

2. Meshing of the desired zone of the compressor and definition of the measurement points performed by the 3D laser vibrometer.

![Measurement mesh](image1)

![Test rig](image2)

![Hammer excitation on the frequency domain](image3)
5. Results: Rotor assembly

1. Both peaks $a$ and $b$ correspond to shaft modal shapes

- $f_1 = 503$ Hz
- $f_2 = 6791$ Hz

Frequency domain response of the structure
5. Results: Rotor assembly

1. Peaks on \( c \) correspond to the 1\(^{st} \) natural frequency of the main blades (around 11kHz).
2. We can see 4 distinct peaks and the compressor has 4 main blades: each blade has its own natural frequency.

Main blades modal shape

Frequency domain response of the structure
5. Results: Rotor assembly

1. Peaks on \( d \) correspond to the 1\(^{st} \) natural frequency of the splitter blades (around 12kHz).

2. We can see 4 distinct peaks and the compressor has 4 splitter blades: each blade has its own natural frequency.
5. Results: Turbine

1. As for the compressor wheel, we can find the first modal shapes of the turbine.
2. FE computations will be performed as soon as the reconstructed CAD design is available.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Mode</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>17695</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>30525</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>54660</td>
</tr>
</tbody>
</table>

Turbine blade modal shapes
5. Conclusions

1. For the compressor wheel computed and measured frequencies match well.

2. The computed and measured modal shapes match as well.

3. Further work
   a. FE analysis of the turbine to compare with measurements.
   b. FE failure simulations to prepare gas stand tests.
   c. Gas stand tests on modified turbochargers to analyze vibration/noise response.
Thank you for your attention.