Root Cause Analysis of a Subsynchronous Vibration on a Variable Speed Gear

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Which application was affected?

Drive train configuration

Motor

Variable speed gear

Centrifugal re-injection compressor
What was the problem?

Subsynchronous vibration signature during FAT

Shaft displacement probe

Housing acceleration probe
How was the problem analyzed?

Root cause analysis methodology

Systematic testing program ______ Modeling & analytical campaign

How was the problem analyzed?

Root cause analysis methodology

Systematic testing program ______ Modeling & analytical campaign

constant torque, constant speed test
constant torque, variable speed test
constant speed, variable load test

\[
M_{\phi_{x}} = \frac{2}{\pi \cos \alpha_0} \times \mu_0 \times |M_T| \times \frac{(\phi_{mx} + \Omega \phi_{my})}{\nu} \times \tanh \left( \frac{\nu}{\nu^*} \right) 
\]

\[
M_{\phi_{y}} = \frac{2}{\pi \cos \alpha_0} \times \mu_0 \times |M_T| \times \frac{(\phi_{my} - \Omega \phi_{mx})}{\nu} \times \tanh \left( \frac{\nu}{\nu^*} \right) 
\]
What where the experimental findings?
Subsynchronous vibration main properties

Load dependency of frequency and amplitude

Frequency increase with load

switch on and amplitude increase

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What were the experimental findings?
Subsynchronous vibration main properties

- **Time**
- **Frequency**
- **Amplitude**

Switch on and amplitude increase.

Frequency decrease with speed.

Speed dependency of frequency and amplitude.

The graph shows:
- A time axis with values ranging from 50 to 350 Hz.
- A frequency axis with values ranging from 0 to 100 Hz.
- An amplitude axis with values ranging from 0 to 200 μm.

The graph indicates that:
- Frequency decreases with speed.
- Amplitude increases with speed.

Overall, the experimental findings highlight the relationship between speed, frequency, and amplitude in subsynchronous vibrations.
What where the experimental findings?

Subsynchronous vibration mode shape

 ✓ Dominant wobbling motion of sun and sun sleeve
 ✓ Minor motion of planets and annulus
What where the theoretical findings?
Multi-body-simulation approach – mode shape

Eigenmode in range of operation speed

mode shape comprises:
- Wobbling motion of sun
- Wobbling motion of planets
- Wobbling motion of spline coupling sleeve

Simulation result in good correlation with measurements
What where the theoretical findings?
Multi-body-simulation approach – frequency dependencies

Load dependency of mode at constant output speed of 13500 rpm

![Graph showing frequency depending on operation load]

- Increasing load

✓ Simulated load dependency in good correlation with measurements

Speed dependency of mode at constant output torque of 6366 Nm

![Graph showing frequency depending on operation speed]

- Increasing speed

✓ Simulated speed dependency in good correlation with measurements
What where the theoretical findings?

Multi-body-simulation approach – switch on/off properties

damping (log dec):
spline

positive damping or log dec
→ no risk of vibration

negative damping or log dec
→ possible risk of vibration by self-excitation
What is the theoretical background of this behaviour?

Destabilization by cross coupling in spline contacts


By means of the coordinate transformations, eqs. (2) and (3), it is found that:

\[ M_0 = \frac{2\nu T}{\pi} \frac{\theta + \Omega \Phi}{\sqrt{\alpha^2 + \beta^2}} \]

\[ M = \frac{2\nu T}{\pi} \frac{\theta - \Omega \Phi}{\sqrt{\alpha^2 + \beta^2}} \] (21)

From eqs. (2) and (7) is found:

\[ \dot{\alpha}^2 + \beta^2 = (\dot{\alpha} + \omega \Omega)^2 = (\dot{\beta} + \omega \Omega)^2 = (\omega - \Omega)^2 |\theta_x|^2 + (\omega + \Omega)^2 |\theta_y|^2 \]

\[ 2(\omega - \Omega)(\omega + \Omega) |\theta_x| |\theta_y| \cos(2\omega t + \Phi_x + \Phi_y) \] (22)

Several authors discuss cross coupling causing destabilizing forces

Cross coupling effect responsible for decreasing log dec of eigenmode

Cross coupling theory implemented in MBS-model
What is the solution approach?
Elimination of the destabilizing spline contacts

Original design with spline coupling

Modified design with diaphragm coupling

new sun
new spray tube
new diaphragm coupling
new labyrinth housing
new output shaft
new spacer
closing plate
What is the difference in simulation?
Multi-body-simulation approach – switch on/off properties

- positive damping or log dec → no risk of vibration
- negative damping or log dec → possible risk of vibration by self-excitation

✓ Log dec with spline coupling can become negative while log dec with diaphragm coupling remains positive
What is the difference in testing?
Validation tests

Comparison of variable speed test sequences

SSV = Subsynchronous Vibration
What is the difference in testing?

Validation tests

Comparison of variable load test sequences

SSV = Subsynchronous Vibration
What is the difference in testing?
Validation test at full load / full speed / full pressure

- n=14300 rpm, P=9.5 MW
- n=10200 rpm, P=3.7 MW

No subsynchronous vibration (SSV)

✓ No SSV present at maximum continuous speed and high load
Successful implementation of modification

<table>
<thead>
<tr>
<th>Variable Speed Gear</th>
<th>Frame [mm]</th>
<th>Power [kW]</th>
<th>Speed [rpm]</th>
<th>Result</th>
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</tbody>
</table>
Lessons learned

✓ Root cause of subsynchronous vibration completely clarified and understood
✓ Systematic root cause analysis method helpful
✓ Systematic testing program as a key to identification of properties
✓ Complementing modeling and analytical work essential for the solution of complex problems

✓ Design rules are derived from the project results for future design of output shaft coupling (spline or diaphragm type)
✓ Precise choice of coupling type warranted