Troubleshooting torsional vibration challenges with rotating machinery
Agenda:

Non stationary phenomena
Practical examples
Order tracking
Torsional vibrations
Angle domain
Simcenter (Testing) solutions
Customer examples
Noise, vibration and durability of machines
Why are rotating components “different”?

Rotation speed can change!

structure-borne

air-borne
A systematic approach: source – transfer – receiver

Critical Loads

Critical Dynamics

Worst Case

Reduce unbalance
Change engine
Change operating range

Source is NOT the reason!
Change specific components (but which ones?)

Work on source AND transfer
Isolate the receiver side

=>

X

=>

X

X
Non-Stationary Signals: Frequency content

FFT
FFT
FFT

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Non-Stationary Signals: Frequency content

FFT

FFT

FFT
Non-Stationary Signals: Frequency content

FFT

FFT

FFT
Non-Stationary Signals: Frequency content
Non-Stationary Signals: Frequency content
Waterfall and Colourmap
Orders and Resonances

- Orders
- Resonances

> frequency >

> speed >

> frequency >

> speed >
Correlate vibration/noise with rotational speed
« n-th order » = peak in FFT at a frequency = n x rotational frequency

Example:
• Rotational speed = 2400 rpm
• 1st order = 2400/60 (Hz) x 1 = peak around 40 Hz
• 2nd order = 2400/60 (Hz) x 2 = peak around 80 Hz
How to measure RPM?

Remote Optical Probe
- Piece of reflective tape needed on shaft

Magnetic Pick-up
- Connected to Engine coder or Starter wheel

\[ \text{Rpm} = 60 \times \frac{1}{\Delta T} \]
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**Practical examples**

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Connected shafts

Pulley Ratio: 3 to 1

Shaft 1

Shaft 2

1st Order – Shaft 1

3rd Order – Shaft 2

Frequency (Hz)

Amplitude

1800

rpm

1800

0 50 100 150 200 250 300
Connected shafts

Pulley Ratio: 3 to 1

What if all speeds are relative to Shaft 2?
Fan blades

Fan spins @ 600 rpm
What is the blade pass frequency?
What is the main order in the noise?

Fan spins @ 600 rpm
600 rpm = 10Hz (shaft)
6 blades = **60Hz** peak in mic

**Blade passing frequency**

Blade passing frequency depends on rpm!

**6th order** is independent from rpm
Gear

Gear spins @ 600 rpm
Gear has 86 teeth
What is the main order?

Gear spins @ 600 rpm
600 rpm = 10Hz (shaft)
86 teeth = 86\textsuperscript{th} order = \textbf{860Hz} peak

\textbf{Gear meshing frequency}

If \( \neq 860\text{Hz} \) => transmission error
Gear 1 spins @ 600 rpm and has 13 teeth connected to gear 2 with 8 teeth

What is the main order of gear 2?

Gear 1 spins @ 600 rpm
600 rpm = 10Hz (shaft)
Gear 2 spins @ 13/8 = 16.25Hz
Order 1.625 (compared to main shaft)

**Gear meshing frequency?**

16.25 * 8 = 10 * 13 = 130 Hz
Gears and prime numbers …

Often – a meshing gear pair will have a prime number of teeth on one or both gears.

If two gears share a common factor, then the same teeth will engage more frequently, leading to wear & damage.

How many rotations will Gear1 rotate before the same two teeth mate again?

Gear1: 60
Gear2: 30
Answer: 1 rotation

Gear1: 65
Gear2: 53
Answer: 53 rotations!
An ‘order’ is a frequency component with a rotational speed dependency.

- **Order 0.5** = camshaft rotation
- **Order 2** = combustion
- **Order 4** = cylinder movement
- Etc.

4-stroke, 4-cylinder engine
Combustion engine
Electric motor
Transmission
Which issues can we detect?

Perfect mesh
Gear 1
Gear 2

Misalignment
Gear 1
Gear 2

Eccentricity
Gear 1
Gear 2

Gear meshing order
1st order modulation
2nd order modulation
Transmission
Order analysis

<table>
<thead>
<tr>
<th>Order offset vs. meshing frequency</th>
<th>Causes</th>
</tr>
</thead>
</table>
| 0                                 | ▪ High meshing forces  
▪ Bad gear teeth design |
| 1                                 | ▪ Load imbalance  
▪ Shaft resonance  
▪ Improper installation |
| 2                                 | ▪ Gear eccentricity  
▪ Manufacturing issue |

![Graph showing order vs. meshing frequency and causes](image-url)
Transmission
Order analysis

Sideband level variation with RPM and load in real life

Root-cause amplification possible due to structural resonances
Bearing defects can be caused by:

**Excessive forces:**
- Load imbalance
- Misalignment
- Shaft vibrations

**Improper maintenance:**
- Insufficient lubrication
- Lubrication aging
- Dust contamination

**Material wear**

**Crack formation**

**Many rotating components with different RPM than output shaft**
Expect unique orders per defective component
## Bearings

### Order analysis

<table>
<thead>
<tr>
<th>Bearing order</th>
<th>Cause</th>
<th>Mathematical frequency</th>
<th>Empirical frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball Pass Frequency Outer (BPFO)</td>
<td>Outer race defects</td>
<td>$BPFO = RPM \cdot \frac{N_B}{2} \left(1 - \frac{B_D}{P_D} \cos(\beta)\right)$</td>
<td>$BPFO = 0.4 \cdot N_B \cdot RPM$</td>
</tr>
<tr>
<td>Ball Pass Frequency Inner (BPFI)</td>
<td>Inner race defects</td>
<td>$BPFI = RPM \cdot \frac{N_B}{2} \left(1 + \frac{B_D}{P_D} \cos(\beta)\right)$</td>
<td>$BPFI = 0.6 \cdot N_B \cdot RPM$</td>
</tr>
<tr>
<td>Ball Spin Frequency (BSF)</td>
<td>Rolling element defects</td>
<td>$BSF = RPM \cdot \frac{P_D}{B_D} \left(1 - \left(\frac{B_D}{P_D} \cos(\beta)\right)^2\right)$</td>
<td>–</td>
</tr>
<tr>
<td>Fundamental Train Frequency (FTF)</td>
<td>Cage defects</td>
<td>$FTF = RPM \cdot \frac{1}{2} \left(1 - \frac{B_D}{P_D} \cos(\beta)\right)$</td>
<td>$FTF = 0.4 \cdot RPM$</td>
</tr>
</tbody>
</table>

|                |                           | $P_D = \frac{D_1 + D_2}{2}$                                                                 |
|                |                           | $N_B = \text{Number of balls}$                                                             |
|                |                           | $\beta = \text{Contact angle}$                                                            |
**Bearings**  
**Order analysis**

- Pitch diameter = 1.548 inch  
- Ball diameter = 0.3125 inch  
- Number of balls = 9

\[
P_D = \frac{D_1 + D_2}{2} \\
N_B = \text{Number of balls} \\
\beta = \text{Contact angle}
\]

<table>
<thead>
<tr>
<th>RPM</th>
<th>BPFO (Hz)</th>
<th>BPFI (Hz)</th>
<th>BSF (Hz)</th>
<th>FTF (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>6.077258</td>
<td>8.922742</td>
<td>3.979451</td>
<td>0.675251</td>
</tr>
<tr>
<td>500</td>
<td>30.38629</td>
<td>44.61371</td>
<td>19.89726</td>
<td>3.376254</td>
</tr>
<tr>
<td>1000</td>
<td>60.77258</td>
<td>89.22742</td>
<td>39.79451</td>
<td>6.752509</td>
</tr>
<tr>
<td>1500</td>
<td>91.15887</td>
<td>133.8411</td>
<td>59.69177</td>
<td>10.12876</td>
</tr>
<tr>
<td>2000</td>
<td>121.5452</td>
<td>178.4548</td>
<td>79.58902</td>
<td>13.50502</td>
</tr>
<tr>
<td>2500</td>
<td>151.9315</td>
<td>223.0685</td>
<td>99.48628</td>
<td>16.88127</td>
</tr>
<tr>
<td>3000</td>
<td>182.3177</td>
<td>267.6823</td>
<td>119.3835</td>
<td>20.25753</td>
</tr>
<tr>
<td>3500</td>
<td>212.704</td>
<td>312.296</td>
<td>139.2808</td>
<td>23.63378</td>
</tr>
<tr>
<td>4000</td>
<td>243.0903</td>
<td>356.9097</td>
<td>159.178</td>
<td>27.01004</td>
</tr>
</tbody>
</table>
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Practical examples
Order tracking
Torsional vibrations
Angle domain
Simcenter (Testing) solutions
Customer examples
Fixed sampling for runups?

**Fixed sampling:** provides global overview

- Basic order analysis (limited maximum order and order resolution)
- Not well suited for fast runups and/or detailed analysis
- High orders are smeared in frequency domain
- At low RPM, no good distinction between orders
- Powerful for measuring resonances
Fixed sampling vs synchronous order tracking

**Fixed sampling**: provides global overview

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- High orders are smeared in frequency domain
- At low RPM, no good distinction between orders
- Powerful for measuring resonances

**Order tracking**: allows accurate order analysis

- High orders, fine order resolution
- Fast runups
- Always good distinction between orders
- Non precise resonance measurements
Fixed sampling vs synchronous order tracking

Fixed Sampling

Synchronous Sampling

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Siemens Digital Industries Software
Fixed sampling vs synchronous order tracking

- **Narrowband Fixed sampling**
  - Constant sampling frequency
  - Frequency spectra and orders
  - Global overview
  - Investigates harmonics vs. resonances
  - Less computationally intensive
  - Higher channel counts

- **Synchronous Order Tracking**
  - Sampling at constant angle increments
  - Order spectra and orders
  - Accurate order analysis
  - Separates closely spaced orders at low rpm’s
  - High orders, fine order resolution
  - Fast run-ups

Why not using both at the same time?
Agenda:
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**Torsional vibrations**
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Torsional vibrations

Why does this RPM curve look fuzzy?

Inertia forces cause fluctuating RPM!
How to measure those speed variations?
How to measure those speed variations?
Analog vs. digital pulse detection

Example:
Transmission error analysis
Maximum 5000 RPM
+ Incremental encoder with 1200 PPR
= ~ 100,000 pulses per second

Analog Tacho
- All type of sensors
- Up to 40,000 pulses per second

Digital Tacho – TTL
- Optical sensors / Incremental encoders
- Up to 1,000,000 pulses per second

Digital Tacho – RS422/485
- Optical sensors / Incremental encoders
- Differential TTL for electrically noisy environment
- Up to 1,000,000 pulses per second
How to measure those speed variations?
Magnetic pickup sensors

😊 Easy to instrument
😊 Sensor price
😊 Gears often part of standard component
😊 No external power required

😊 Pulses per revolution not flexible, equal to # gear teeth
😊 Sensitive to teeth dimensions, manufacturing tolerances
How to measure those speed variations?
Optical sensors

😊 Easy instrumentation, on any shaft or gear wheel
😊 High pulse rates, depends on zebra tape

😊 Sensitive to ambient light
😊 Zebra tape defects
How to measure those speed variations?
Incremental Encoders

Three output signals:

- Square wave outputs
- Quadrature square wave outputs
- Single pulse/rev as absolute reference

😊 Extremely accurate
😊 Extremely high number of pulses
😊 Includes direction of rotation

 رمضان
Complex instrumentation
 رمضان
Mass loading

Very convenient when the instrumentation can be part of the test bench

Agenda:
Non stationary phenomena
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Torsional vibrations
**Angle domain**
Simcenter (Testing) solutions
Customer examples
What is Angle Domain analysis?

Application examples

- Gear rattle
- Piston Noise
- Valve Impact Noise
- Combustion profile
- Engine knock
- Camshaft bending
- Engine surface vibration
- Torsional vibrations
- Engine ancillaries
- Bearing forces
- Valve train dynamics
- Unbalanced inertia forces
- Cylinder to cylinder variation of combustion
- Bending of crankshaft
- Gear rattle
What is Angle Domain analysis?

Cylinder pressure analysis example

- Offset between cylinders
- Variable pulse length

Direct comparison of cylinder pressure at any RPM
What is Angle Domain analysis?
Cylinder pressure analysis example

- **Gated analysis**
  - E.g. Gate 1 = Valve inlet
    Gate 2 = Combustion

- **Offset compensation**
  - Align phenomena with fixed angle offset
What is combustion analysis?

P-V diagram
What is combustion analysis?
Mean Effective Pressure – IMEP / PMEP / NMEP

Indicated Mean Effective Pressure (IMEP)
The IMEP abbreviation often refers to the Gross Indicated Mean Effective Pressure

\[
IMEP = \frac{\Delta \alpha}{V_s} \sum_{i=1}^{n_i} p(i) \cdot \frac{dV(i)}{d\alpha}
\]

Pumping Mean Effective Pressure (PMEP)

\[
PMEP = \frac{\Delta \alpha}{V_s} \sum_{i=p_1}^{n_2} p(i) \cdot \frac{dV(i)}{d\alpha}
\]

Net Mean Effective Pressure (NMEP)

\[
NMEP = \frac{\Delta \alpha}{V_s} \sum_{i=1}^{n_2} p(i) \cdot \frac{dV(i)}{d\alpha}
\]
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Digital Transformation with a Holistic Digital Twin

Ideation

Realization

Utilization
Simcenter Portfolio
Engineer innovation for rotating machinery performance

Simcenter™
Engineer innovation.
Simulate. Explore. Test.
Simcenter Portfolio
Engineer innovation for rotating machinery performance

Noise & Vibration
Rattle, Whine, Torsional Vibrations, Rotor Dynamics, N&V Levels

Reliability
Structural integrity, Durability, Thermo-fluids, EMC, Maintenance

Performance
Efficiency, Controls, Flowrate, Torque Power, Power Conversion

Integration
Multi-attribute Balancing, Sizing, Troubleshooting, Data Management, IOT
Simcenter Testing Solutions
Single platform multi-physics applications portfolio

Structural Dynamics
Acoustics
Vibro-Acoustics
Rotating Machinery
Durability
Vibration Control
Dynamic Environmental

Data acquisition
Data analytics
Data sharing and reporting
Data management
Rotating machinery

Order tracking

Signature testing

Time data acquisition and processing

Torsional vibration analysis

Turbine testing

Angle domain analysis
Simcenter Portfolio
Engineer innovation for rotating machinery performance
Model Based System Testing (MBST)

Simcenter Amesim model

Electrical motor

Transmission

Belt

RPM

Varying belt speed

Simcenter Testlab measures RPM

Virtual sensor Varying belt speed
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Noise, vibration and durability of machines
Why are rotating components “different”?

Rotation speed can change!
Industrial pumps
Signature testing - Vibration troubleshooting

Challenge
• Troubleshoot a wide range of noise and vibration problems on pumps, valves, actuators.
• Better understand the underlying phenomena
• Worldwide standardization of tools used

Solution
• Simcenter SCADAS Recorder & Simcenter Testlab
• Tokens based licensing for worldwide sharing of resources

Benefit
• 30% investment saving thanks to single tool for routine measurements & advanced engineering
• 40% faster insight into problem root causes
• 35% efficiency gain via collaboration worldwide

“The tokens concept allows us to offer a variety of capabilities to the industry partners we work with, as the tasks and requirements differ from project to project.”
Bearings
Simcenter Testxpress analyzer – More efficient servicing @ end customer

Challenge
• More efficient and effective on-site interventions
• More systematic and detailed analysis of noise and vibration issues

Solution
• Application = troubleshoot noise and vibration issues in assembled product
• Product = Simcenter Testxpress FFT analyzer with envelope analysis

Benefit
• Solve conflicts with end user OEM
• Envelope analysis points out the guilty part of the bearing
• Full frequency details available

The Simcenter Testxpress software is so easy to use, customers are up and running within the hour.
High precision gears
Simcenter Soundbrush – Objectively compare noise of different designs

**Challenge**
- Dispute between OEM and supplier on the “guilty component” - risk liability claims
- Quickly and objectively compare different noise sources and different designs

**Solution**
- Application = quickly compare noise generated by different components
- Product = Simcenter Soundbrush

**Benefit**
- Released from liability claims
- Real-time visual identification of different noise sources

*Simcenter Soundbrush helps objectively comparing noise generated by the different components.*
Electrical motor
Operational modal analysis – End user complaint on vibration levels

**Challenge**
- No in-house NVH experience on how to solve customer complaints on high vibrations
- Trial and error approach
- Inefficient reporting takes 2 days

**Solution**
- Application = reduce vibration levels and increase lifetime of mount brackets
- Product = Simcenter Testlab operational modal + Polymax and batch reporting

**Benefit**
- Gain experience via ES technology transfer
- Systematic source transfer receiver approach leads to solution
- Higher efficiency via batch reporting

*The efficiency increase is incredible – using Simcenter Testlab Polymax, operational modal and batch reporting.*
Printing plate production machine
Simcenter SCADAS XS – Reduce time/cost for global servicing

Challenge
- How to avoid costly engineer travel time for simple troubleshooting task
- Need for mobile measurement equipment

Solution
- Application = local vibration troubleshooting by an operator, engineer stays @ HQ
- Product = Simcenter SCADAS XS with tablet and predefined test template

Benefit
- Simcenter SCADAS XS is shipped
- Operator can do the test
- Engineer only analyzes the data

Thanks to the Simcenter SCADAS XS, a typical intervention went from 1 week down to only 2 days.
Wood working machine
Modal analysis – Increase production speed + improve finishing quality

**Challenge**
- Unexpected quality problems at certain operating speeds, machines run sub-optimal
- How to balance production speed vs. quality vs. energy efficiency

**Solution**
- Application = avoiding resonances that affect produced quality
- Product = Simcenter Testlab modal analysis

**Benefit**
- Systematic understanding of dynamics in the machine that might affect quality
- Machines run more efficient

*Moving from mass production to tailor-made machines requires full understanding of the dynamics.*
Thank you.

Frank Demesmaeker  
Business Development Manager  
Simcenter Testing Solutions

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