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”?

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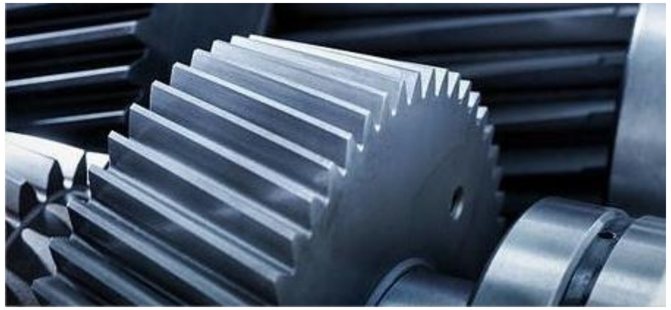
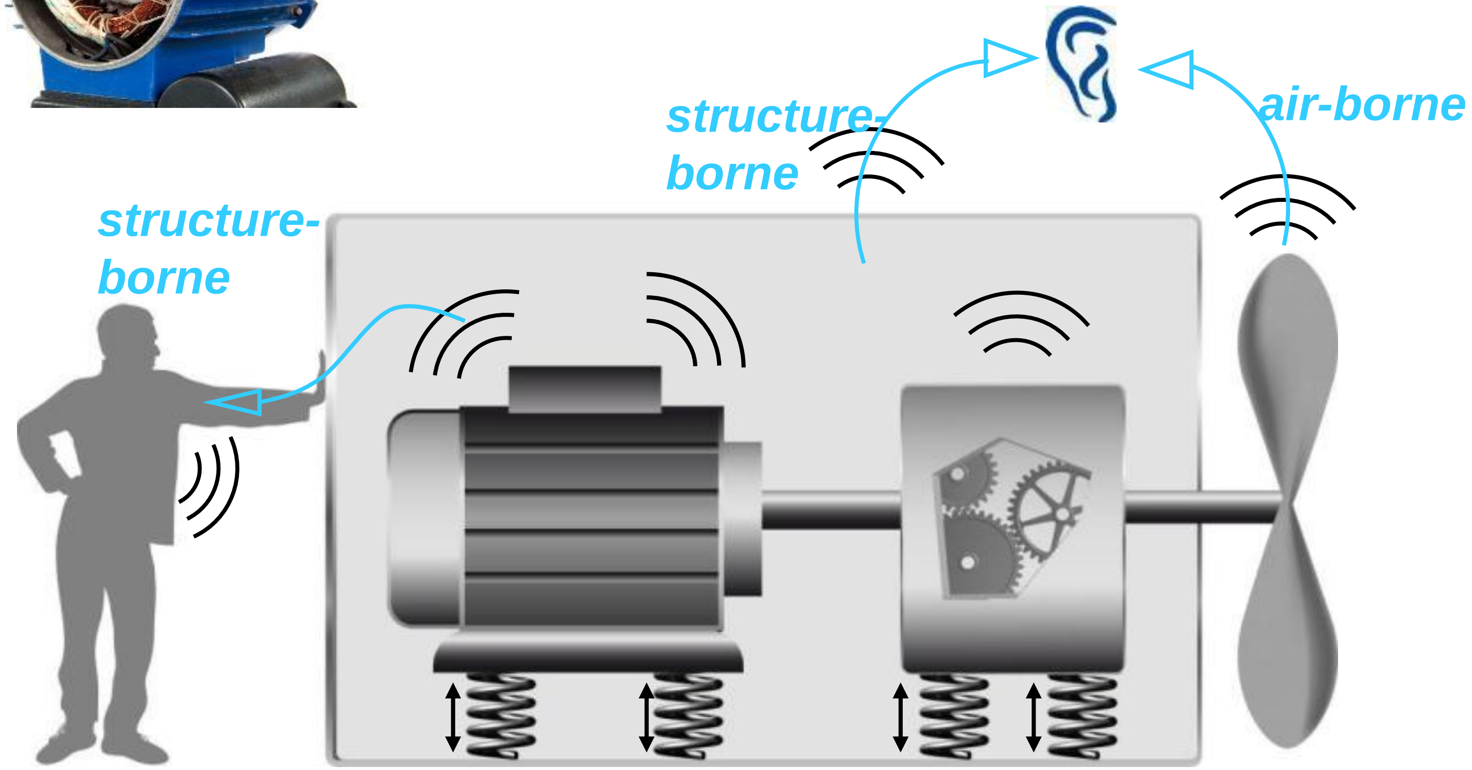


Rotation speed
can change !



A systematic approach: source – transfer – receiver

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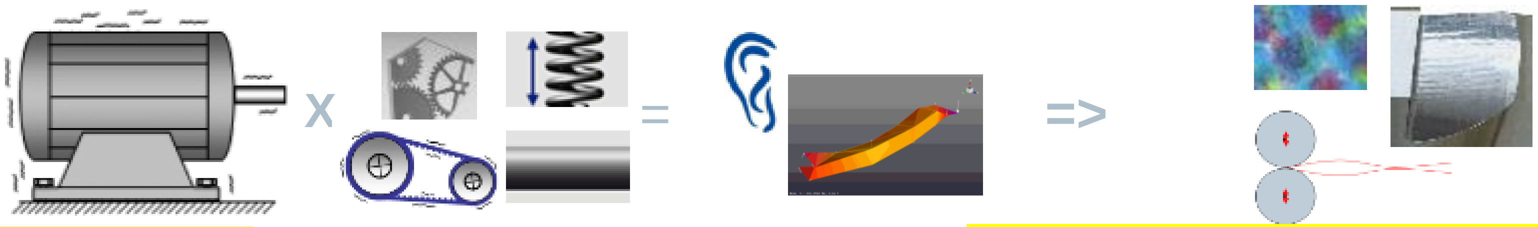
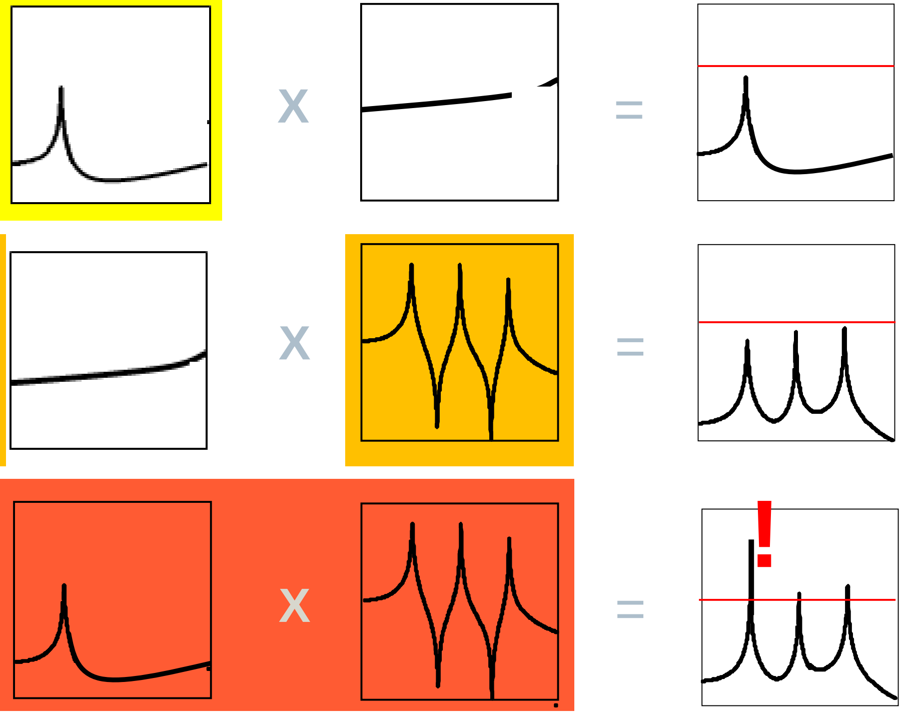
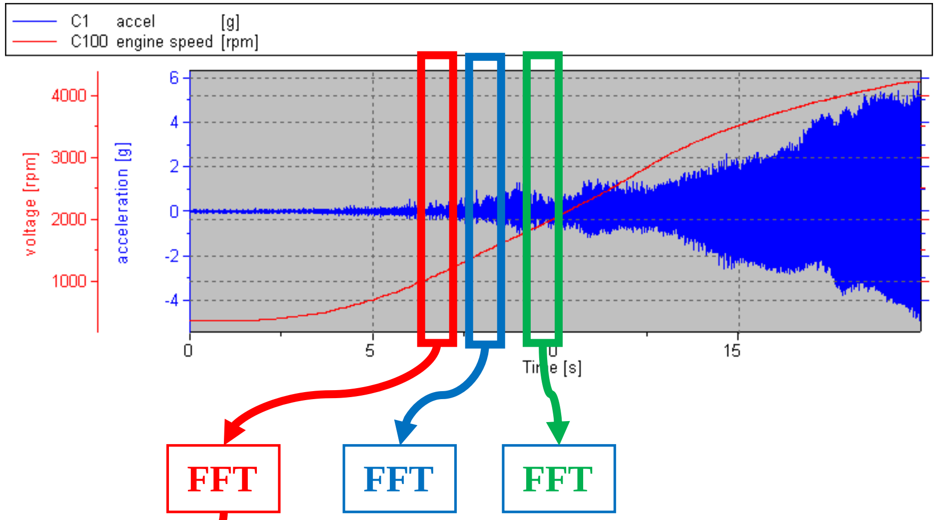
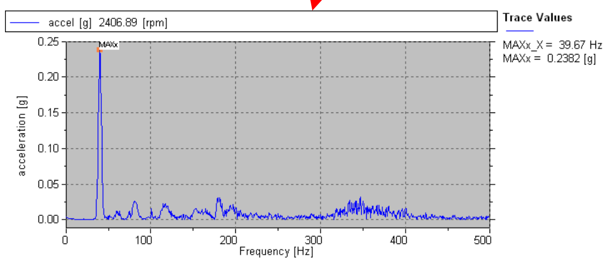


Case	Source		Transfer		Receiver	Action
Critical Loads		X		=		Reduce unbalance Change engine Change operating range
Critical Dynamics		X		=		Source is NOT the reason ! Change specific components (but which ones ?)
Worst Case		X		=	!	Work on source AND transfer Isolate the receiver side



Non-Stationary Signals: Frequency content





Non-Stationary Signals: Frequency content

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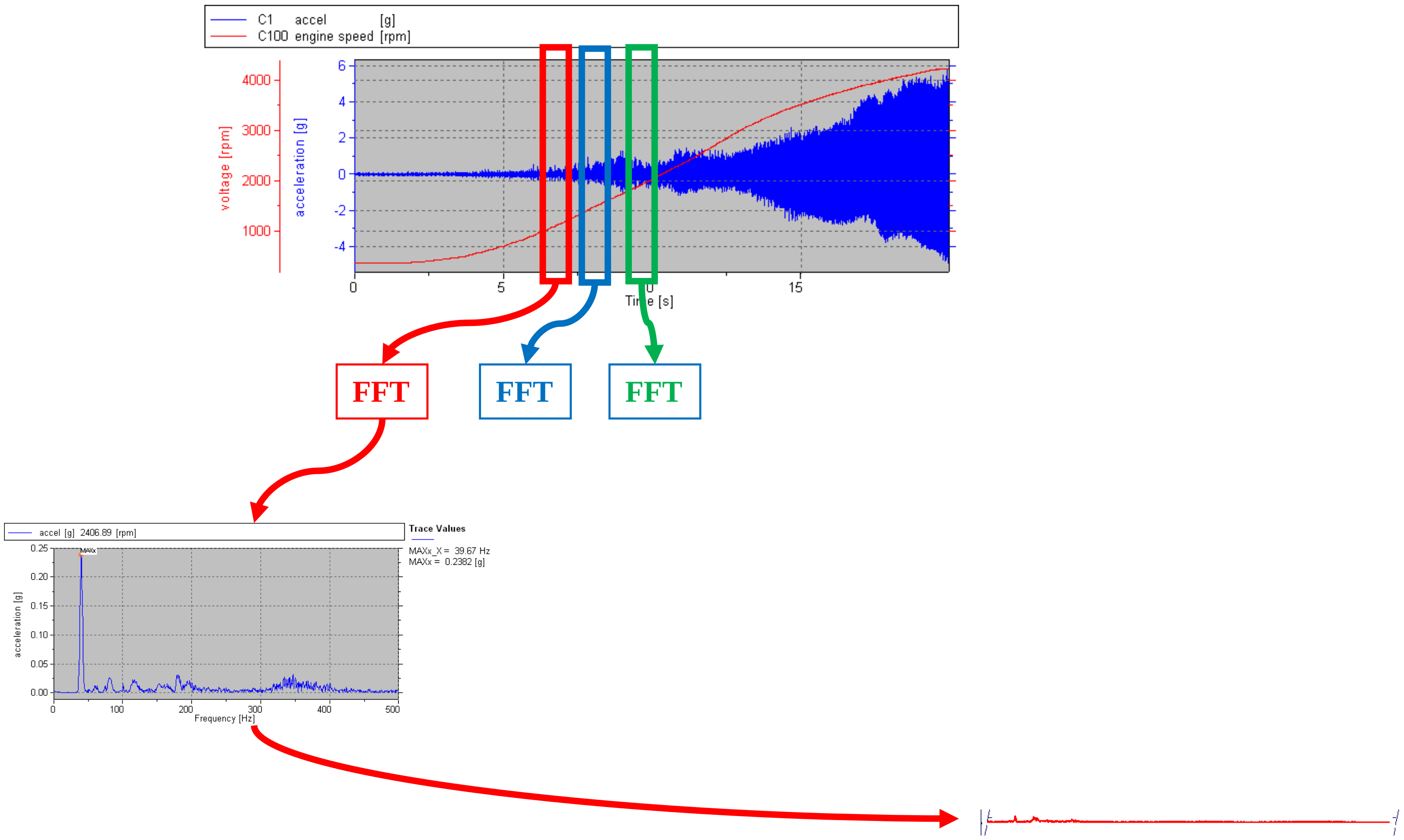
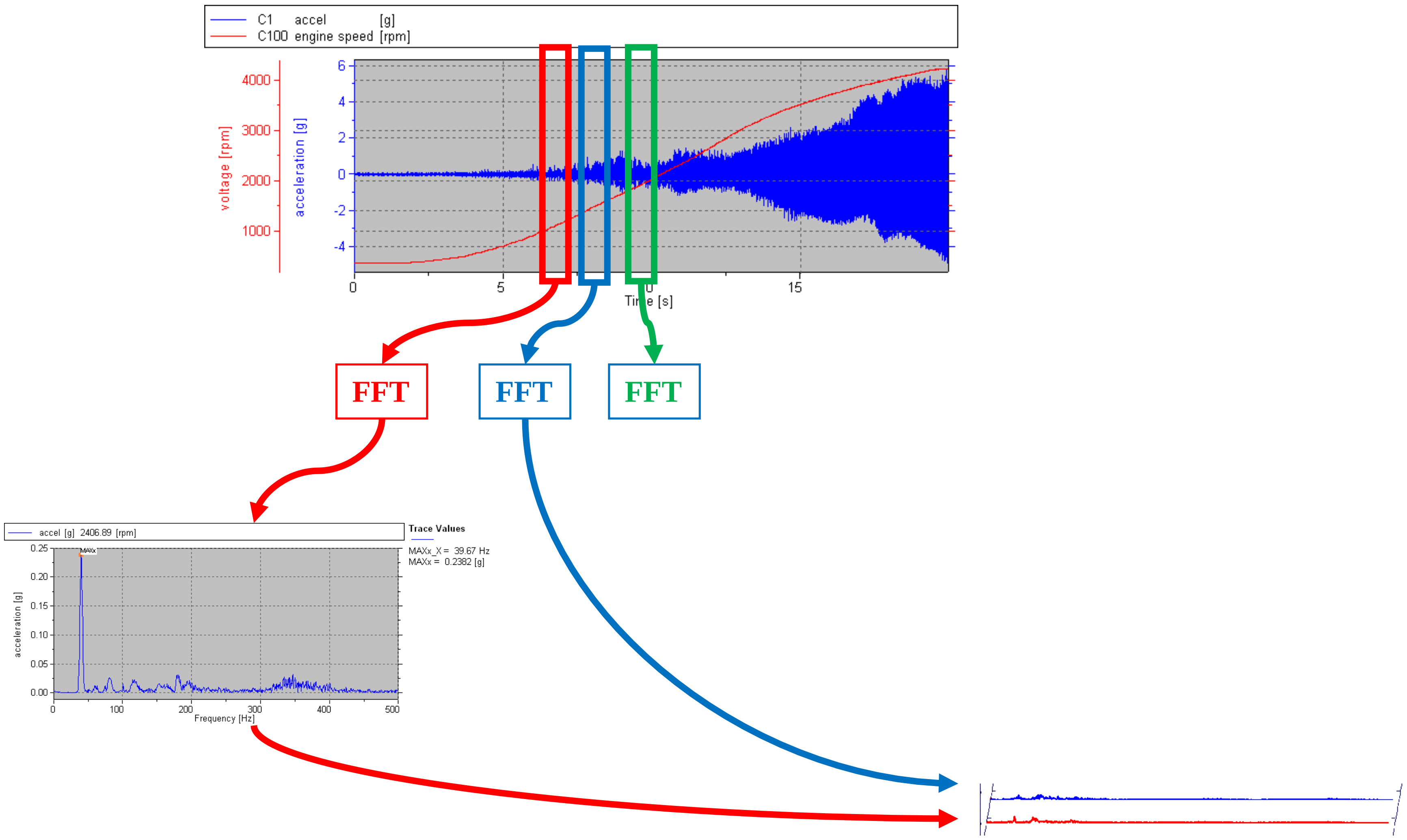


Non-Stationary Signals: Frequency content



Non-Stationary Signals: Frequency content

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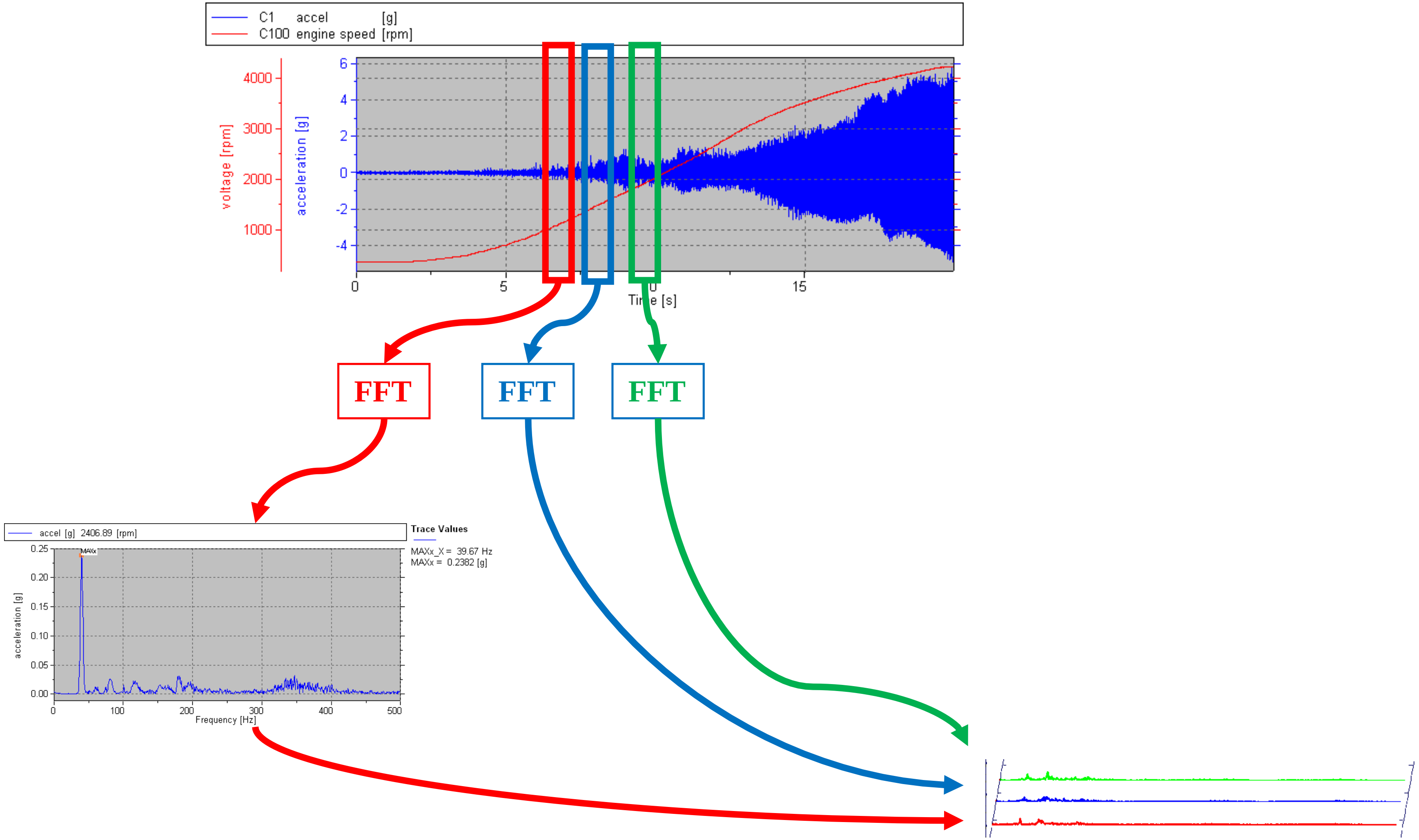
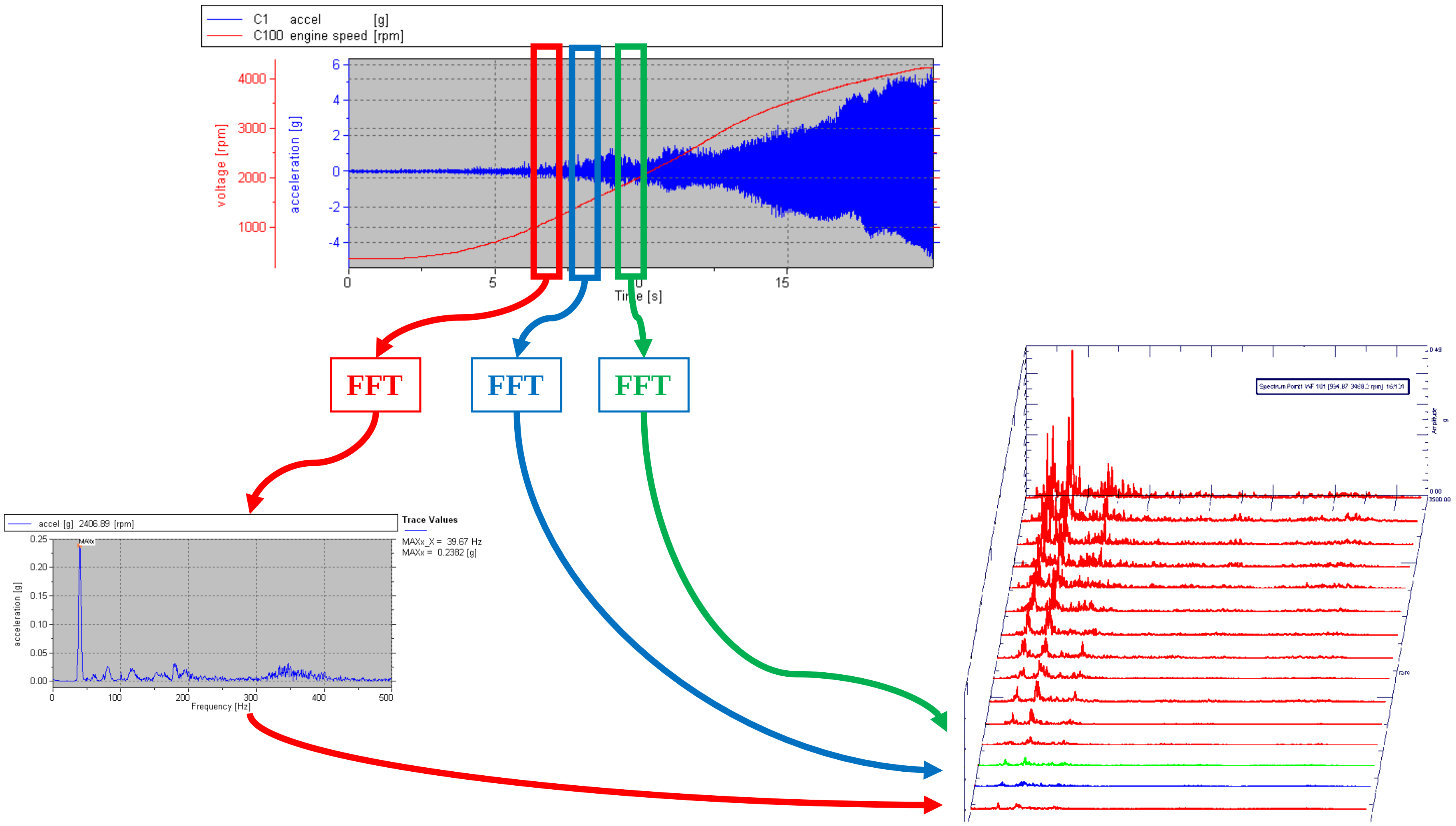
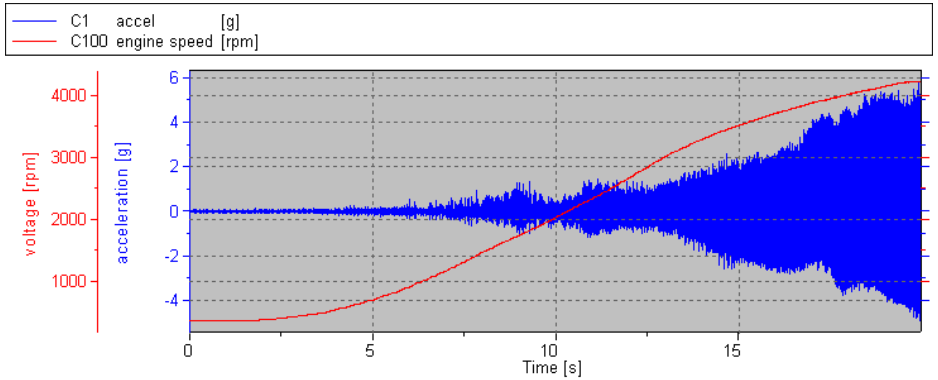
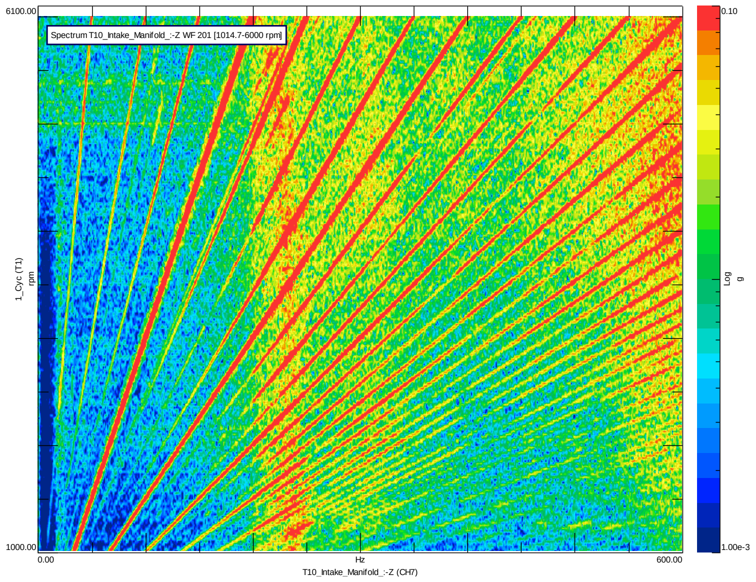


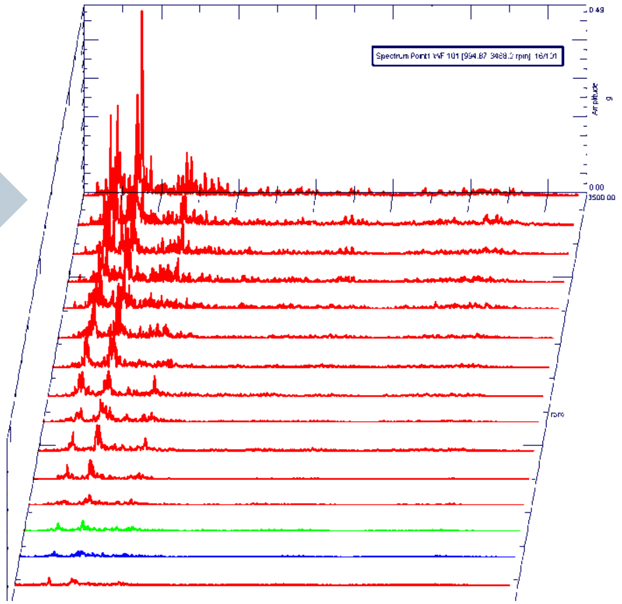
Non-Stationary Signals: Frequency content



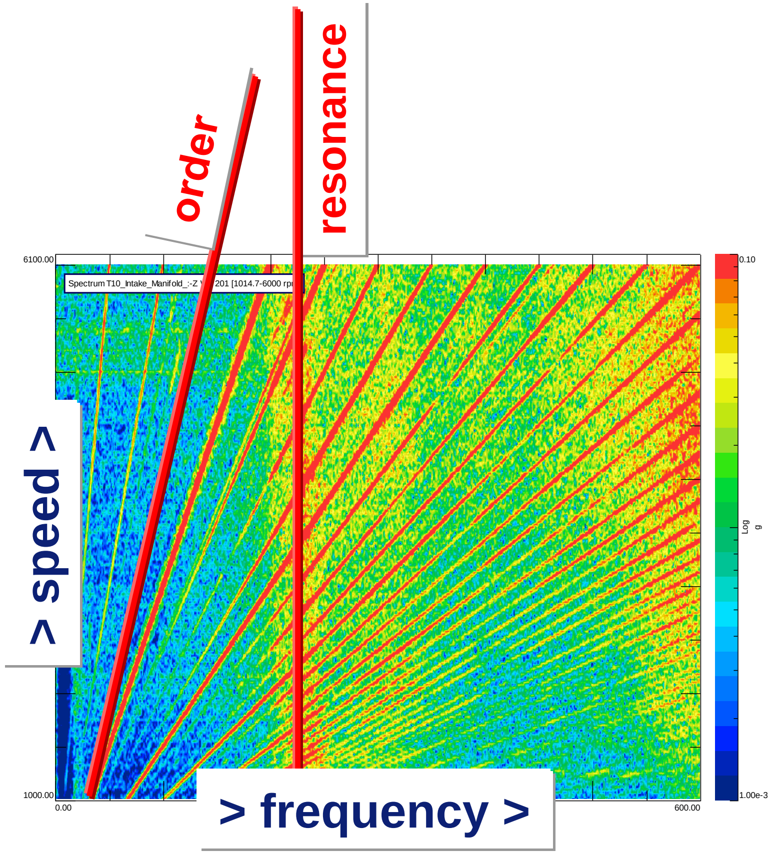
Waterfall and Colourmap

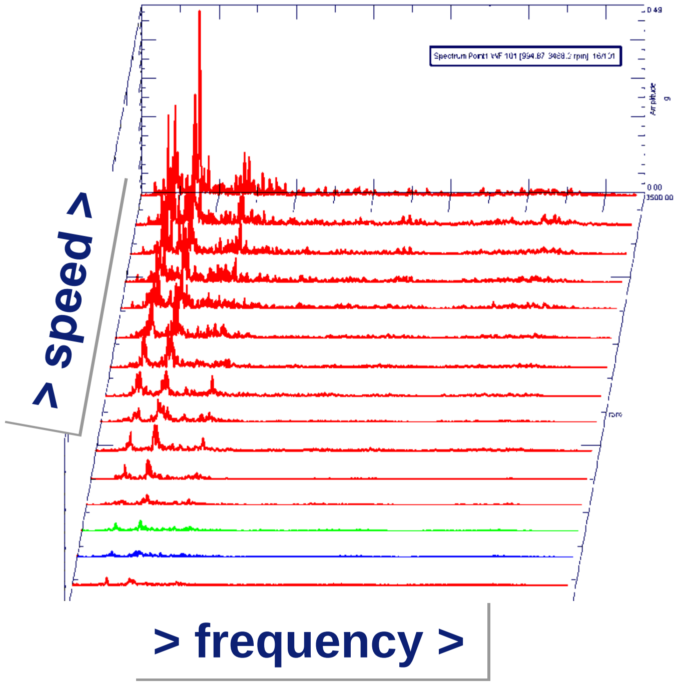




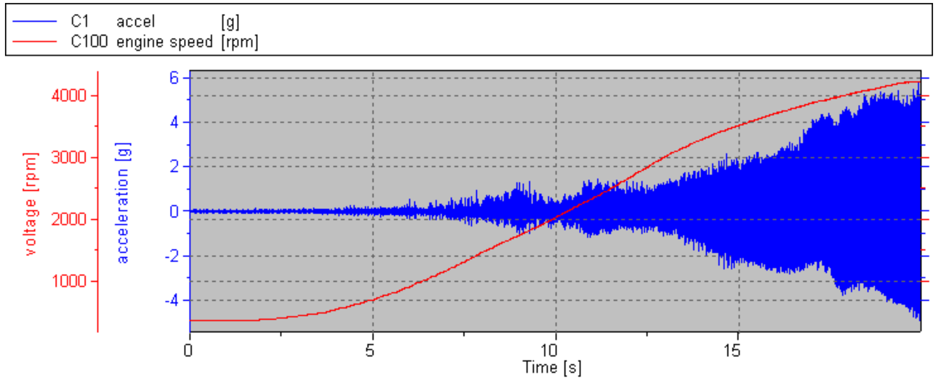


Orders and Resonances



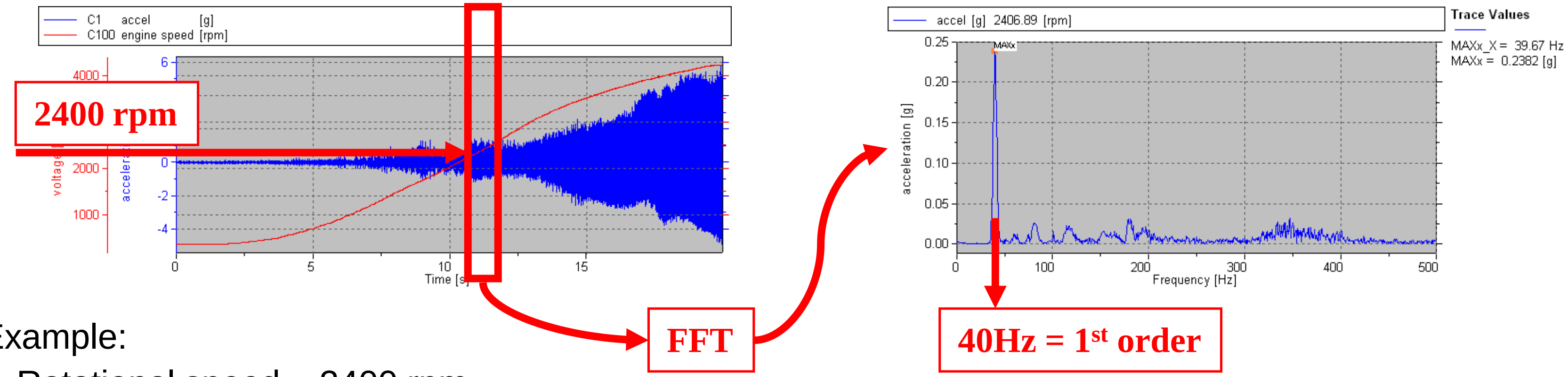


Relation between frequency and order



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?

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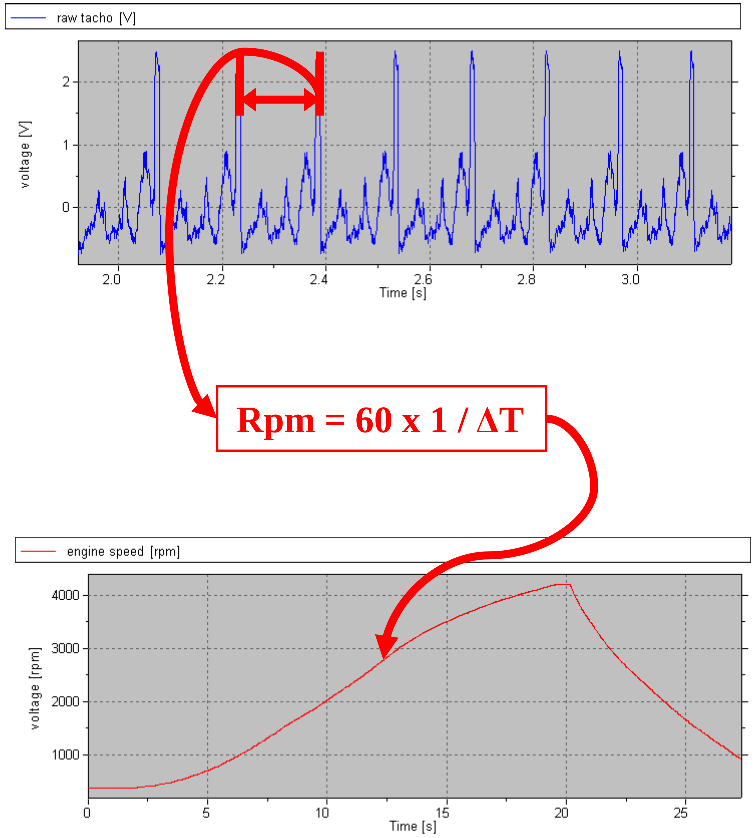
Remote Optical Probe

- Piece of reflective tape needed on shaft

Magnetic Pick-up

- Connected to Engine coder or Starter wheel



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Connected shafts

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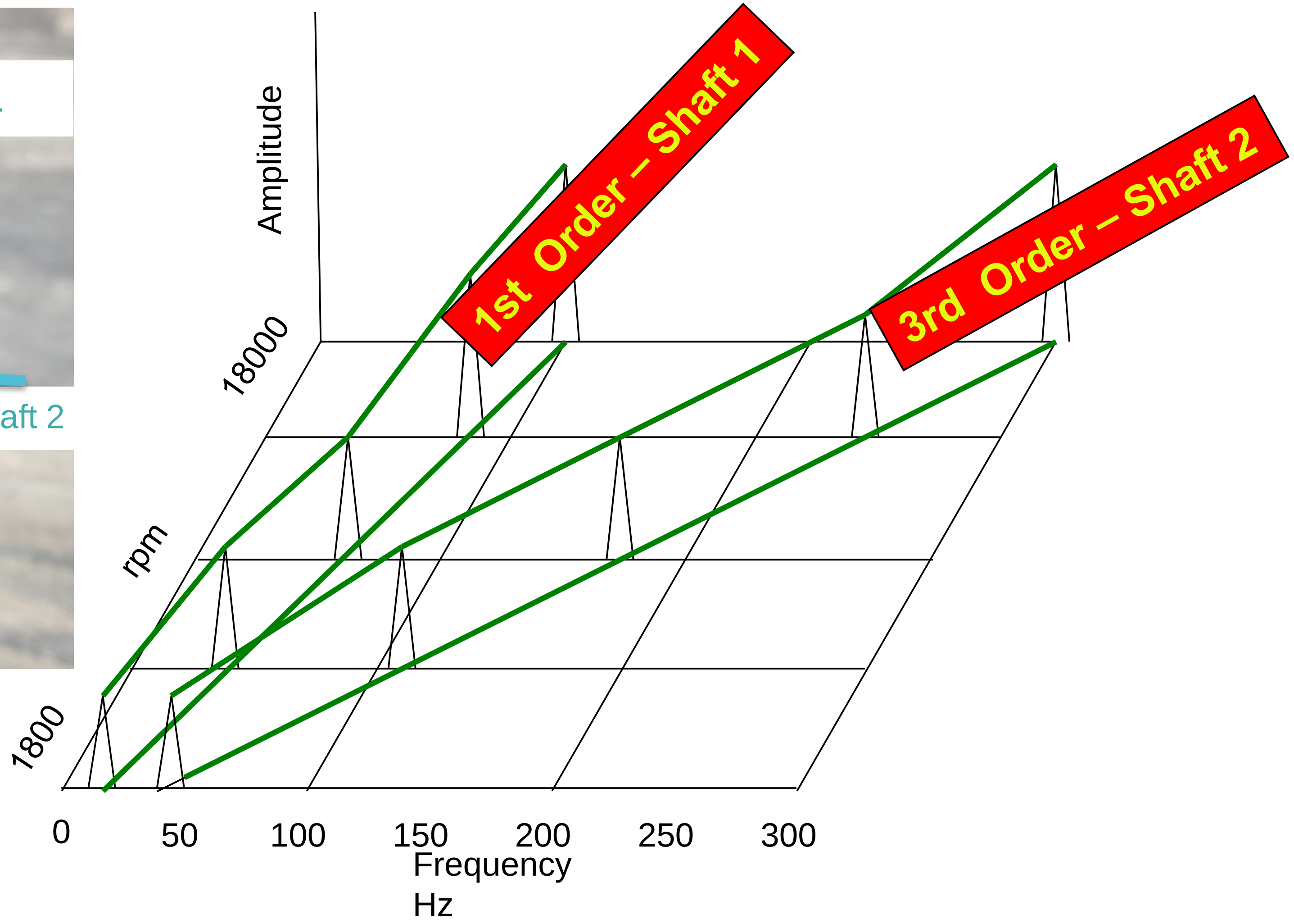
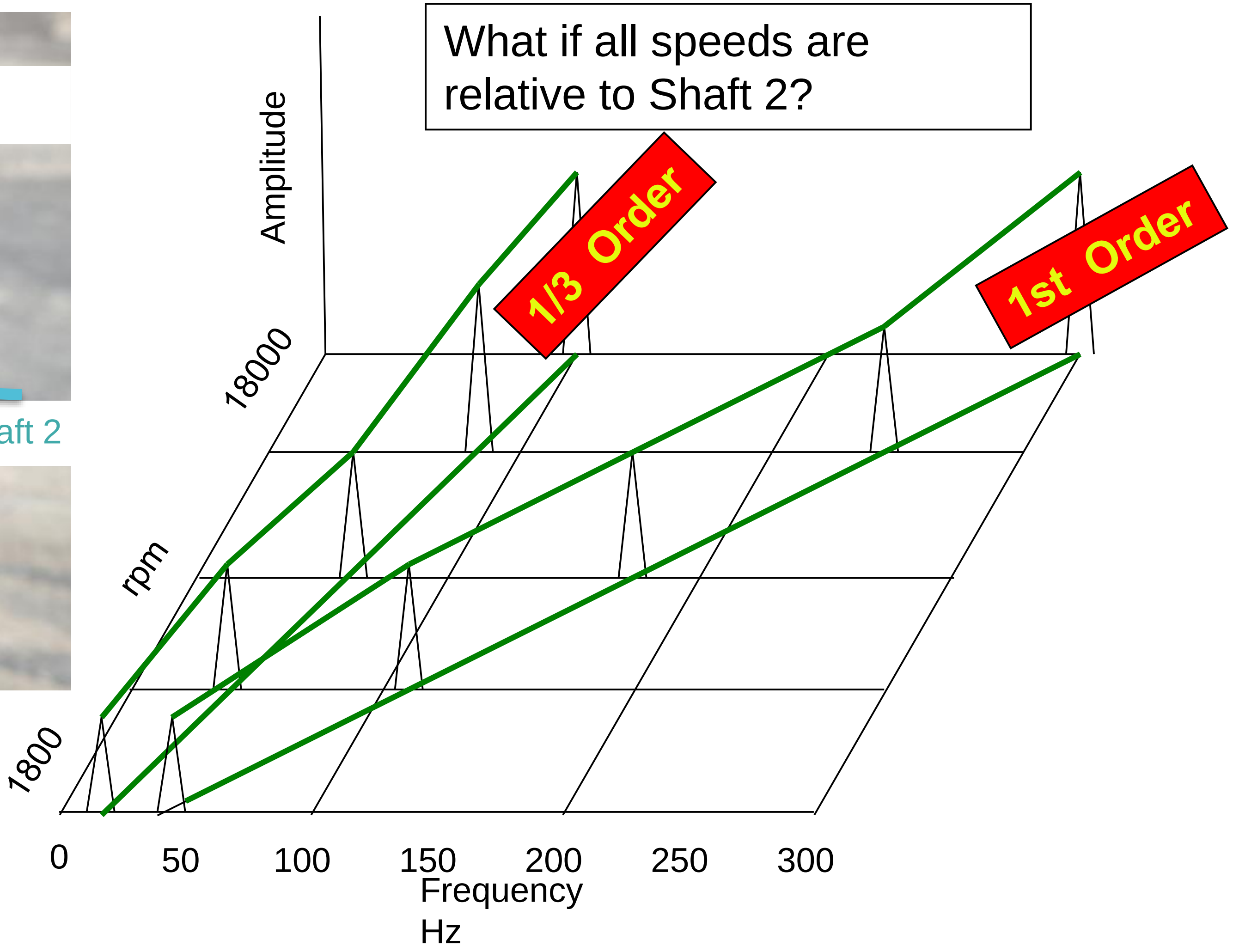


Connected shafts



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)

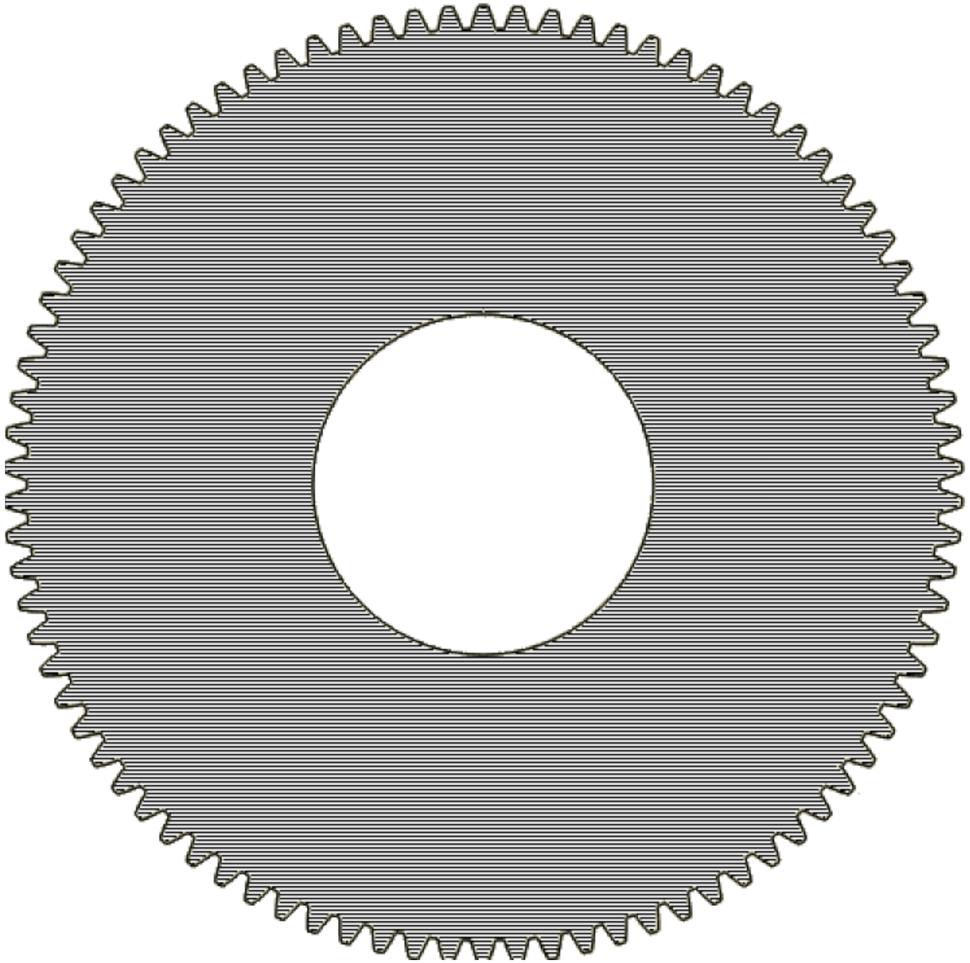
6 blades = **60Hz** peak in mic

Blade passing frequency

Blade passing frequency depends on rpm !

6^{th} order is independent from rpm

Gear



Gear spins @ 600 rpm

Gear has 86 teeth

What is the main order?

Gear spins @ 600 rpm

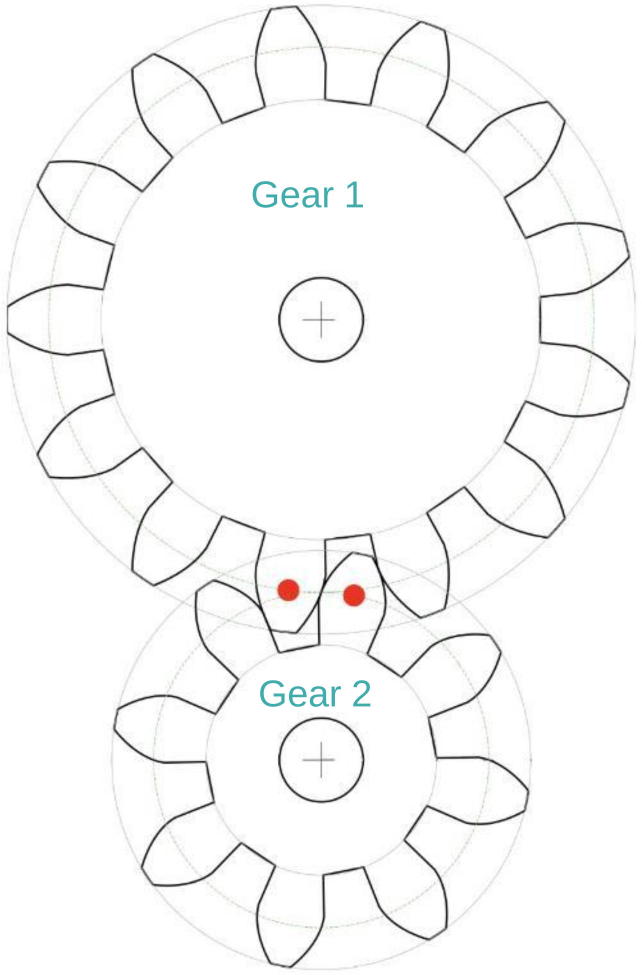
600 rpm = 10Hz (shaft)

86 teeth = 86^{th} order = **860Hz** peak

Gear meshing frequency

If ≠ 860Hz => transmission error

Connected gears



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)

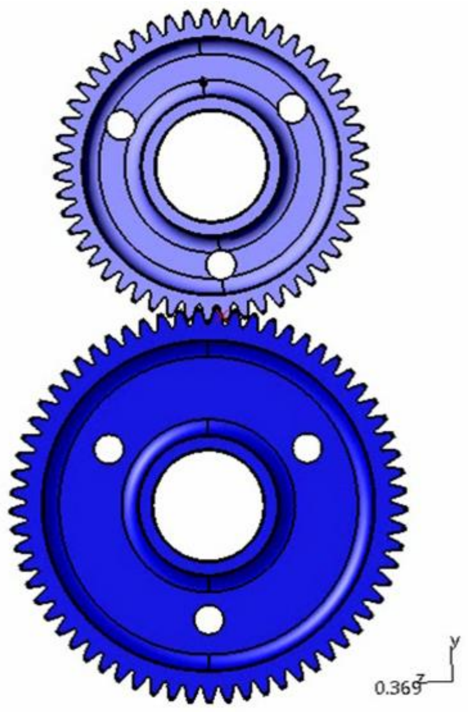
Gear meshing frequency ?

16.25 * 8 = 10 * 13 = **130 Hz**

Gears and prime numbers …

1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50
51	52	53	54	55	56	57	58	59	60
61	62	63	64	65	66	67	68	69	70
71	72	73	74	75	76	77	78	79	80
81	82	83	84	85	86	87	88	89	90
91	92	93	94	95	96	97	98	99	100

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!

Combustion engine

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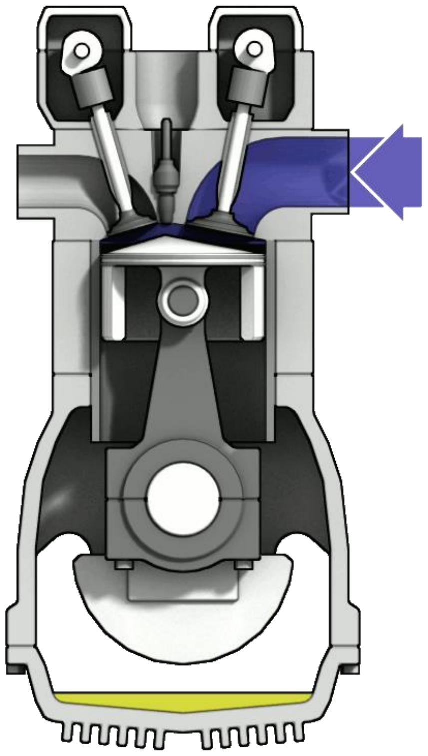
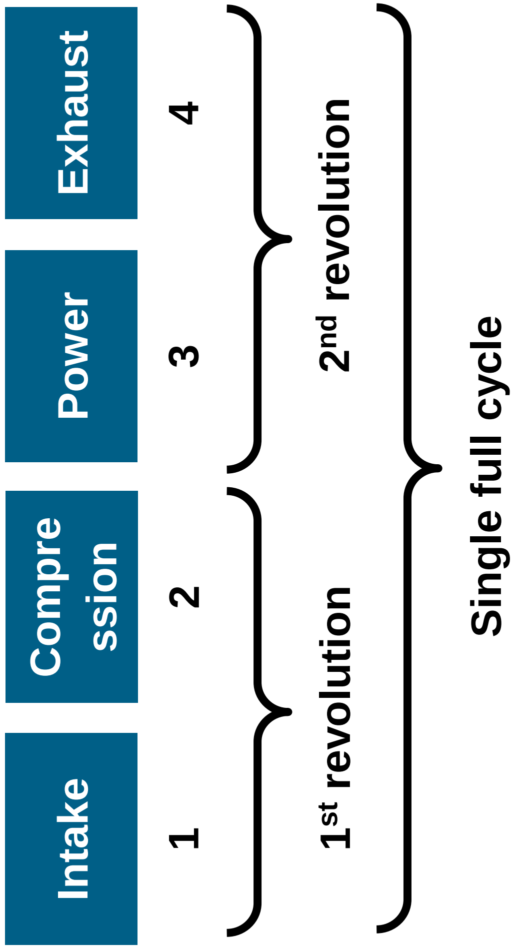
1



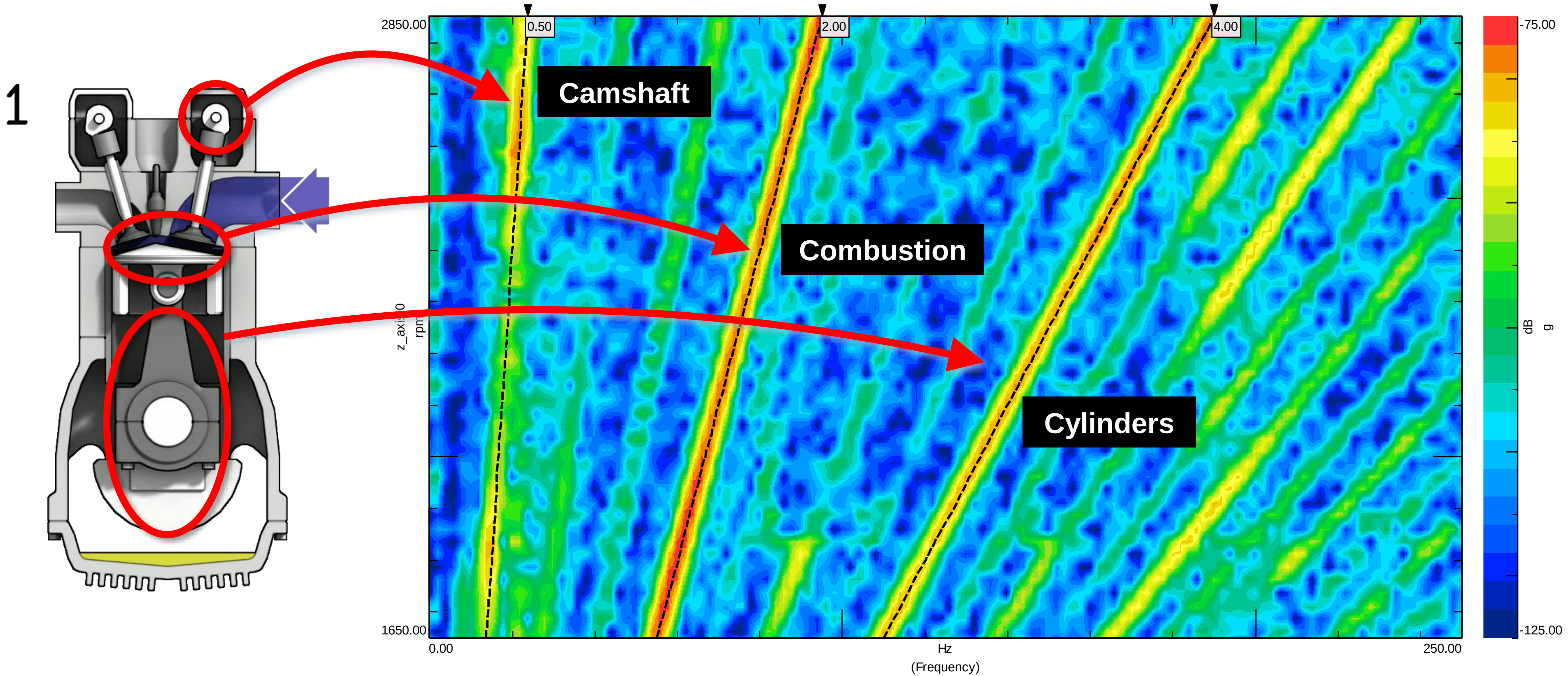


An ‘order’ is a frequency component with a rotational speed dependency

4-stroke, 4-cylinder engine

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

Combustion engine



Electric motor

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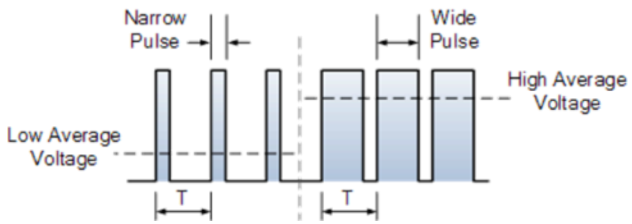

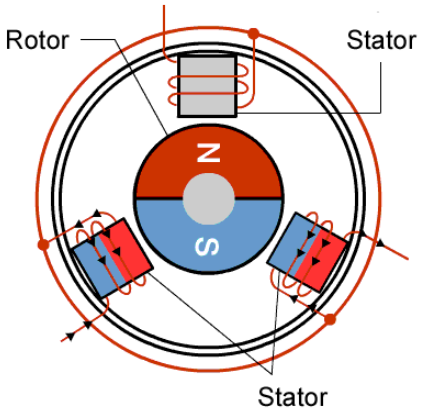

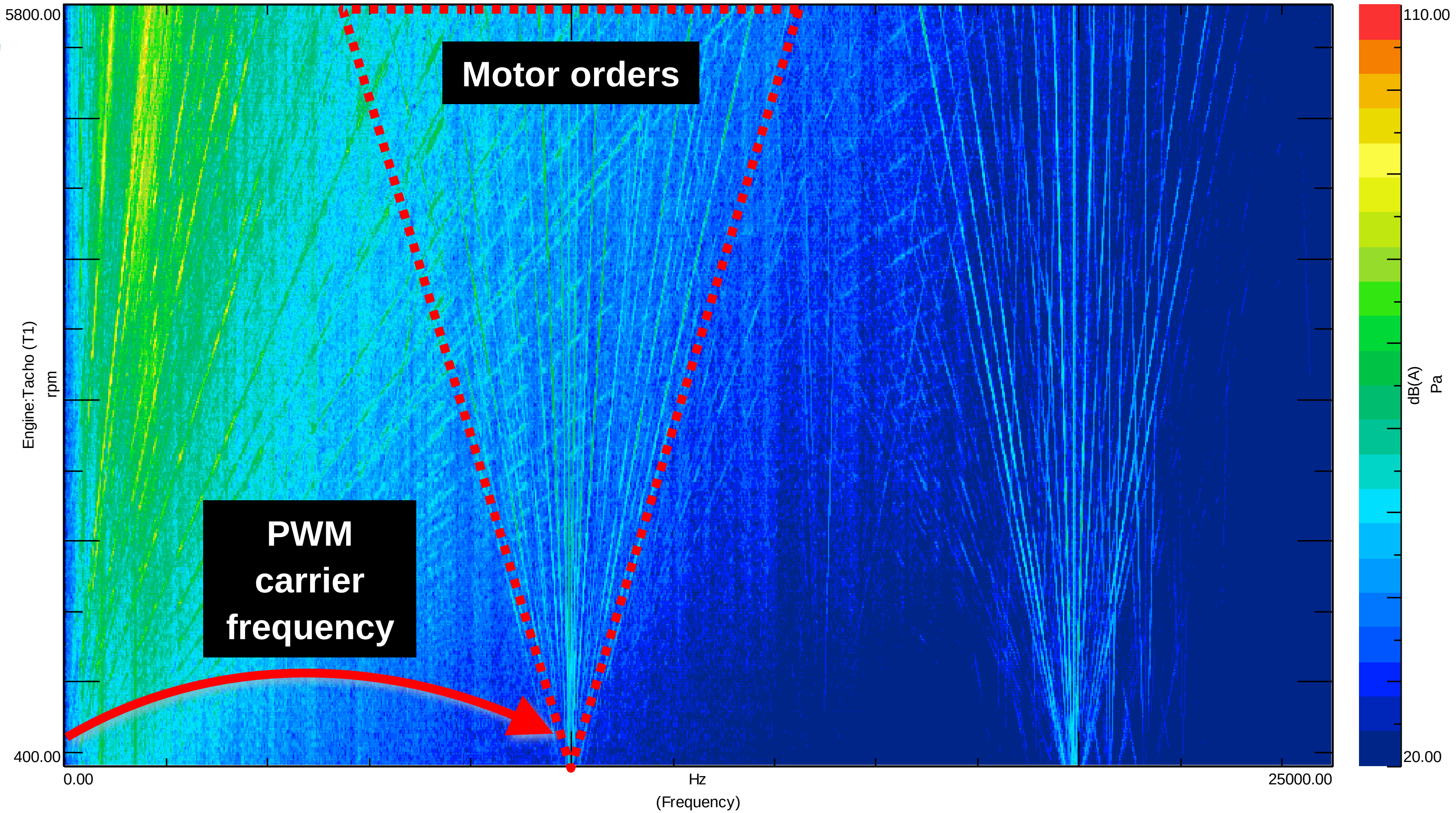

Transmission
Which issues can we detect?

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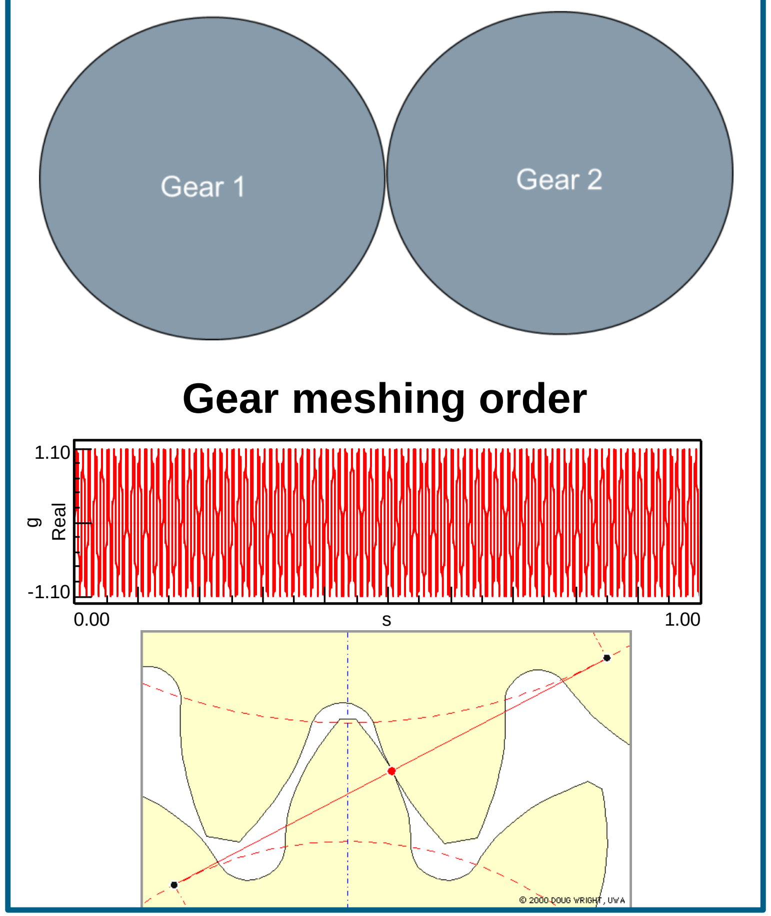
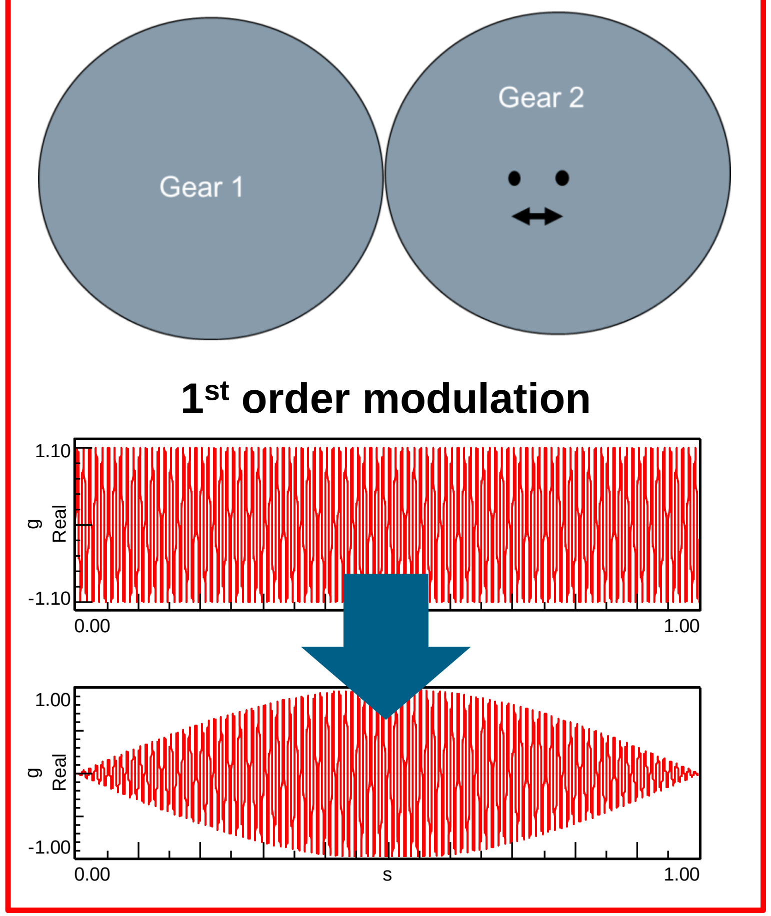
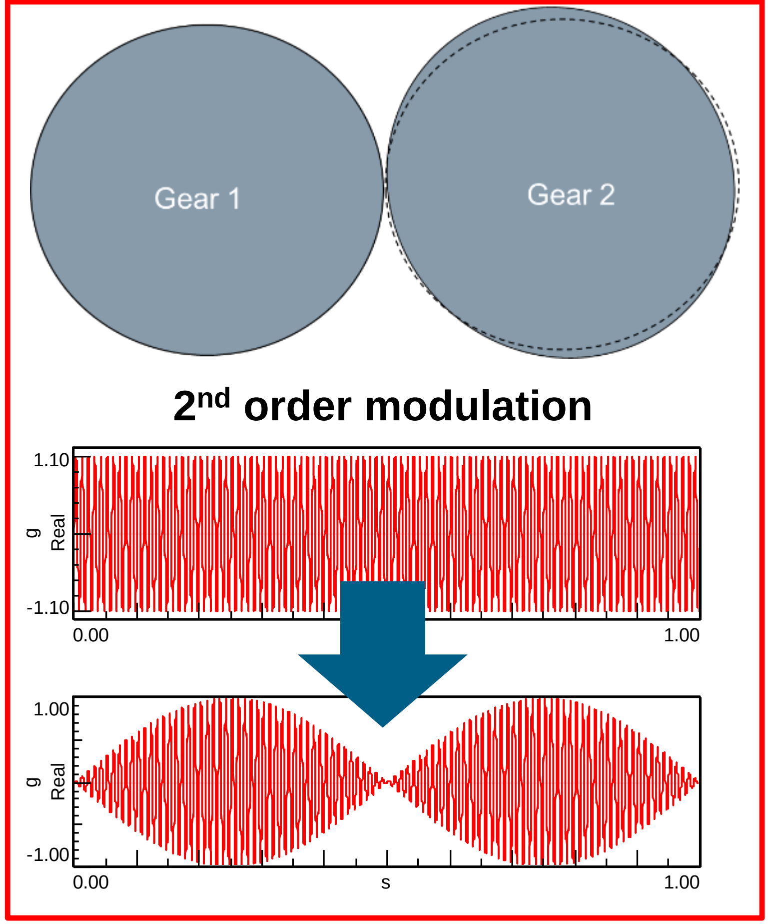
Perfect mesh



Misalignment



Eccentricity



Transmission
Order analysis

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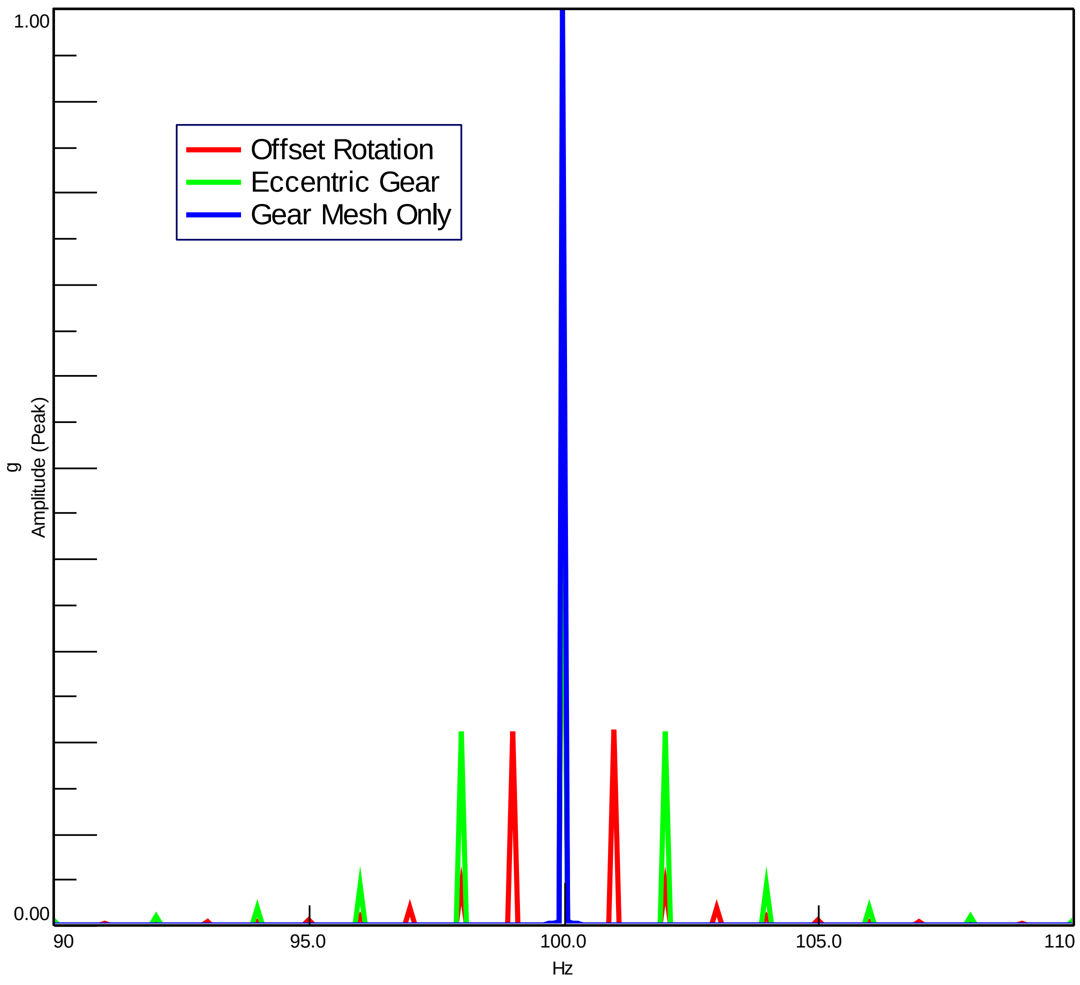
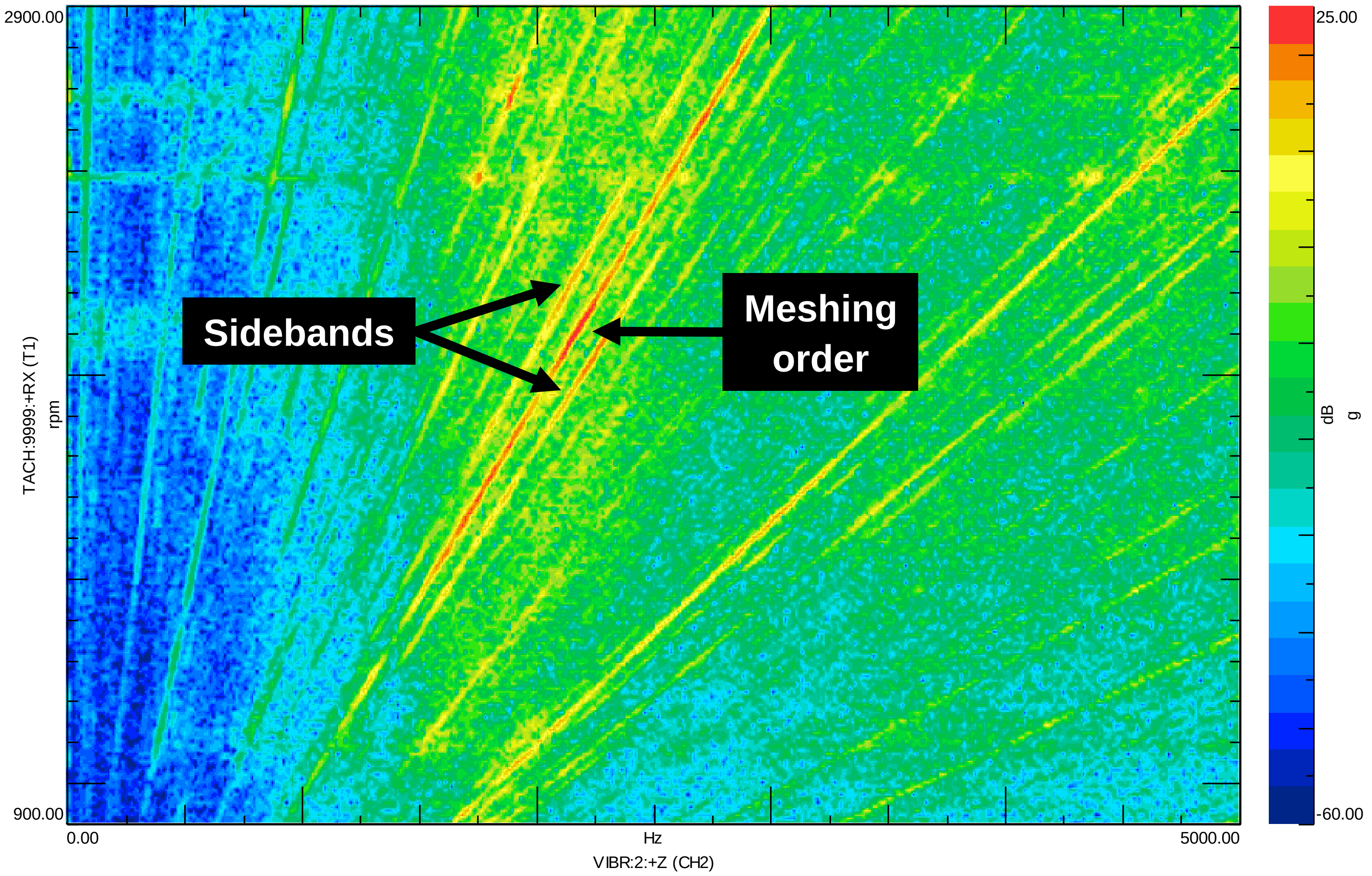
Order offset vs. meshing frequency	Causes
0	▪ High meshing forces ▪ Bad gear teeth design
1	▪ Load imbalance ▪ Shaft resonance ▪ Improper installation
2	▪ Gear eccentricity ▪ Manufacturing issue



Transmission
Order analysis

Sideband level variation with RPM and load in real life

Root-cause amplification possible due to structural resonances



Bearings
What causes bearing defects?

Outer race

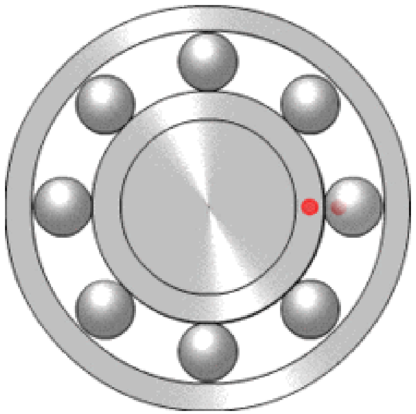
Roller cage

Rollers

Inner race

Many rotating components with different RPM than output shaft

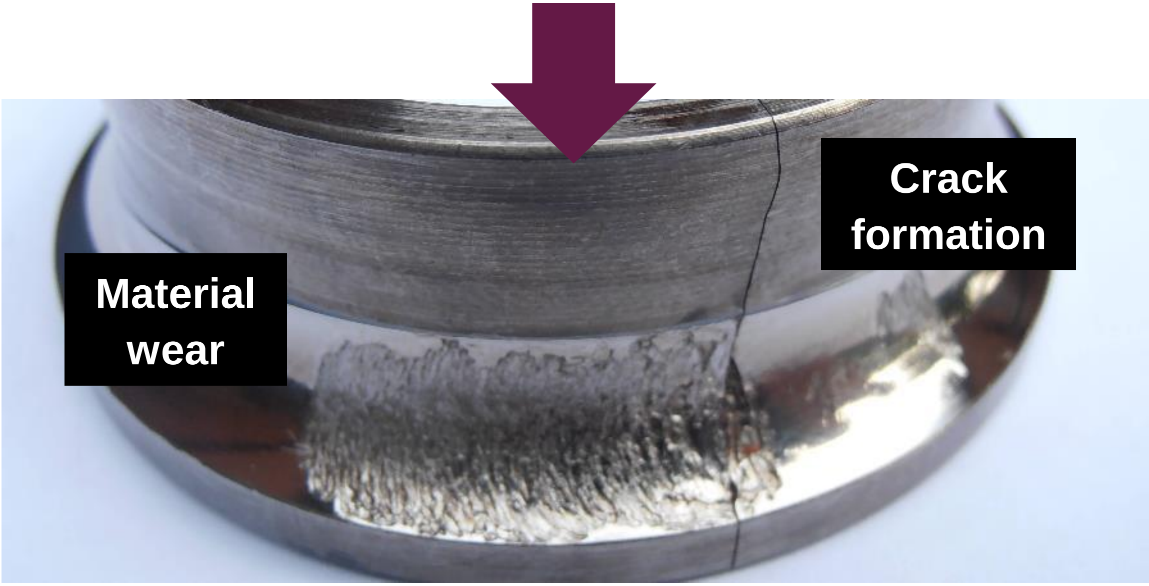
Expect unique orders per defective component



What causes bearing defects?

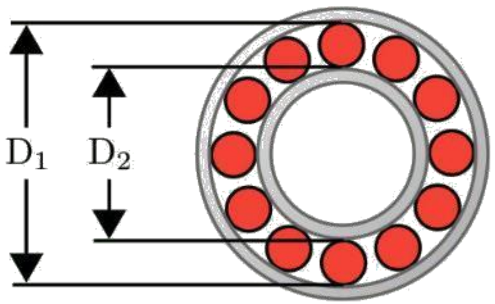
Improper maintenance:
- Insufficient lubrication
- Lubrication aging
- Dust contamination

Excessive forces:
- Load imbalance
- Misalignment
- Shaft vibrations



Bearings

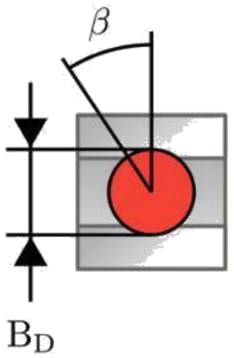
Order analysis



$$P_D = \frac{D_1 + D_2}{2}$$

$$N_B = \text{Number of balls}$$

$$\beta = \text{Contact angle}$$



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

Bearings
Order analysis

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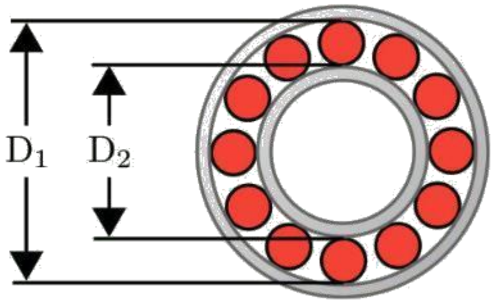
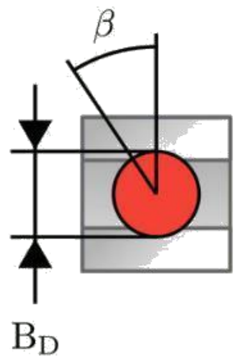
- Pitch diameter = 1.548 inch
- Ball diameter = 0.3125 inch
- Number of balls = 9



$$P_D = \frac{D_1 + D_2}{2}$$

N_B = Number of balls

β = Contact angle



RPM	BPFO (Hz)	BPFI (Hz)	BSF (Hz)	FTF (Hz)
100	6.077258	8.922742	3.979451	0.675251
500	30.38629	44.61371	19.89726	3.376254
1000	60.77258	89.22742	39.79451	6.752509
1500				
2000				
2500	151.9315	223.0685	99.48628	16.88127
3000	182.3177	267.6823	119.3835	20.25753
3500	212.704	312.296	139.2808	23.63378
4000	243.0903	356.9097	159.178	27.01004

O = 3.646 | **O = 5.354** | **O = 2.387** | **O = 0.405**

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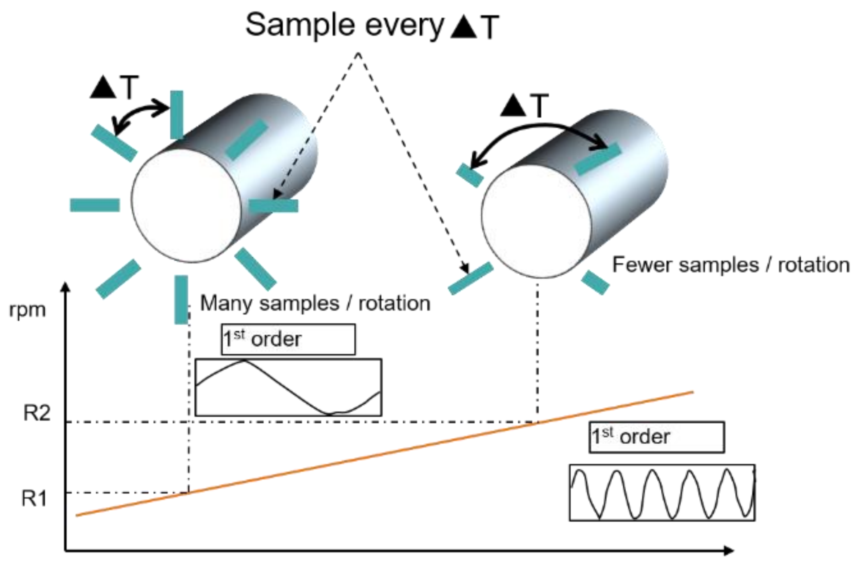
Fixed sampling for runups?

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



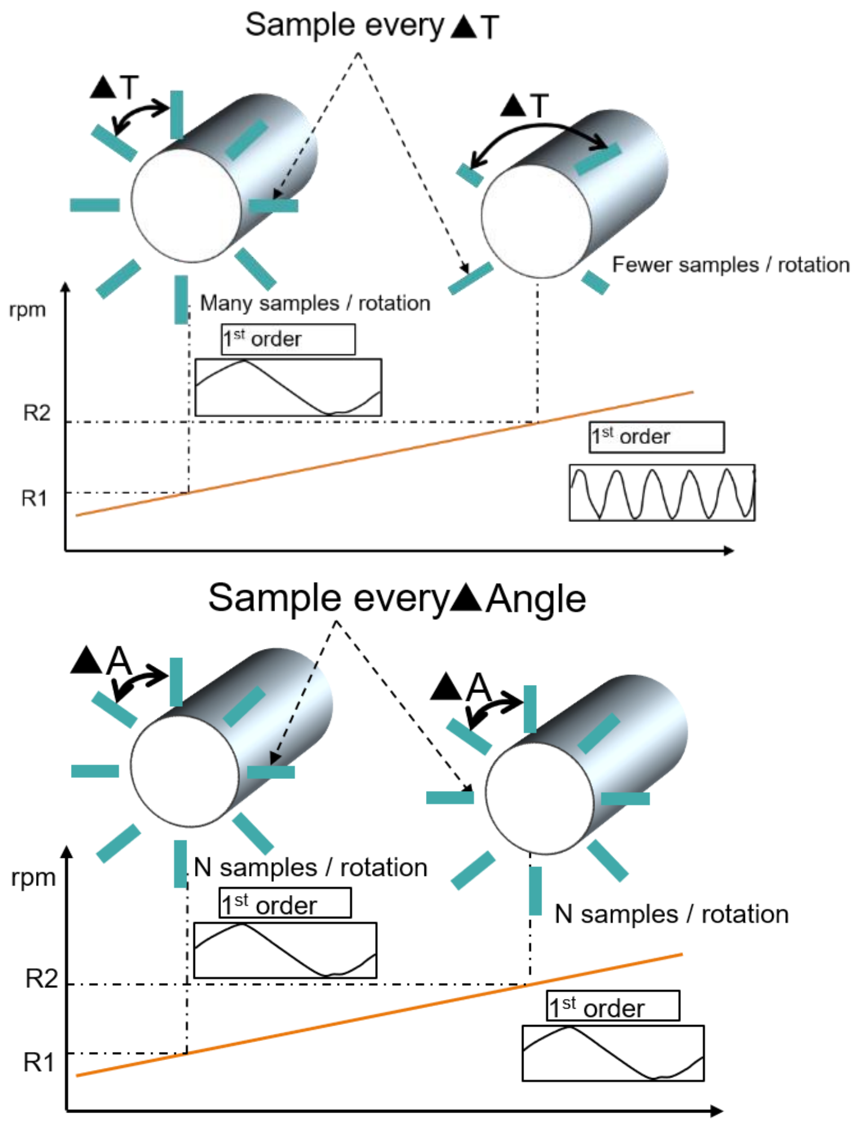
Fixed sampling vs synchronous order tracking

<u>Fixed sampling</u>: 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

<u>Order tracking</u>: 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

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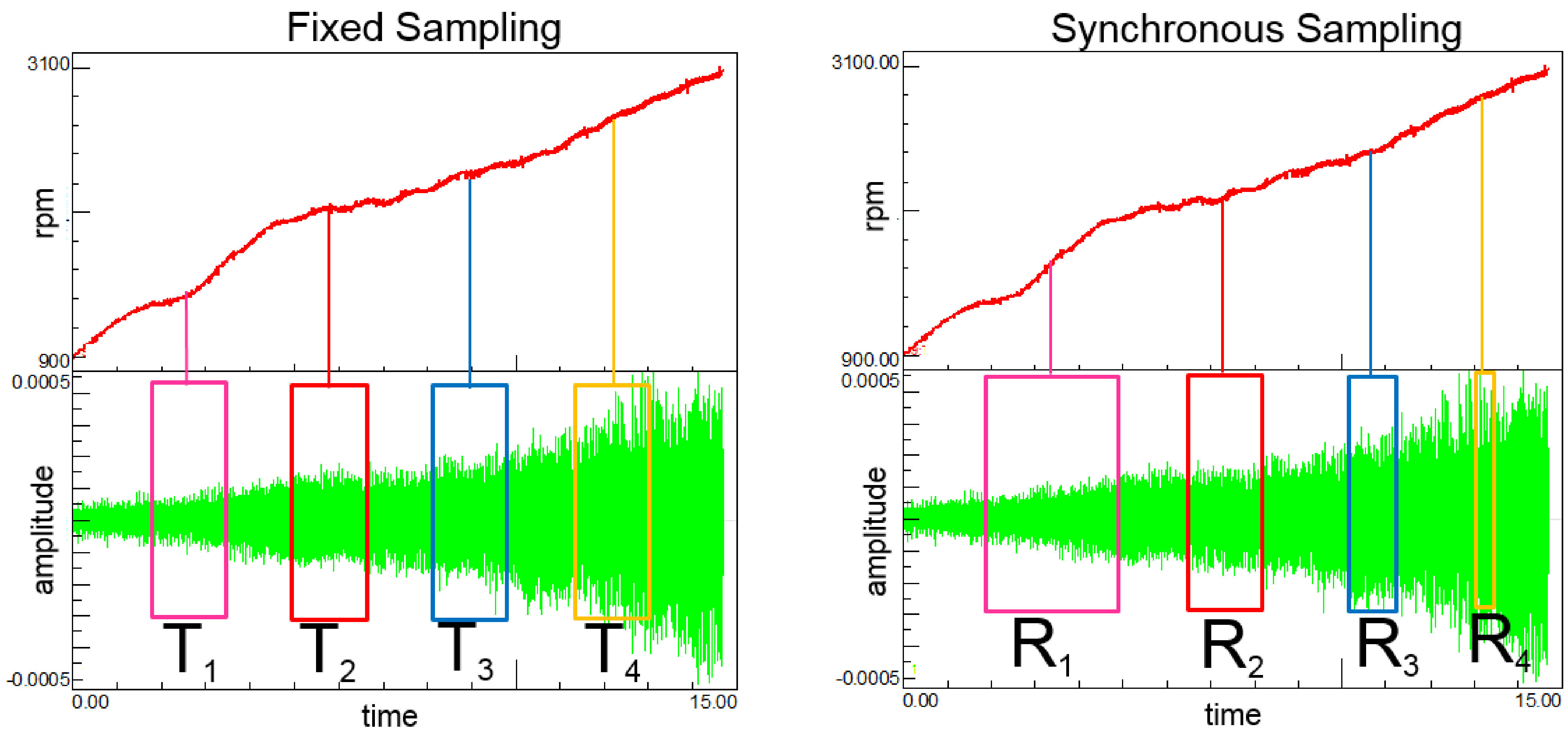

Fixed sampling vs synchronous order tracking

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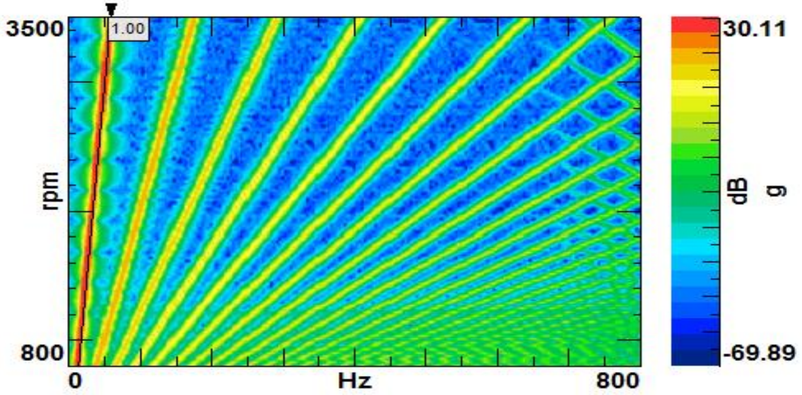
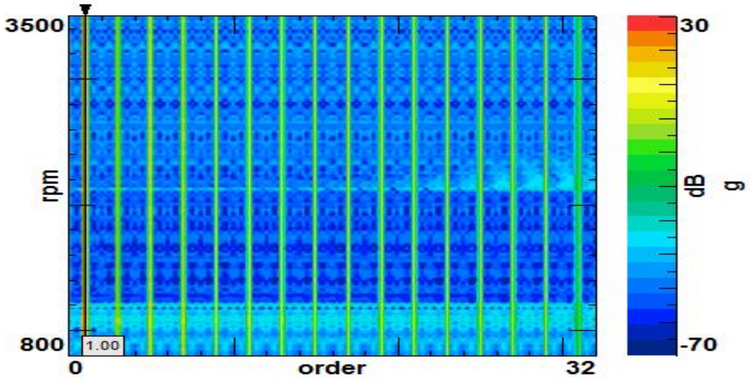
- **Narrowband Fixed sampling**
  - Constant sampling frequency
  - Frequency spectra and orders



  - 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?

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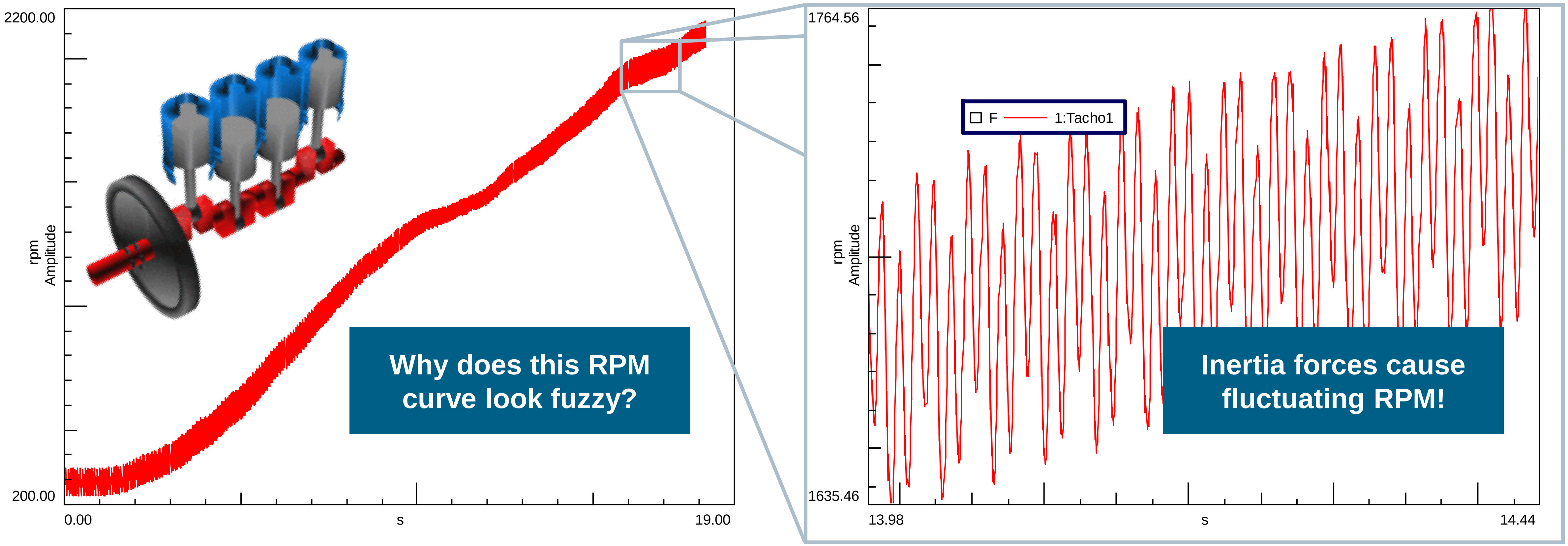
Torsional vibrations



How to measure those speed variations?

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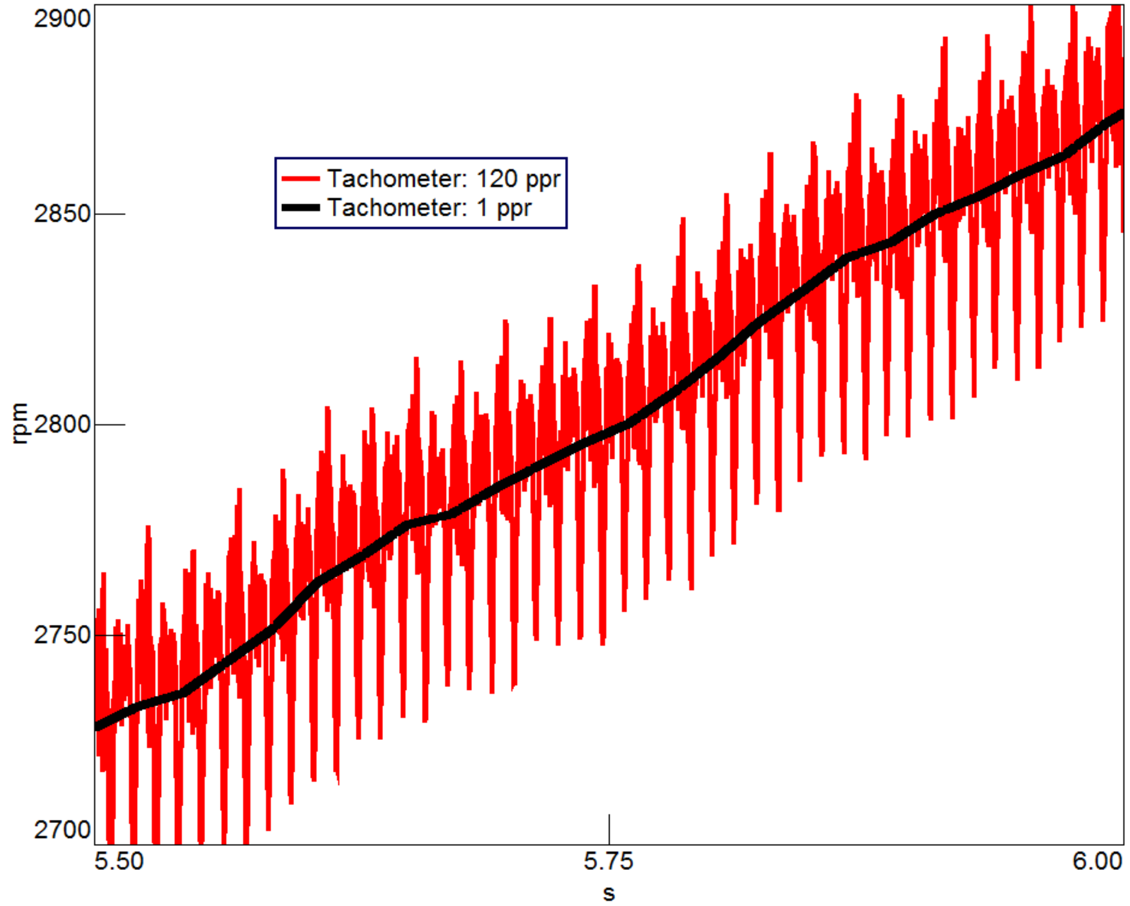
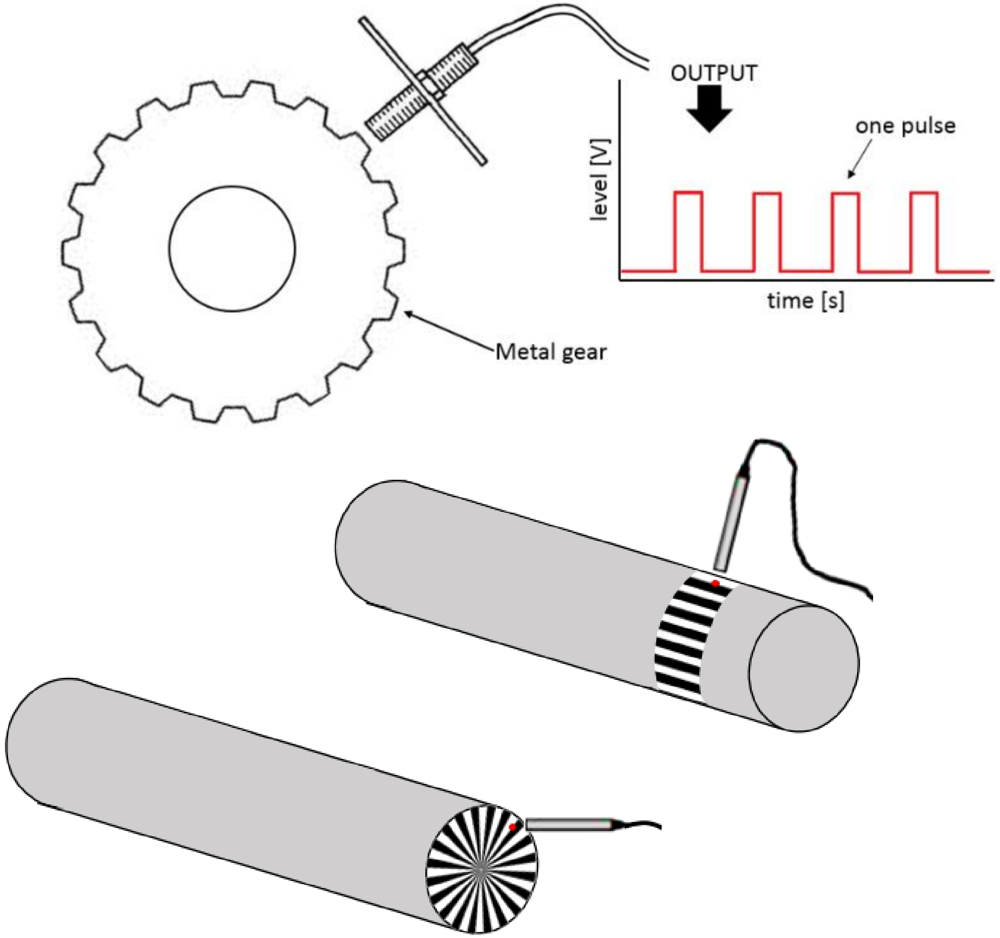




How to measure those speed variations?

Analog vs. digital pulse detection

Example:

<u>Transmission error analysis</u>

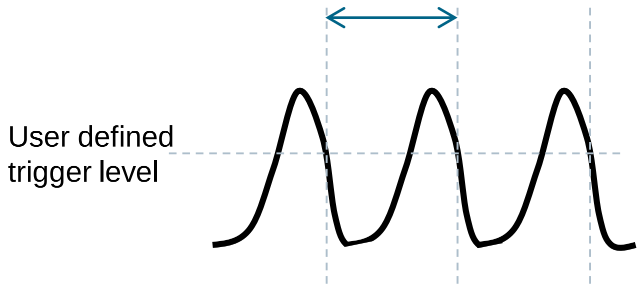
Maximum 5000 RPM

+

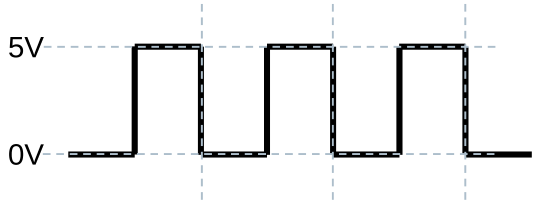
Incremental encoder with 1200 PPR

=

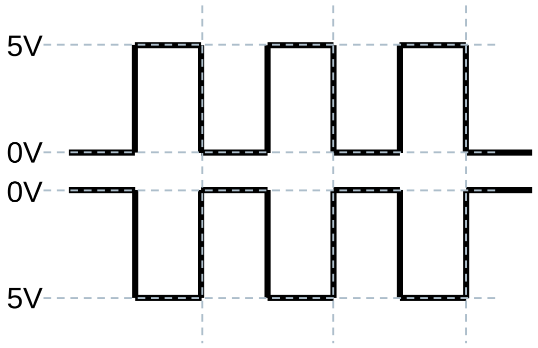
~ 100.000 pulses per second



Analog Tacho
- All type of sensors
- Up to 40.000 pulses per second



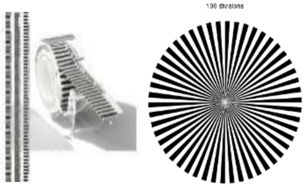
Digital Tacho – TTL
- Optical sensors / Incremental encoders
- Up to 1.000.000 pulses per second



Digital Tacho – RS422/485
- Optical sensors / Incremental encoders
- Differential TTL for electrically noisy environment
- Up to 1.000.000 pulses per second

Torsional Laser

Magnetic



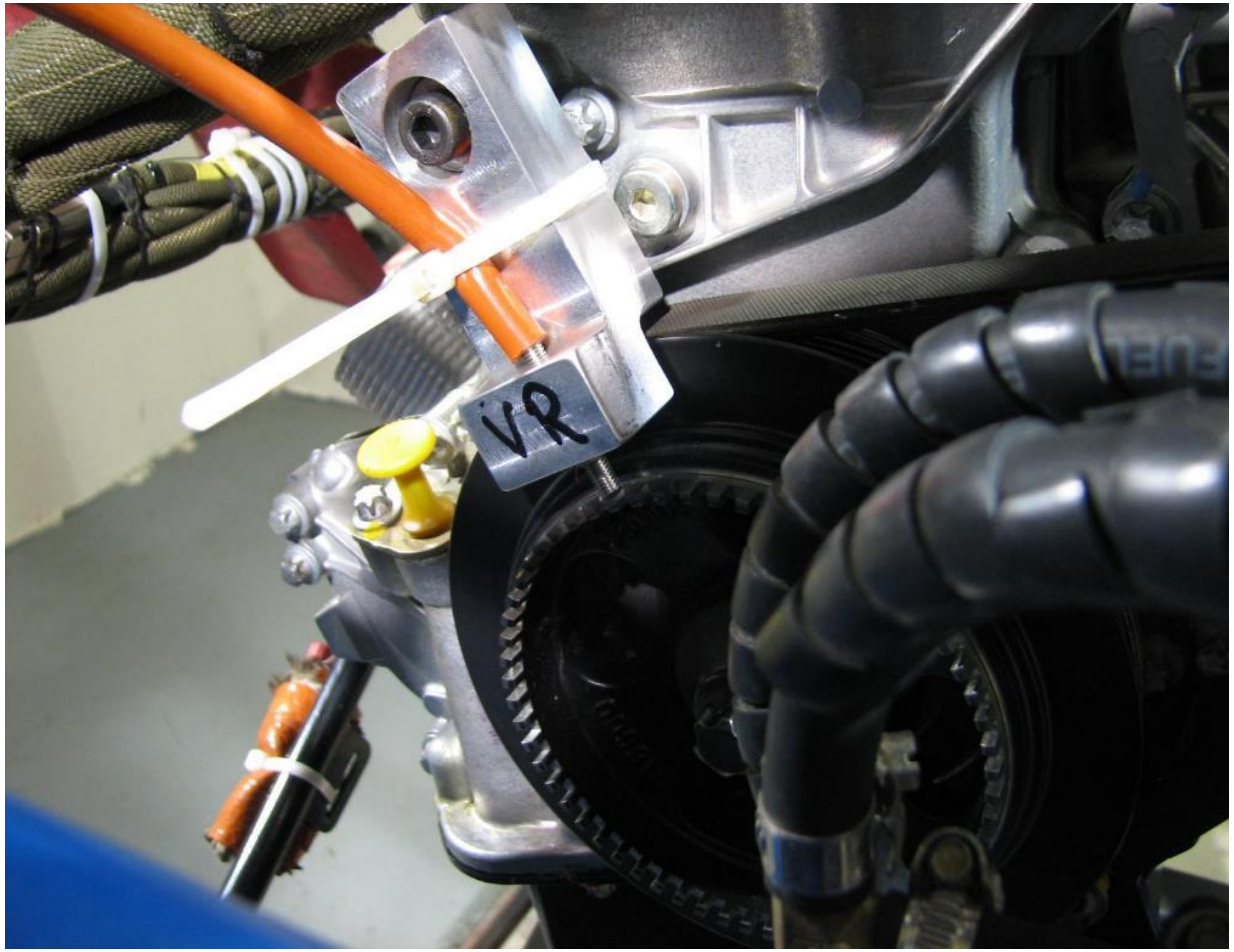
Optel-Thevon optical probes

Incremental Encoder

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

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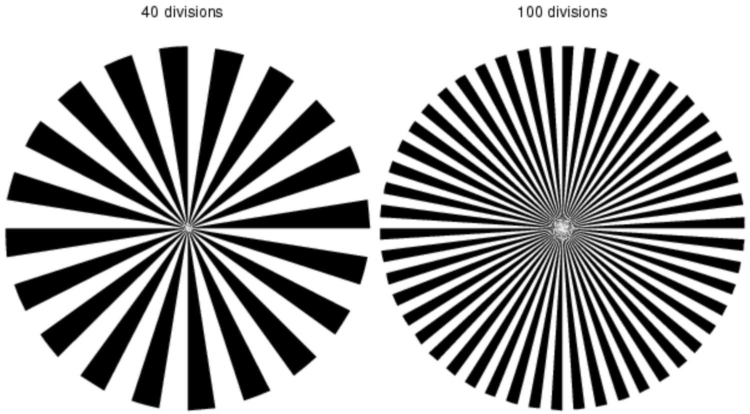
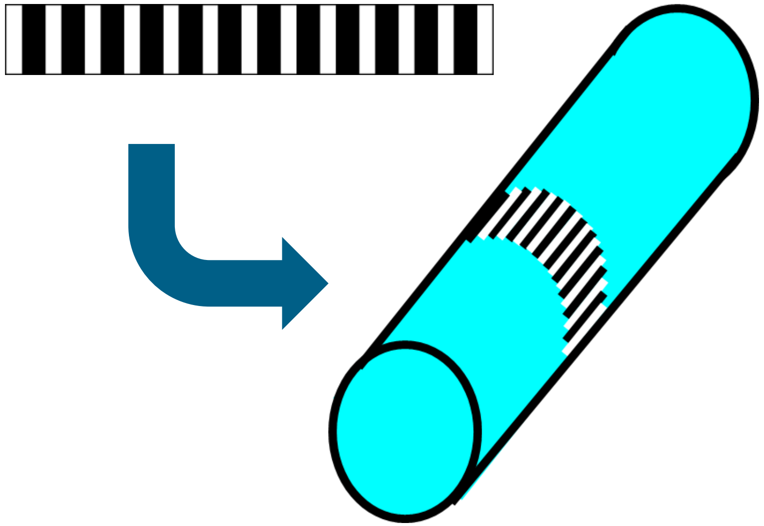
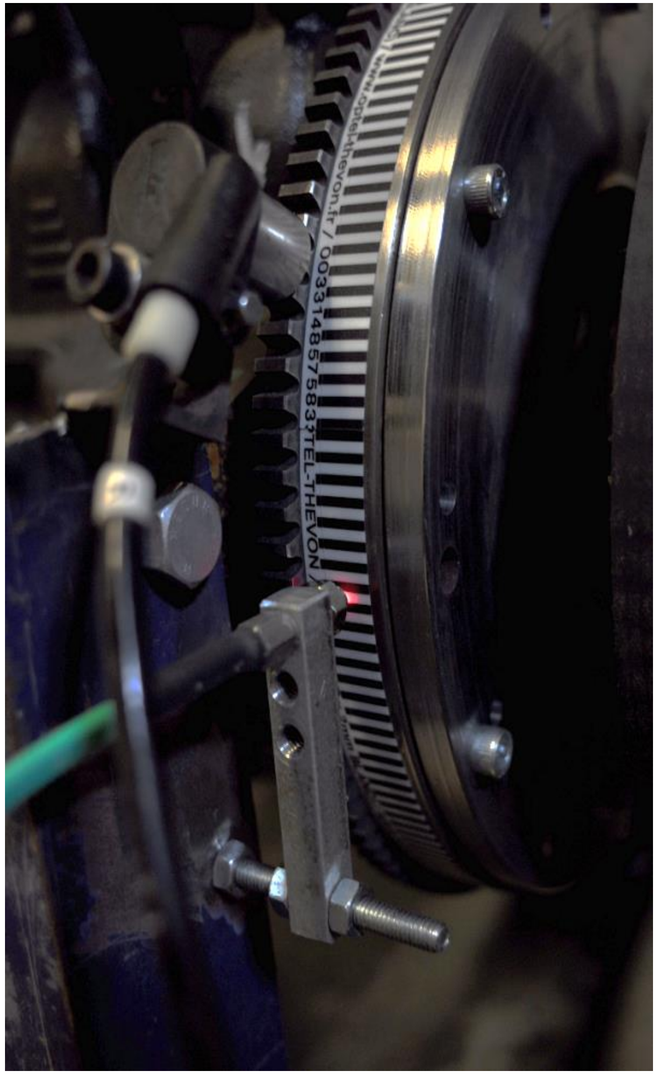
- ☺ Easy instrumentation, on any shaft or gear wheel
- ☺ High pulse rates, depends on zebra tape

- ☹ Sensitive to ambient light
- ☹ Zebra tape defects





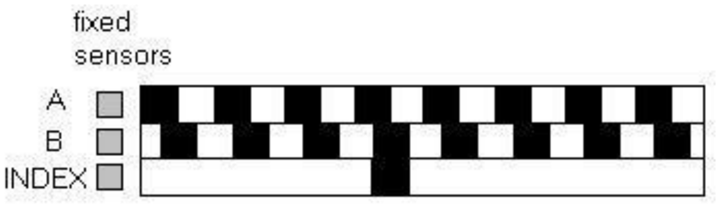


How to measure those speed variations?
Incremental Encoders

http://www.heidenhain.com/en_US/products/rotary-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

- Complex instrumentation
- Mass loading

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

Agenda:

Non stationary phenomena
Practical examples
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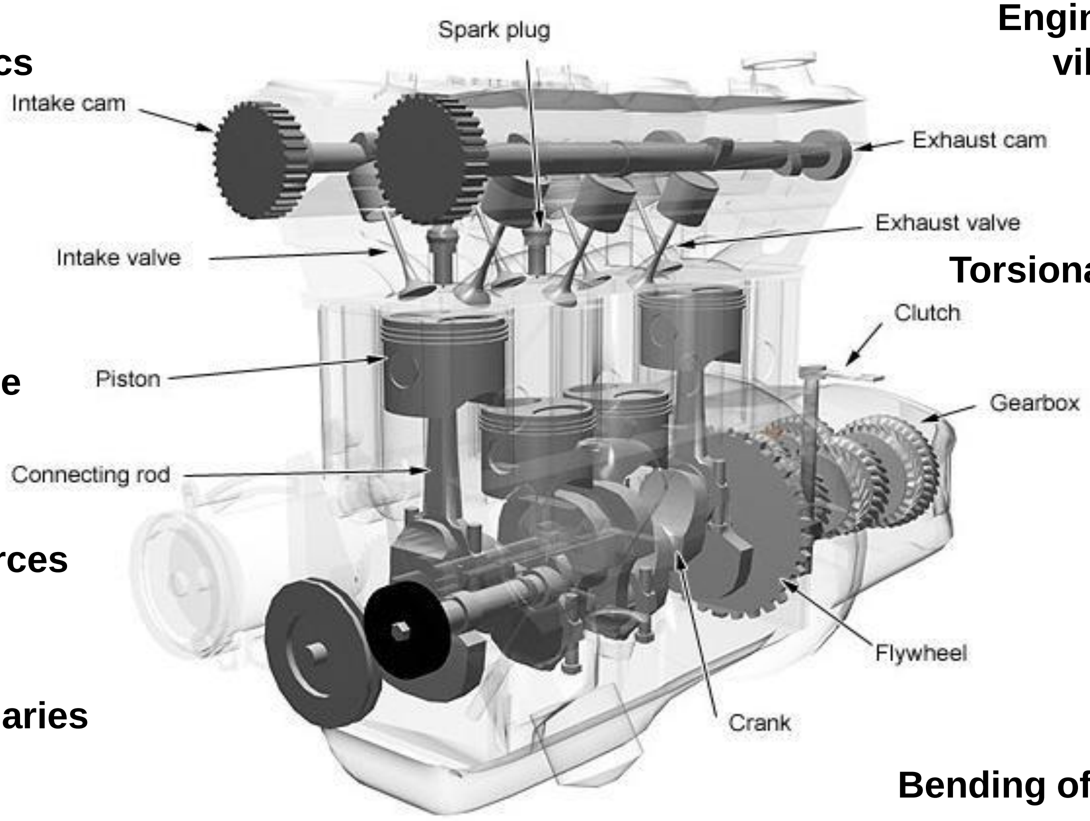
What is Angle Domain analysis?
Application examples



Combustion profile

Engine knock

Camshaft bending

Engine surface vibration

Valve train dynamics

Valve Impact Noise

Torsional vibrations

Piston Noise

Bearing forces

Gear rattle

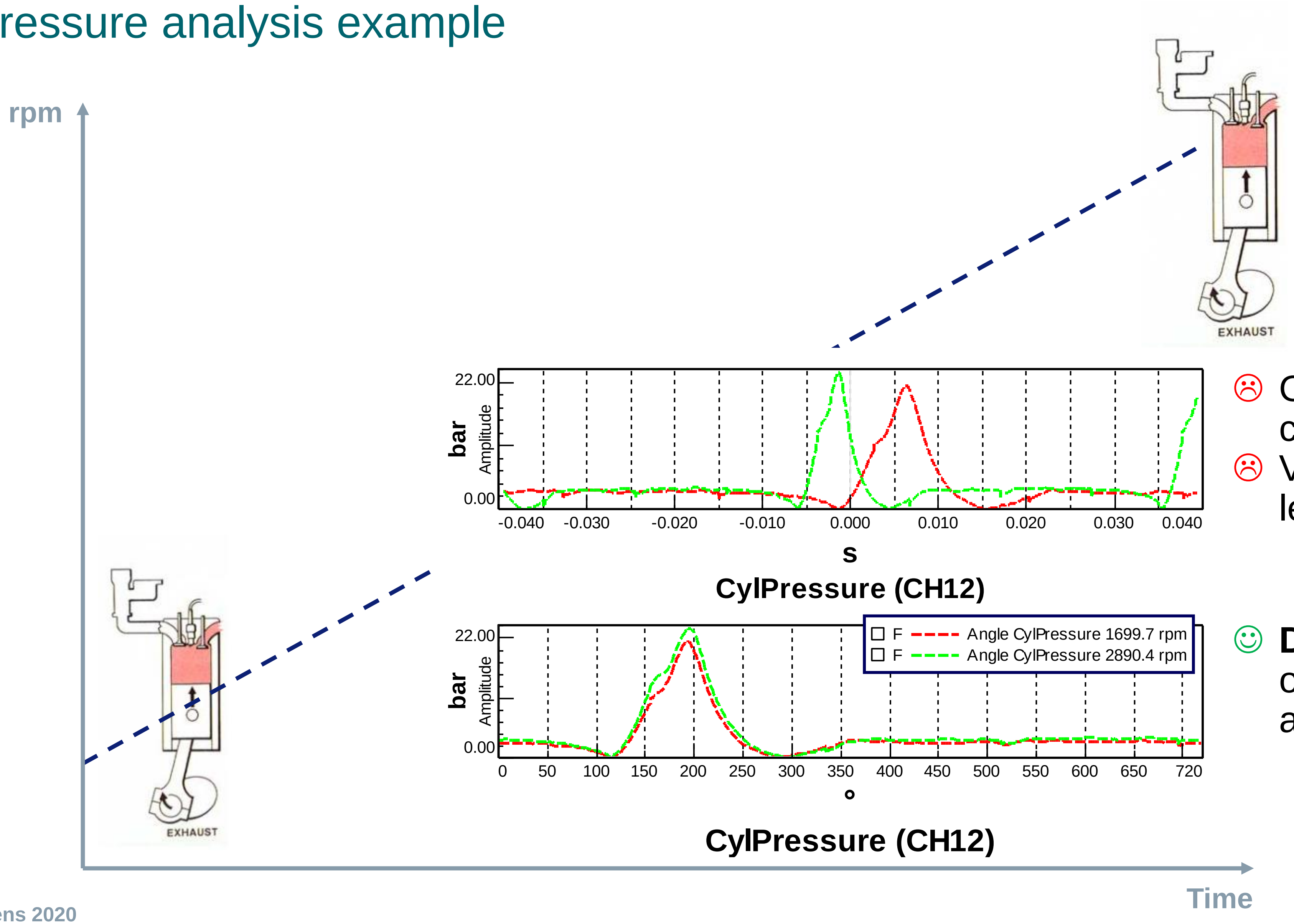
Engine ancillaries

Bending of crankshaft

Unbalanced inertia forces

Cylinder to cylinder variation of combustion

What is Angle Domain analysis?
Cylinder pressure analysis example



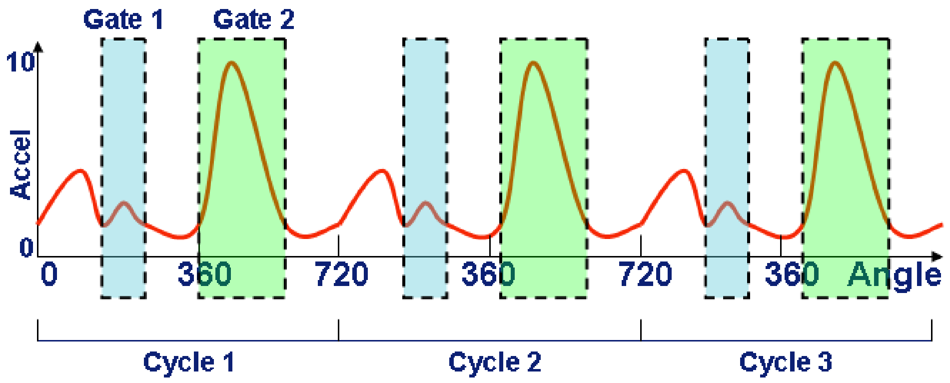
- ☹ Offset between cylinders
- ☹ Variable pulse length

- ☺ **Direct comparison** of cylinder pressure at any RPM

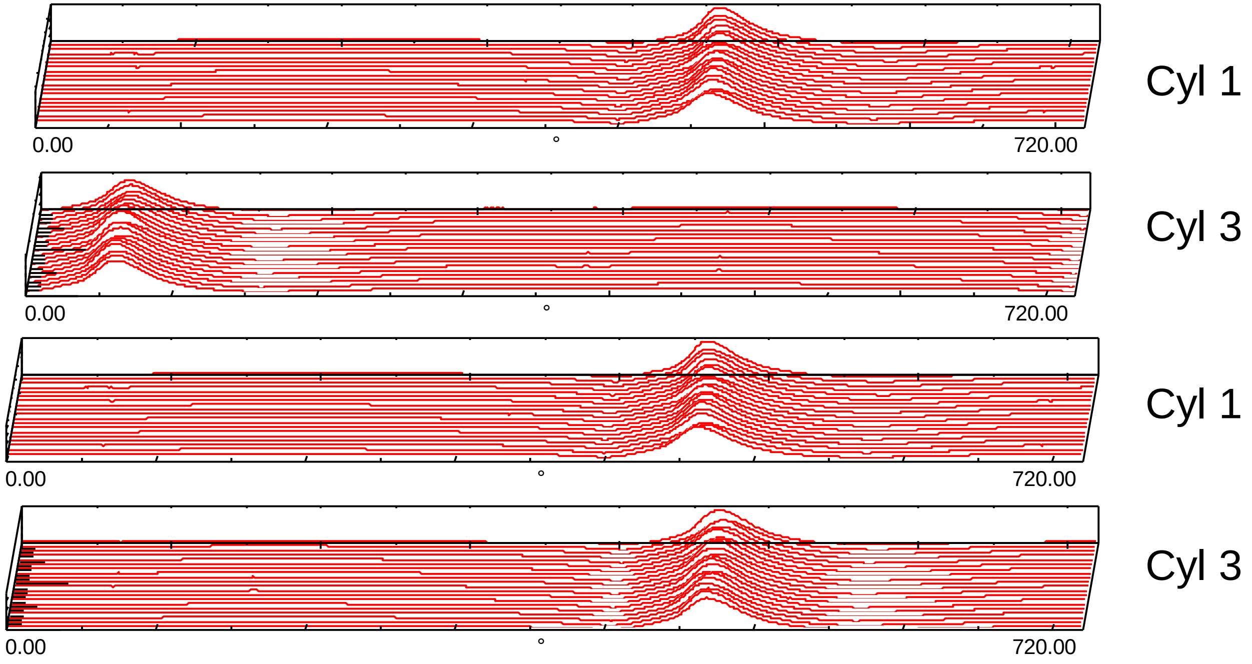
What is Angle Domain analysis?

Cylinder pressure analysis example

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

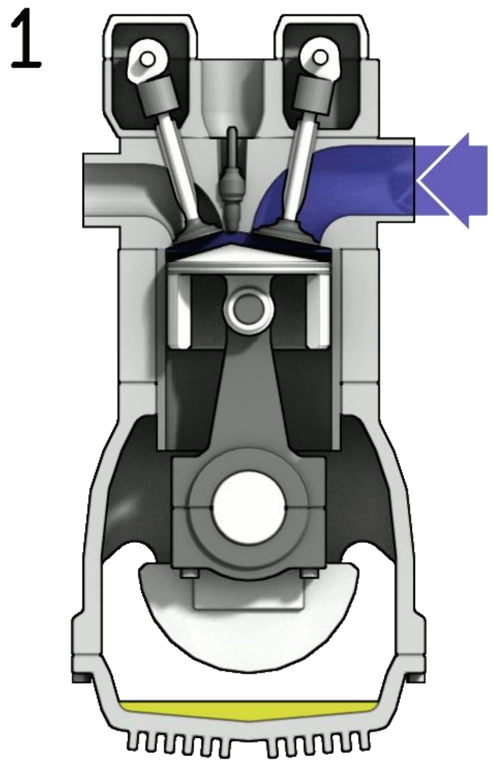


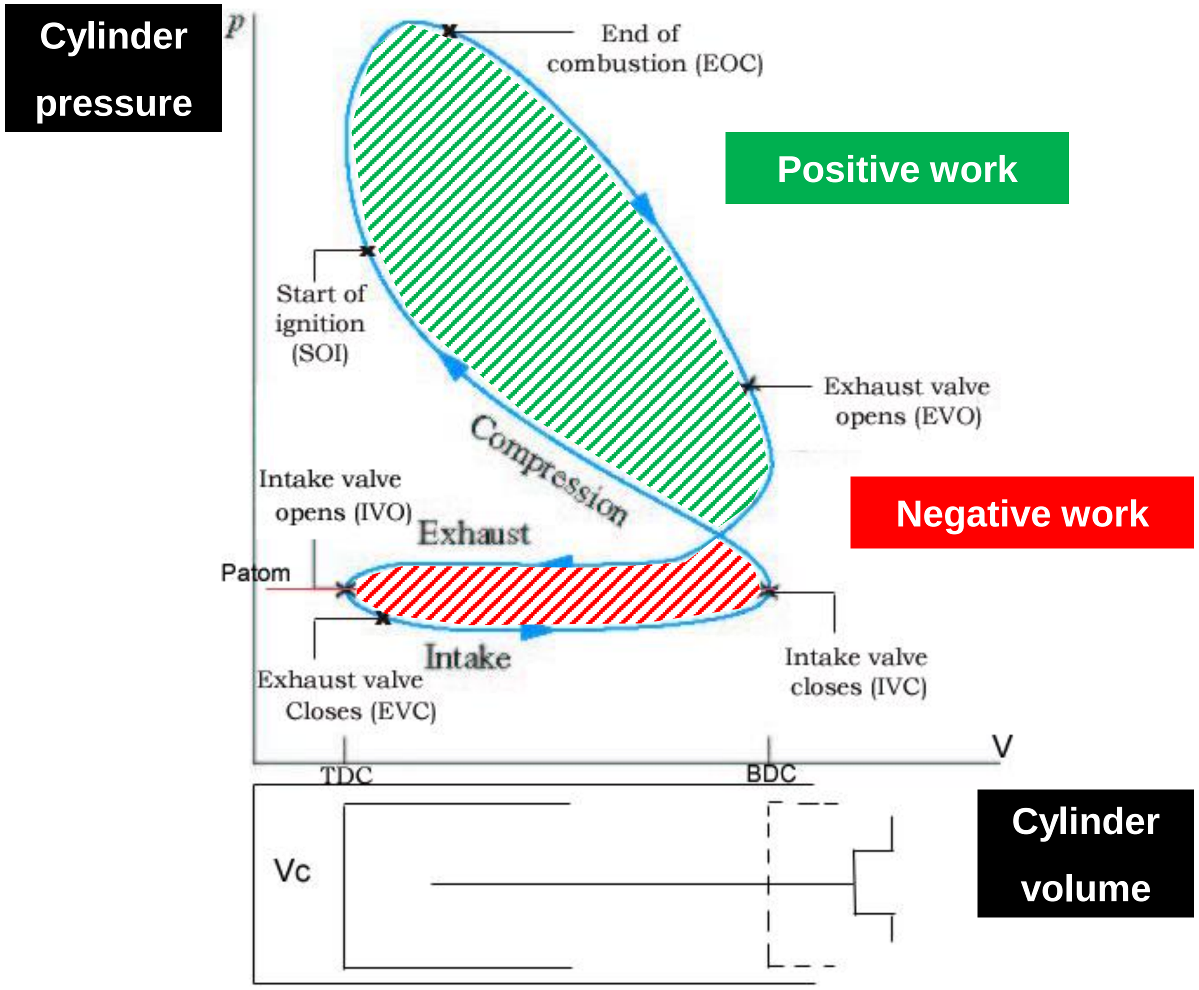
- **Offset compensation**
  - Align phenomena with fixed angle offset



What is combustion analysis?

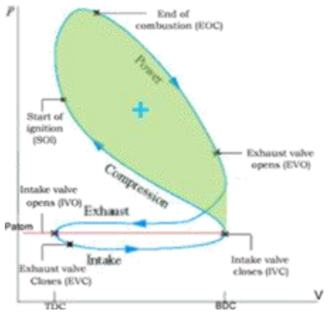
P-V diagram





What is combustion analysis?

Mean Effective Pressure – IMEP / PMEP / NMEP

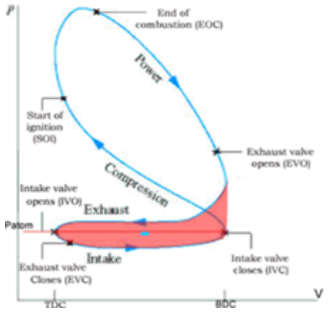


Indicated Mean Effective Pressure (IMEP)

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

$$IMEP = \frac{\Delta\alpha}{V_s}\sum_{n_{i1}}^{n_{i2}} p(i).\frac{dV(i)}{d\alpha}$$

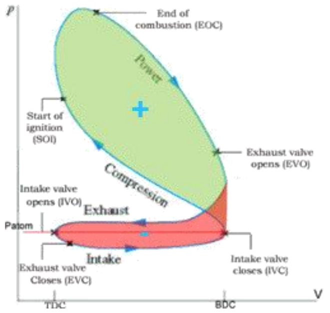
How much energy is my combustion delivering?



Pumping Mean Effective Pressure (PMEP)

$$PMEP = \frac{\Delta\alpha}{V_s}\sum_{n_{p1}}^{n_{p2}} p(i).\frac{dV(i)}{d\alpha}$$

How much energy is lost during operation?



Net Mean Effective Pressure (NMEP)

$$NMEP = \frac{\Delta\alpha}{V_s}\sum_{n_1}^{n_2} p(i).\frac{dV(i)}{d\alpha}$$

How efficient is my engine control strategy?

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Digital Transformation with a Holistic Digital Twin

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Ideation

Realization

Utilization

Simcenter Portfolio

Engineer innovation for rotating machinery performance

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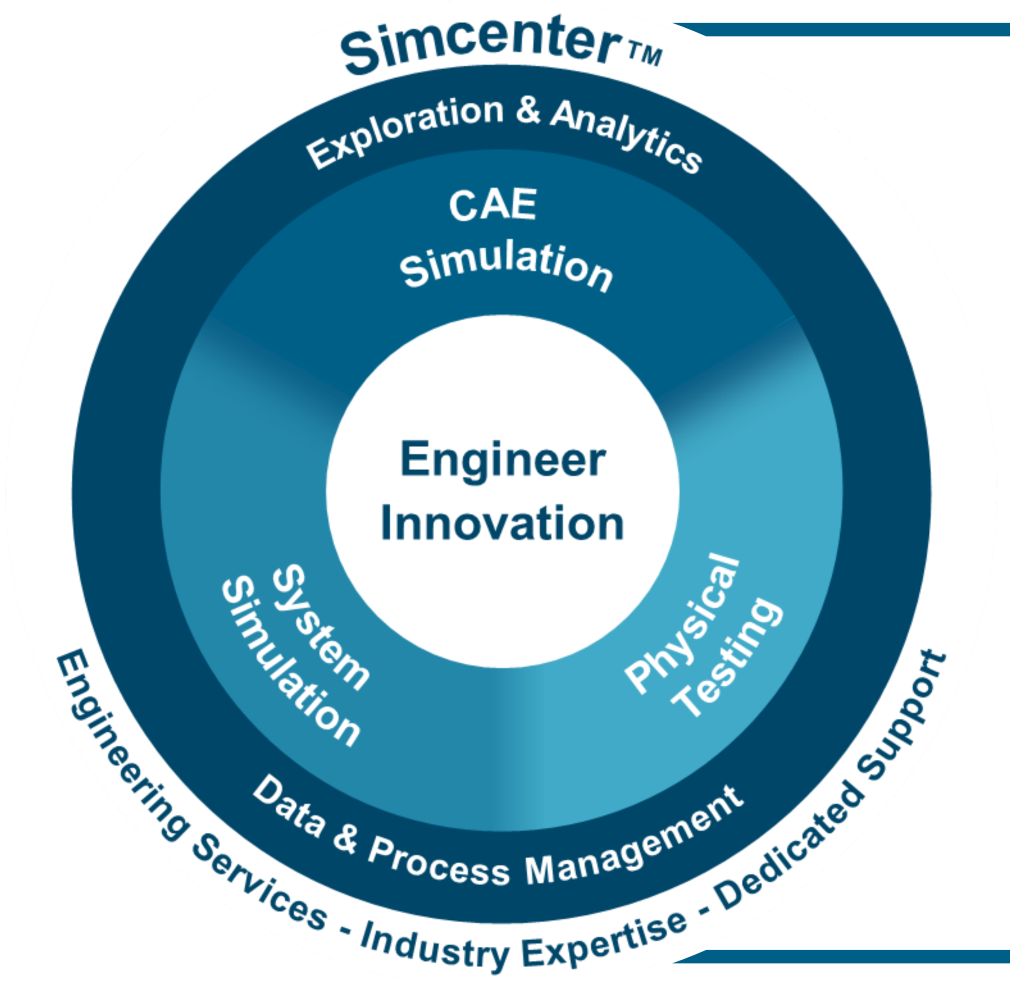

Simcenter™

Engineer innovation.

Simulate. Explore. Test.

Simcenter Portfolio

Engineer innovation for rotating machinery performance

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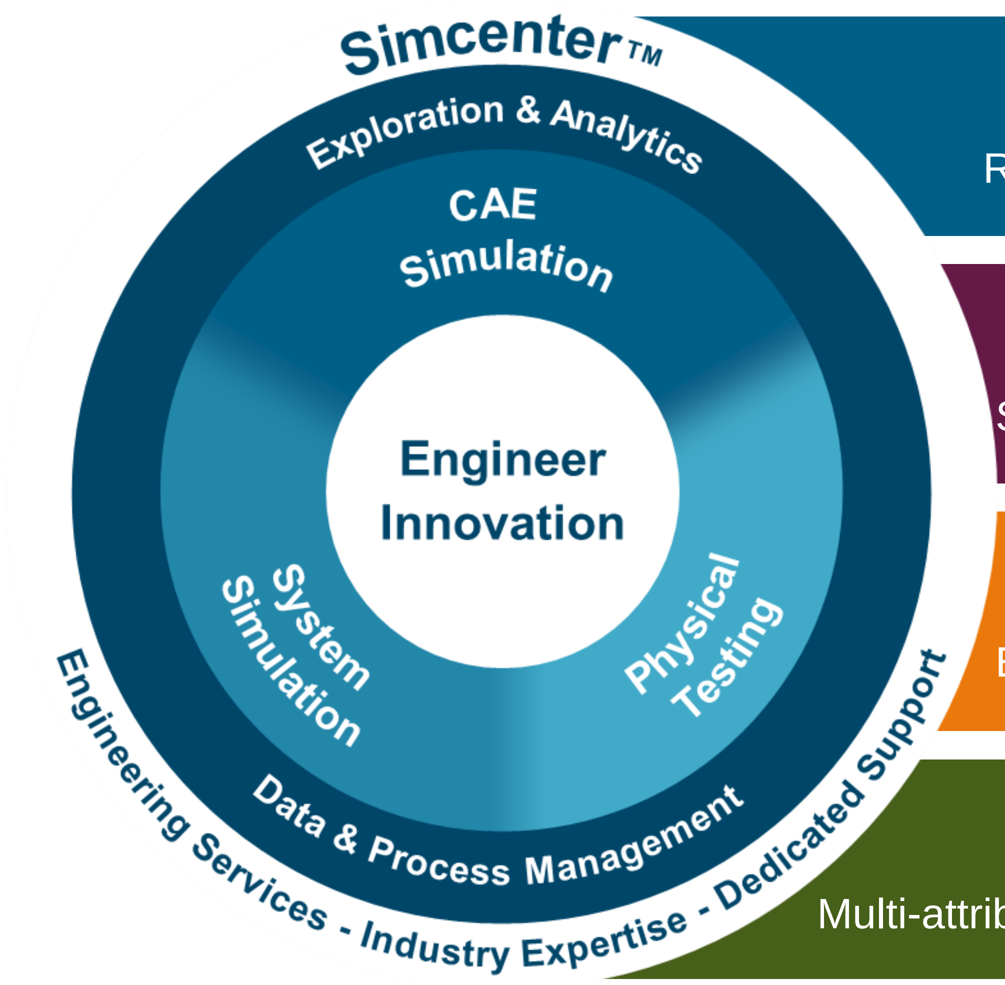


Noise & Vibration

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

Reliability

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

Performance

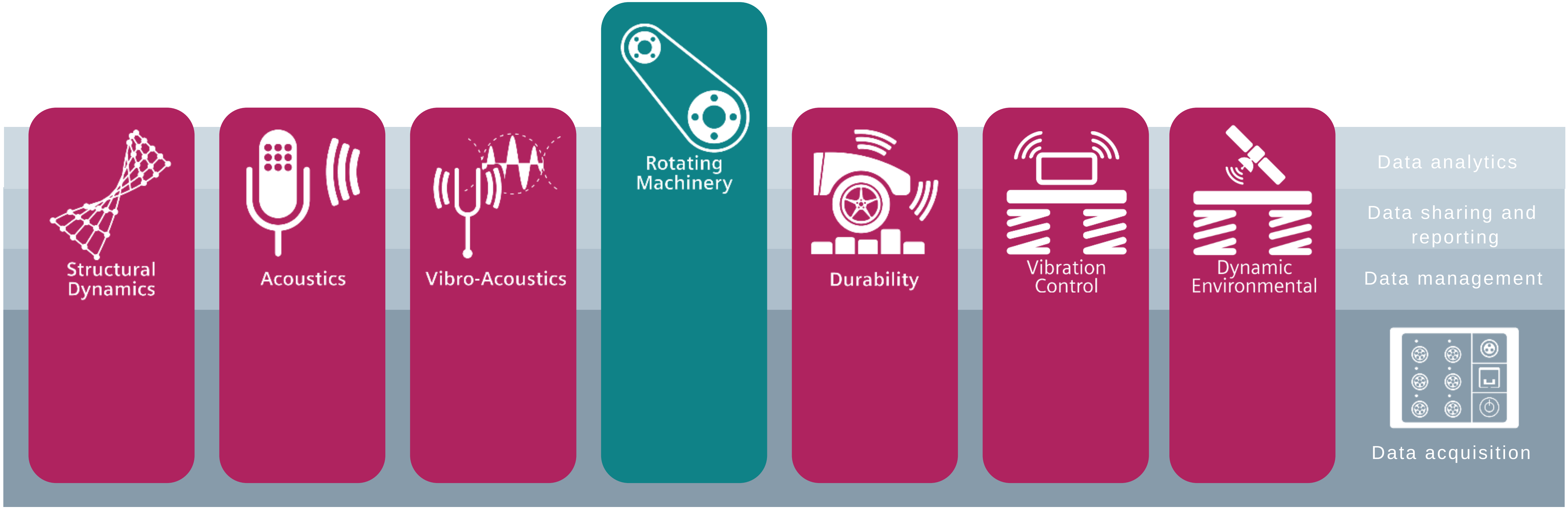
Efficiency, Controls, Flowrate, Torque Power, Power Conversion

Integration

Multi-attribute Balancing, Sizing, Troubleshooting, Data Management, IOT

Simcenter Testing Solutions

Single platform multi-physics applications portfolio



Rotating machinery

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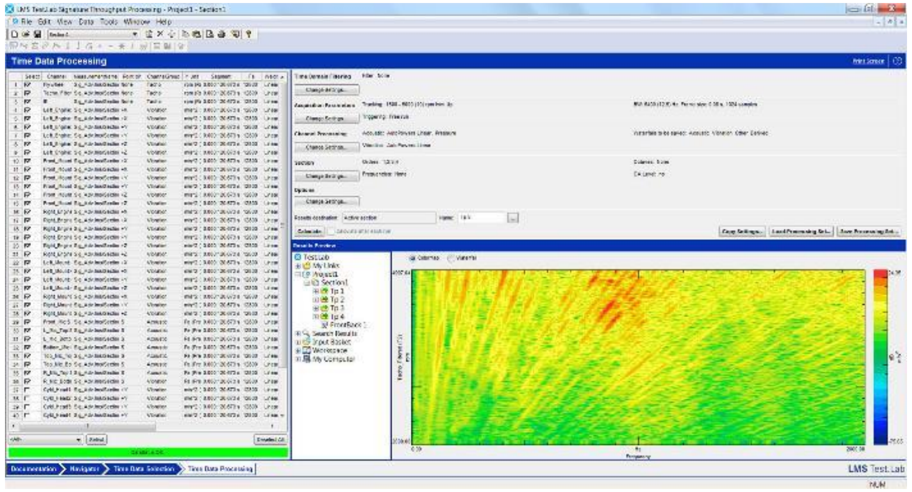
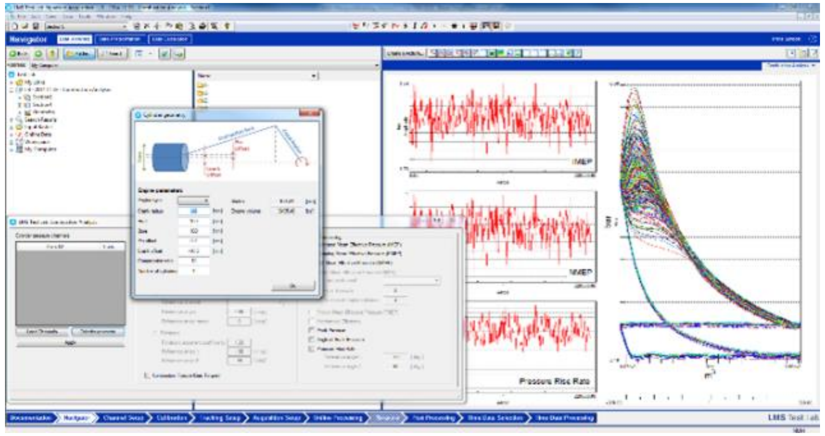
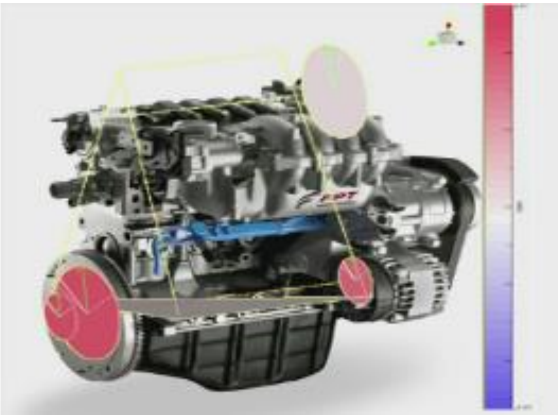


Time data acquisition and processing

Torsional vibration analysis





Order tracking

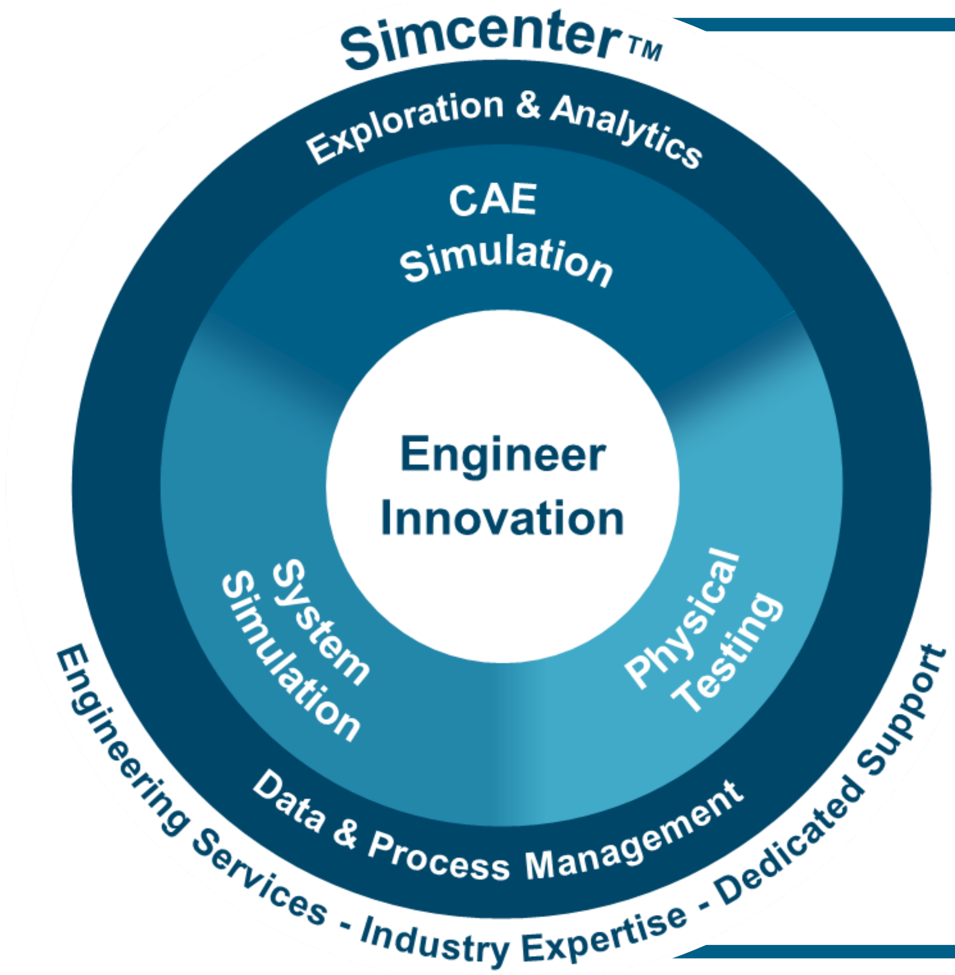
Signature testing

Turbine testing

Angle domain analysis

Simcenter Portfolio

Engineer innovation for rotating machinery performance



Test for Simulation

Validate Simulation models with real-life Tests

- Model validation & updating
- Model parameter identification
- Load identification
- Test data analysis expertise

Test with Simulation

Combined use of Test and Simulation

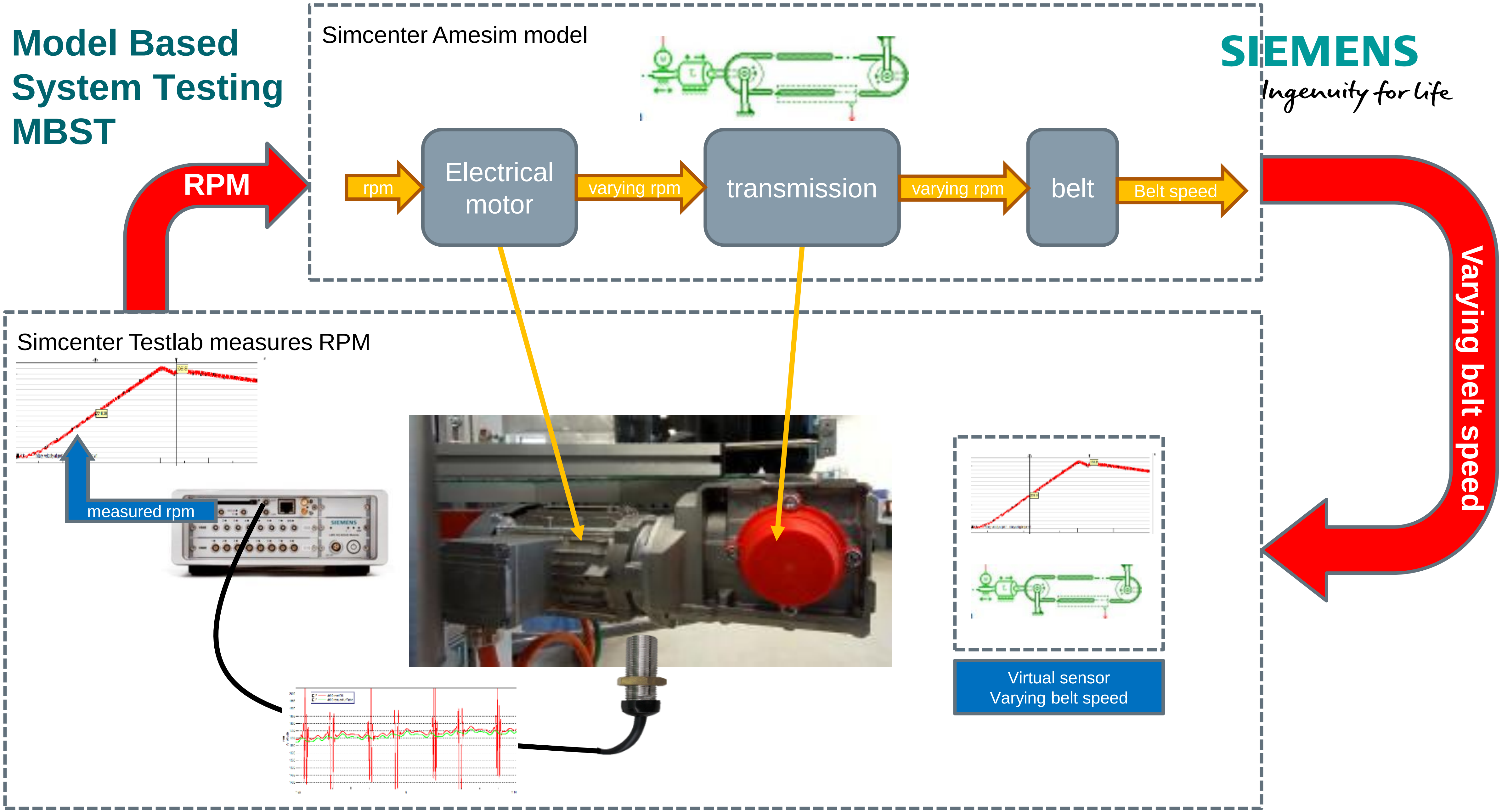
- Hardware-in-the-loop testing
- System-in-the-loop testing
- Human-in-the-loop testing
- Virtual sensing

Simulation for Test

Apply Simulation for more productive and realistic testing

- Virtual testing
- Optimal sensor/excitation

Model Based System Testing MBST



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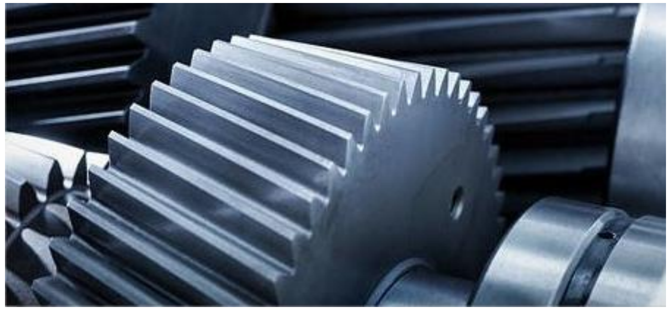
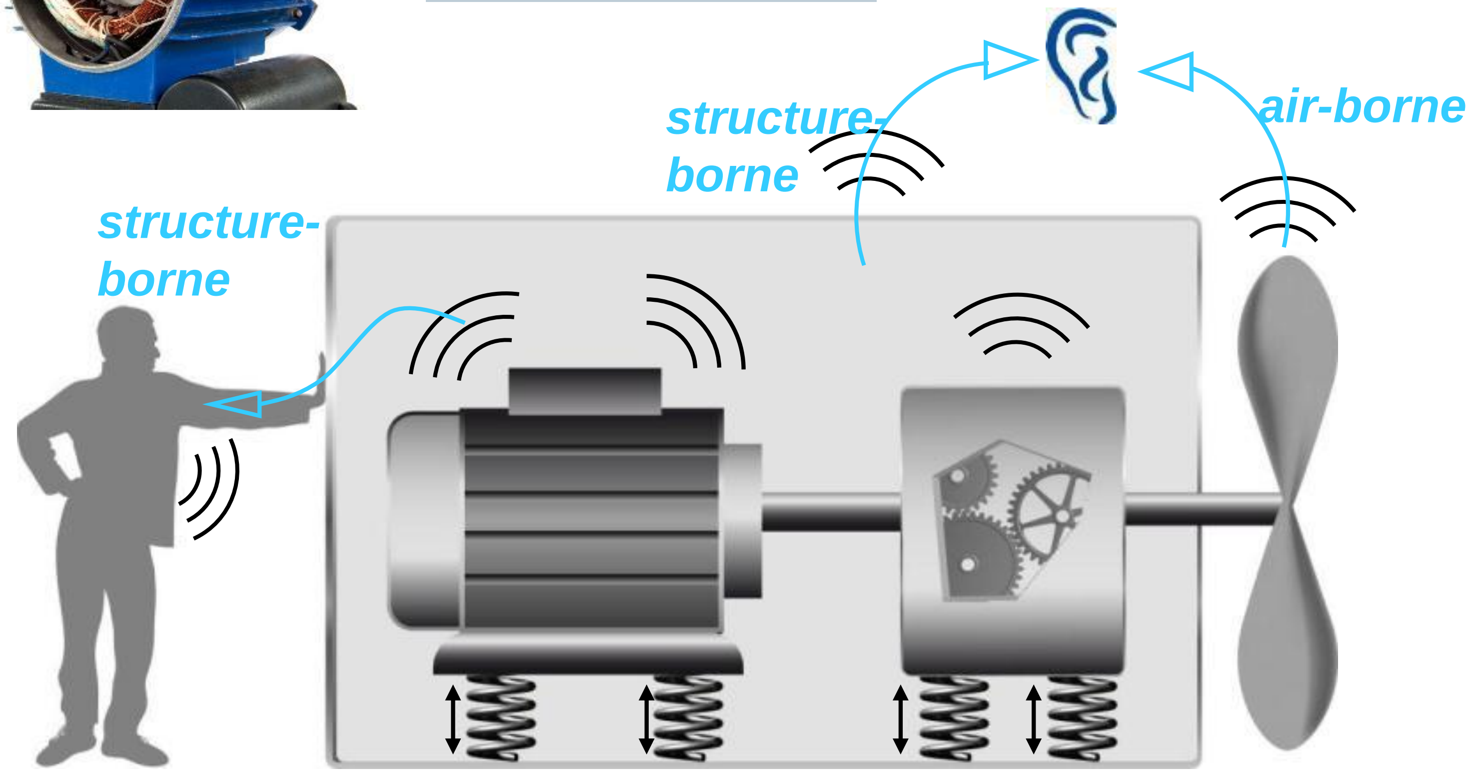
Noise, vibration and durability of machines
Why are rotating components “different”?



Rotation speed can change !



Industrial pumps

Signature testing - Vibration troubleshooting

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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

"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."

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

Bearings

Simcenter Testxpress analyzer – More efficient servicing @ end customer

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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

The Simcenter Testxpress software is so easy to use, customers are up and running within the hour.

Benefit

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

High precision gears

Simcenter Soundbrush – Objectively compare noise of different designs

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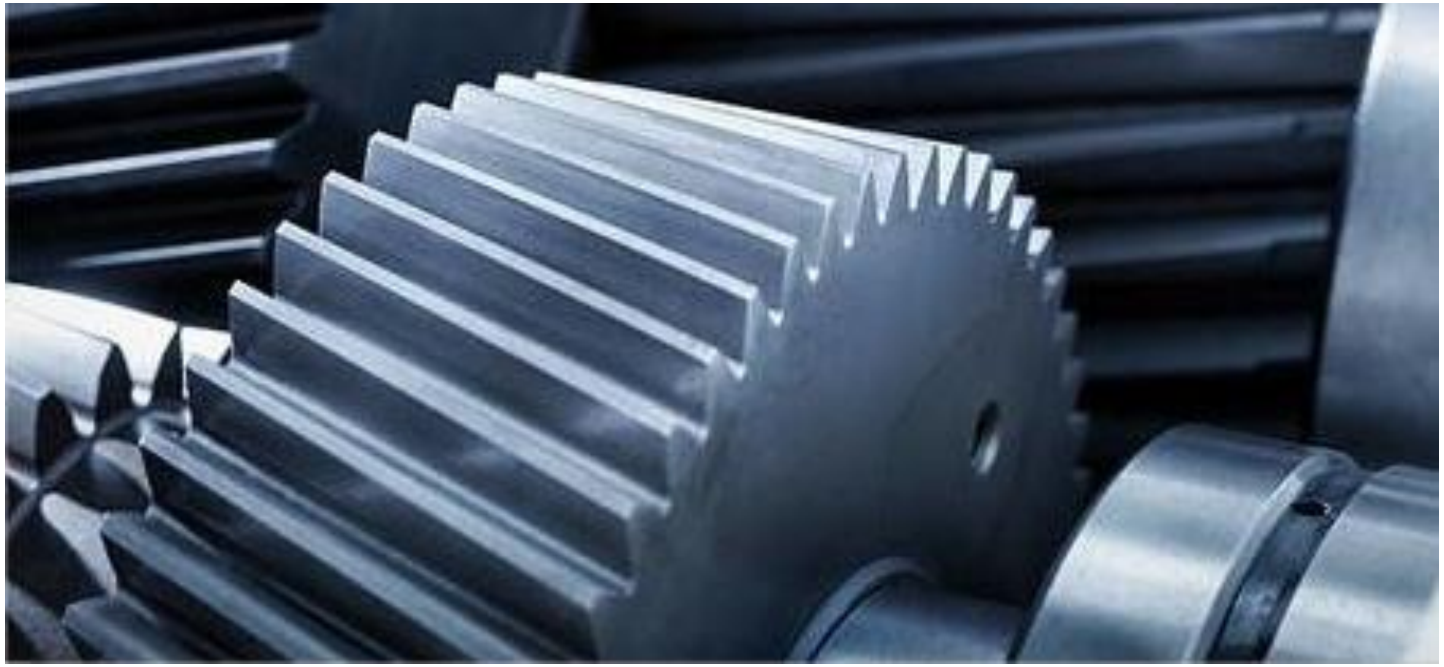

Challenge

- 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

The efficiency increase is incredible – using Simcenter Testlab Polymax, operational modal and batch reporting.

Benefit

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

Printing plate production machine

Simcenter SCADAS XS – Reduce time/cost for global servicing

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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

Thanks to the Simcenter SCADAS XS, a typical intervention went from 1 week down to only 2 days.

Benefit

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

Wood working machine

Modal analysis – Increase production speed + improve finishing quality

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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

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

Benefit

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

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Thank you.

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