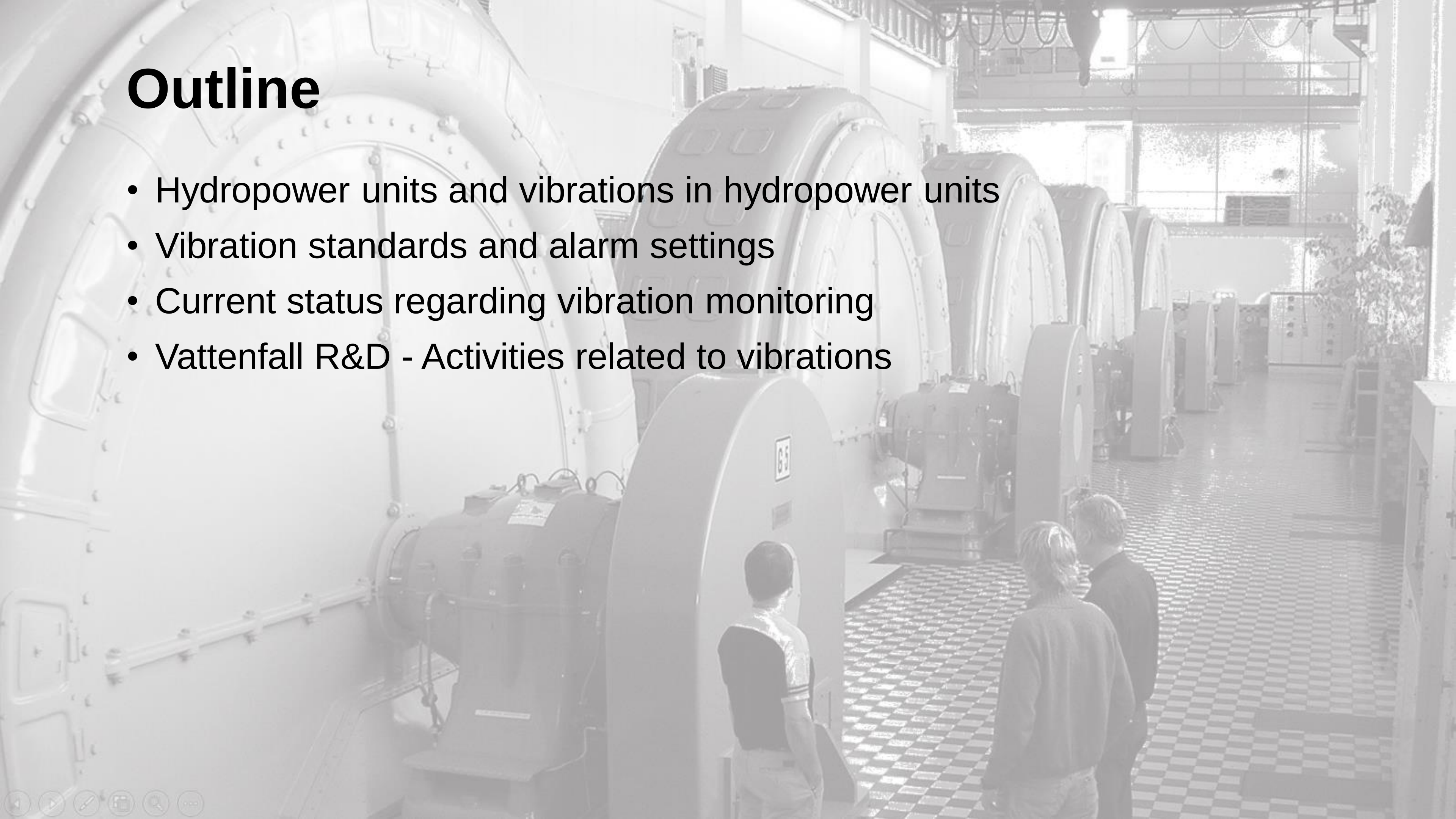
Vibration management in the hydropower industry

Vibrations in nuclear applications 2018

Mattias Nässelqvist, 2018-11-13

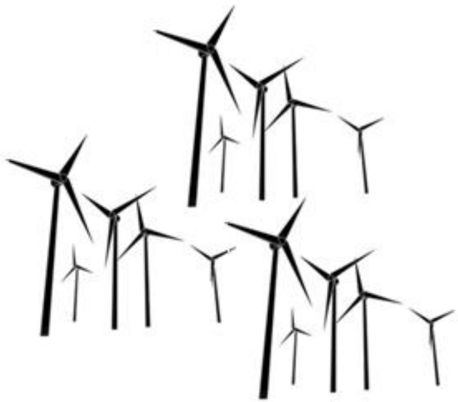
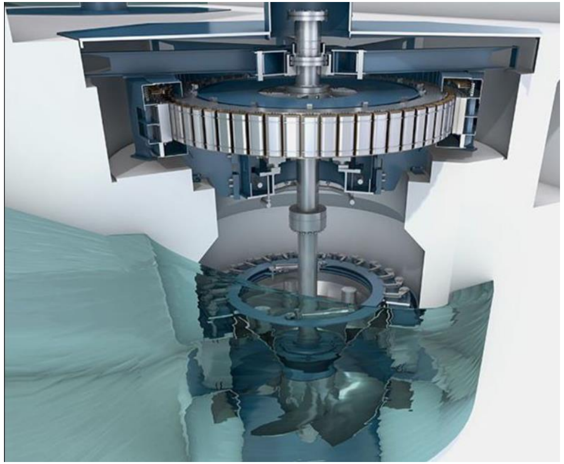
Outline

- Hydropower units and vibrations in hydropower units
- Vibration standards and alarm settings
- Current status regarding vibration monitoring
- Vattenfall R&D - Activities related to vibrations



Power generation within Vattenfall

Methods to identify maintenance needs and harmful vibration levels

Wind	Hydro	Nuclear
Statistics	← ? →	Extensive analysis and measurements
		
~ 1100 units	~ 130 units	~ 7 units
2-8 MW	10 – 500 MW	800 – 1200 MW
0 – 10 years	5 – 100 years	30 – 40 years
7.5 TWh/y (~3 GW)	36 TWh/y (~8 GW)	48 TWh/y (~7 GW)

(Power plants within BA Heat and pump storage are excluded)

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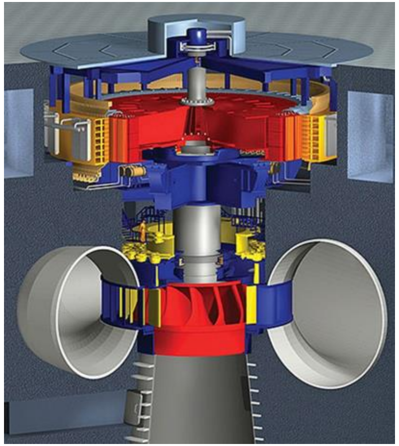
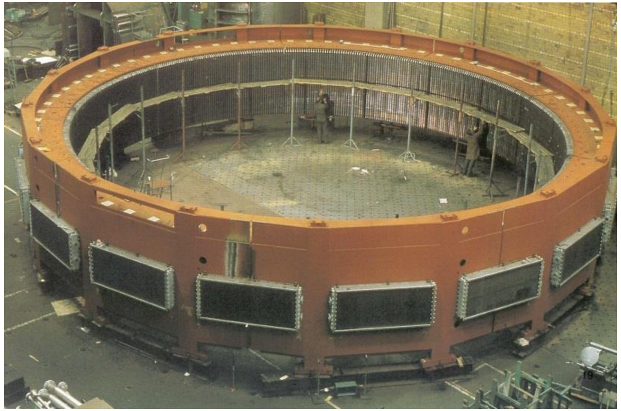
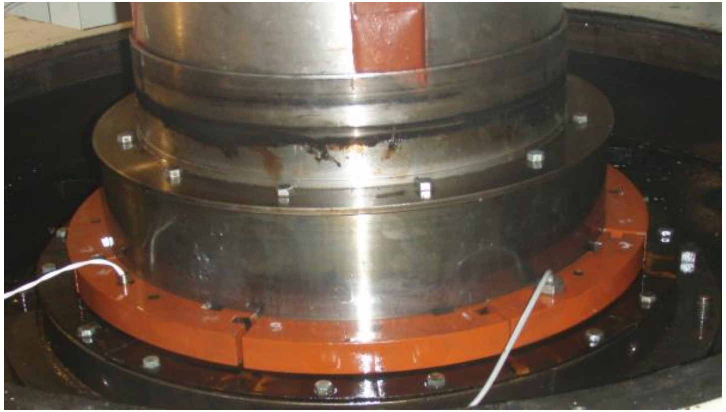
Hydropower units

- Almost all large hydropower units are vertical
- The guide bearing are hydrodynamic bearings
- The unis are designed for at least 40 years operation
- Three types of runners dominates the market: Kaplan, Francis and Pelton
- Hydropower units can be very large
- Rotor diameter up to 16 m, bearing clearance ~ 0.3 mm
- High UMP (typical value ~300 - 500 MN/m)

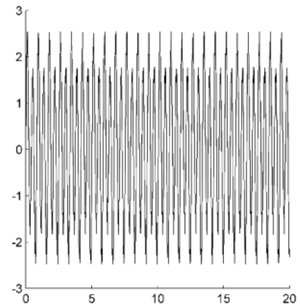


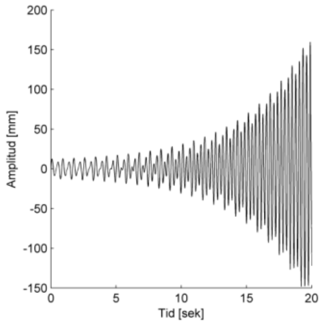




Vibrations in hydropower units

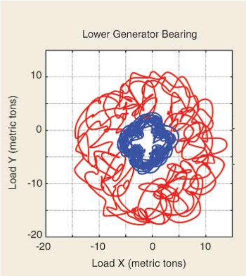
- Forced vibrations
  - The vibration frequency is the same as the frequency of the exciting force, the vibration amplitude depends on the amplitude of the exciting force and structure properties.
- Resonances
  - The vibration frequency is dependent of properties of the structure (both the rotating and stationary structure), the amplitude is increasing exponentially and the stability of the system determines the amplitude of the vibration.
  - When a forced vibration coincides with a natural frequency resonances with high vibration amplitudes occurs.
  - Examples of excitation sources are disturbances from the runner and shape deviations in the stator
- Bearing instabilities
  - Negative preload
  - Oil whirl

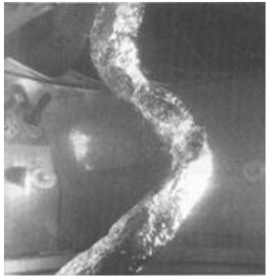




Examples of forced vibrations

- Mechanic unbalance
  - Symptom: Vibrations before and after magnetization, dominant frequency 1xΩ, (anisotropies causes vibrations at (1+n)xΩ). The vibration amplitude is determined from: $F = me\Omega^2$
- Electric unbalance
  - Stator eccentricity:
    - Symptom: Static displacement of shaft when generator is magnetized (often causes a decrease in shaft "vibration" since bearings becomes stiffer at higher static loads)
  - Rotor eccentricity:
    - Symptom: High vibration levels arise after magnetization, dominant frequency 1xΩ,
  - Shape deviations in rotor and stator:
    - Symptom : High vibration levels at multiples of synchronous speed after magnetization
- Flow induced vibrations
  - ”Vortex rope”
    - Symptom : 0.3 – 0.5 x Ω
  - Blade frequency
    - Symptom : Vibrations at the blade frequency

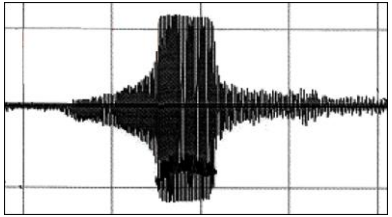




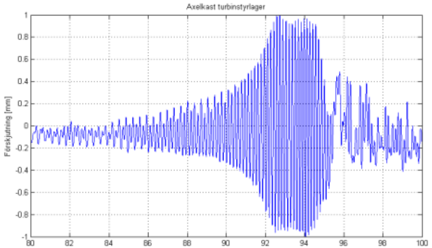
Flexible stators and rotors change shape at magnetization and affects the symptoms.

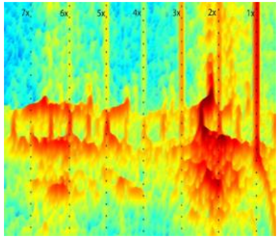
Examples– Resonances in hydropower units

- Problem 1xΩ_{dr}

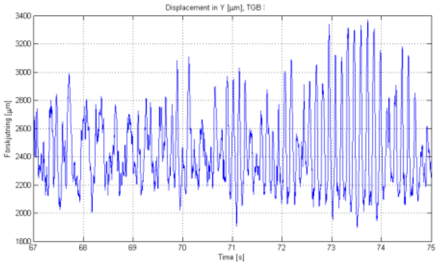


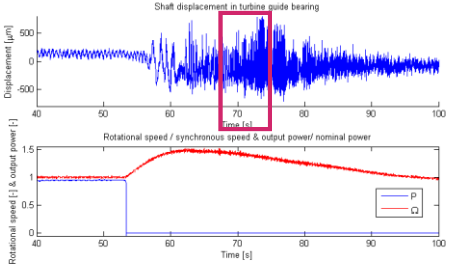
- Problem ~2xΩ_{dr}





- Problem ~7Hz





Vibration standards and alarm settings

- "Optimized" mechanical designs of new hydropower units requires normal vibration levels
- Vibration problems increased due to changed operation modes for hydropower units: base load → load regulation
  - Operation outside "optimal efficiency point"
  - Increased regulation of runner and guide vane
  - Increased number of starts and stops
- Current vibration standards are difficult to apply on existing hydropower units (exist no standardized methodology regarding Alarm and Trip settings in hydropower units)
- Vattenfall R&D have studied hydropower units dynamic behavior over several years
- Our "philosophy" is to use physical relationships instead of statistical data to determine the allowable vibration levels

Examples of our publications:

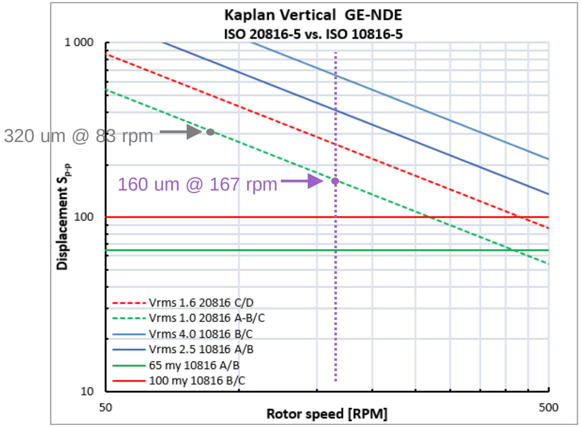
- *A Methodology for Protective Vibration Monitoring of Hydropower Units Based on the Mechanical Properties*. Journal of Dynamic Systems, Measurement *and Control*
- *Bearing load measurement in hydropower unit using cylindrical strain gauges installed inside pivot pin.* Experimental Mechanics.
- *Vibration Analysis – Force and Vibration Relationship.* CEATI Report
- *Vibration and Alarm Settings for Hydro Machines with Hydrodynamic Guide Bearings.* CEATI Report
- *Radial Dampers Impact on Shaft Vibration at Resonance*, IAHR

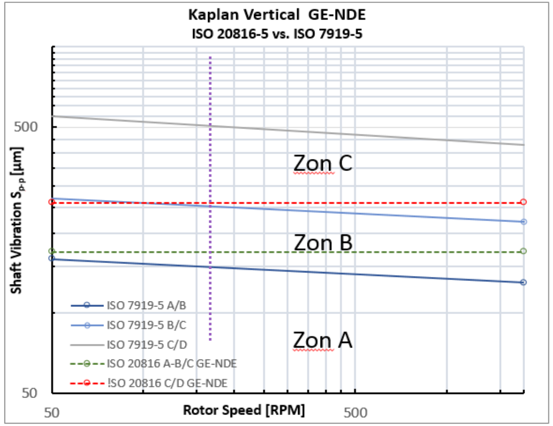
Standards – Vibrations and balancing

Vibration standards for hydropower units exists and hydropower units are (in general) equipped with some kind of vibration monitoring equipment.

- Existing standards
  - ISO – 7919-5: Evaluation of machine vibration by measurements on rotating shafts - Machine sets in hydraulic power generating and pumping plants
  - ISO – 10816-5: Evaluation of machine vibration by measurements on non-rotating parts - Machine sets in hydraulic power generating and pumping plants
  - ISO – 1940-1: Balance quality requirements for rotors in a constant (rigid) state

New ISO 20816-5

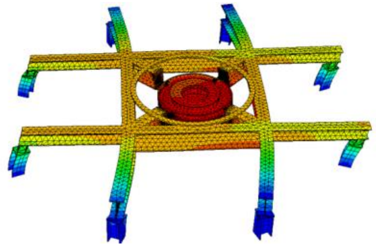


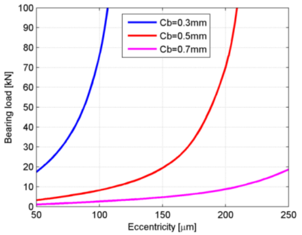


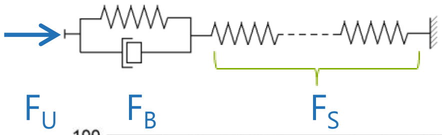
Radial forces

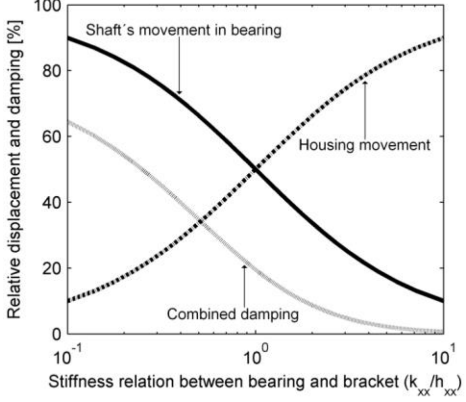
Limit radial displacement, maximize damping

- Unbalance force, $F_U = me\Omega^2$
- If electromechanical and hydraulic forces are neglected the following relation applies regarding shaft displacement (ε)
- $F_B = F_U = K_B\varepsilon + C_B\varepsilon' + M_B\varepsilon'' \approx K_B\varepsilon + C_B\varepsilon'$
- These forces also propagates through to the support structure according to the following relation:
- $F_S = F_U = K_s u$, where u is the bearing housing displacement and the vibration velocity of the housing is u'
- If the support structure is flexible in relation to the bearing stiffness the combined damping will be low (the displacements will primary occur in the support structure)









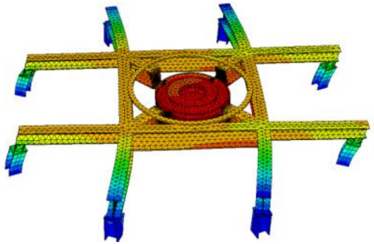
Example ISO 20816-5 / ISO 1940-1

Generator - Comparison between standards regarding radial loads

Example data: Ω_0= 167 rpm, m_R = 200 ton,

Stiffness support structure: k_U = 2E8 N/m, k_L = 3.6E9 N/m

C_b = 0.5 mm (same properties for both bearings)

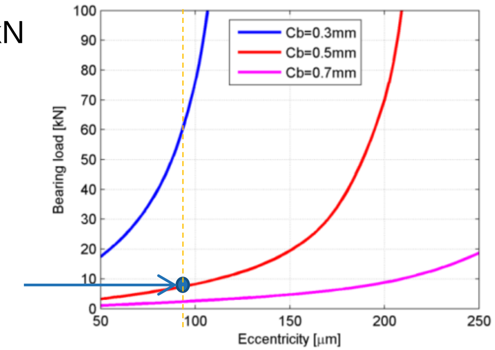


Shaft displacement- Force to reach zone C in ISO-20186-5:

~ 9 kN according to the figure

(if C_b is 0.2 mm approx. 1000 kN is needed to reach zone C)

1 - 1000 kN



Housing vibration - Force to reach zone C in ISO-20816-5 (10816-5) :

Upper bearing:

Limit 170/2 (100/2) µm gives $f_U=k_U$*85E-6 =17 (10) kN

Lower bearing:

Limit 100/2 (50/2) µm gives $f_L=k_L$*50E-6 = 180 (90) kN

200 kN

Maximum allowed bearing load according to ISO-1940:

22 kN/2 = 11 kN

Max UMP-forces (NGTR requirement):

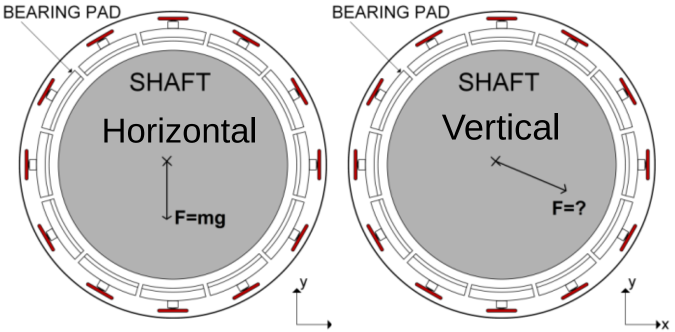
5%*25*3E5/2 = 45/2 kN = 23 kN

~35 kN

Rotor mass [kg]	Rotor speed [rpm]	Unbalance force G6.3 [kN]	Balancing radius [m]	Unbalance mass [kg]	Residual unbalance [kg·m]
200000	167	22	4,5	16	72
500000	83	27	7	52	363
100000	500	33	1,5	8	12

Challenges regarding alarm settings

- Why is it difficult to identify alarm settings for large vertical machines with hydrodynamic journal bearings?
  - Almost all units are “unique”
  - Vertical machines does not have a predefined load/position in the bearing
  - The stiffness of a hydrodynamic guide bearing is non linear and depends on the eccentricity/bearing load
    - Bearing loads/shaft displacements are caused by:
      - Mechanical unbalance
      - Unbalance magnetic pull force
      - Flow properties in turbine/impeller
      - Alignment etc.

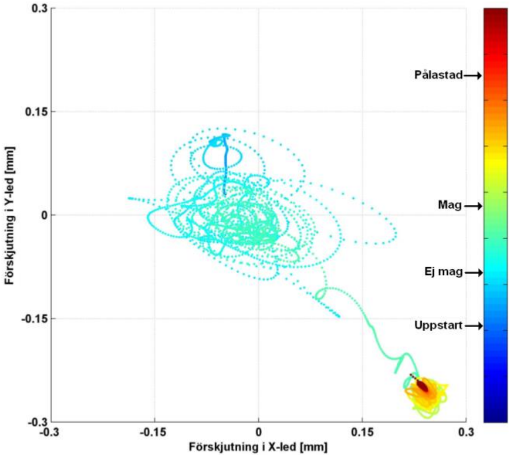


  - Bearing housing vibrations does not consider static loads
  - These challenges applies both hydropower units and large pumps

Static and dynamic displacements/forces

Important to monitor both static and dynamic shaft displacements, especially in large hydropower units.

- Static displacements/loads can be caused by:
  - Shape deviation in generator due to sliding stator feet and floating rotor rim
    - High radial magnetic pull forces (300 – 500 kN/mm)
  - Low stiffness of the bearings support structures
  - Turbulent flow conditions in runner



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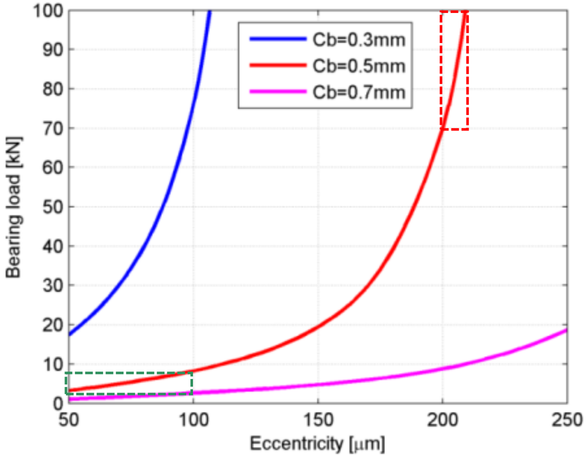


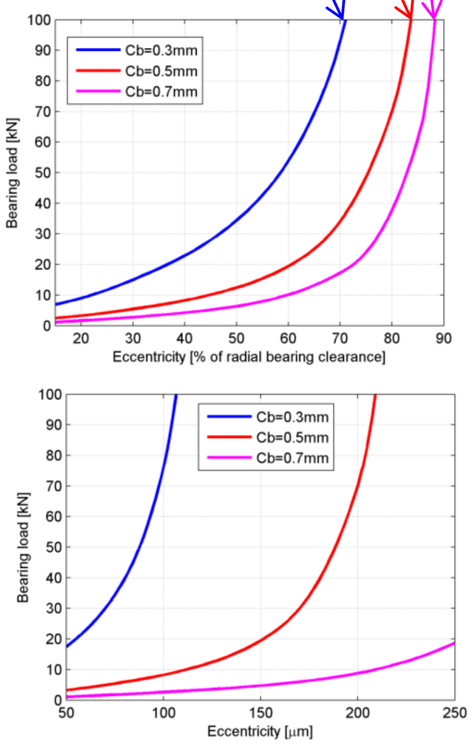
“Default settings” for vibration monitoring system

Recommendations regarding acceptable shaft displacements is not possible to give if present bearing clearance is unknown

- Alternative I: Determine present bearing clearance and allow shaft displacement up to 70-80% of present bearing clearance (only for tilting pad bearings)
    - 70% at small clearance (radial clearance ≤ 0.15 mm)
    - 80% at large clearance (radial clearance ≥ 0.25 mm)
    - 75% vid normal bearing clearance
- Alternative II: Measure distance between shaft and bearing surface: alarm ~70 µm, trip ~40µm

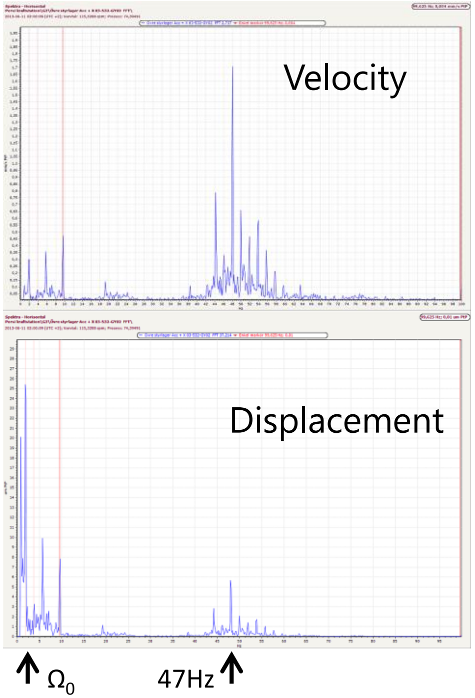
It is difficult to monitor distance between shaft and bearing surface since thermal changes influence support structure, sensors and bearing clearance.

- Alternative III: Measure bearing housing displacements, determine support structure stiffness and determine displacements at 100 kN (alarm) and 200 kN (trip) (these values are valid for hydropower units of average size)



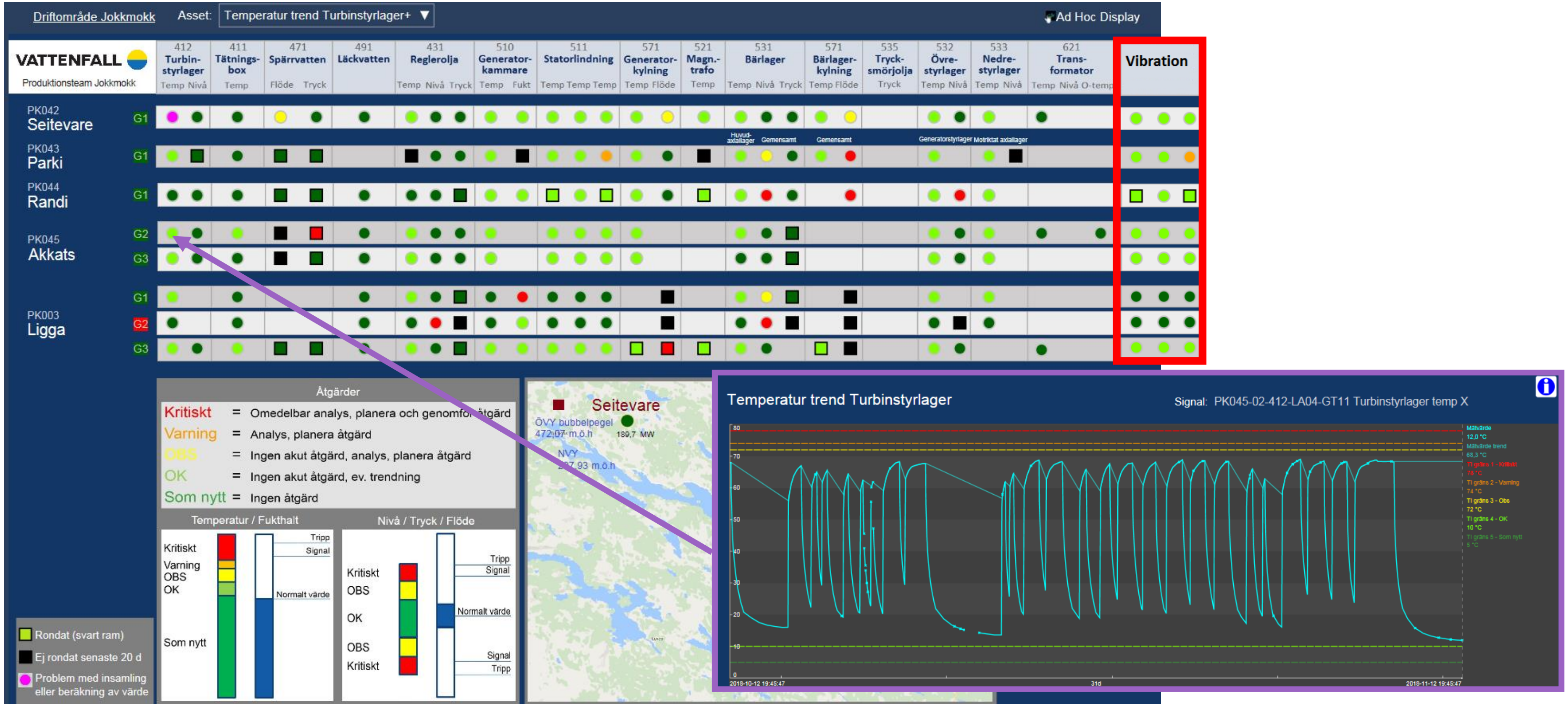
Current status regarding vibration monitoring

- Two suppliers (Damill and SKF) to limit variation in systems across rivers
- System and sensor setup depends of unit calcification (A+, A, B or C)
  - A+: 4 displacement sensors each bearing, 2 accelerometers, high resolution data
  - C: 1 accelerometer at each bearing, 1 Hz rms-value (rms of 0.5-10Hz, 10 sec)
- It is important to know what the system measures
  - Acceleration, displacement velocity or displacement
    - p-2-p, p, Smax
    - RMS (frequency range and time, 0.5-10 Hz)
  - Filtering
  - Type of sensors (velocity/displacement, accuracy of sensors, frequency range, thermal stability of sensor, installation etc.)
  - Presentation
    - FFT (frequencies, windowing)
- Ongoing activity to visualize vibration status in OSI PI



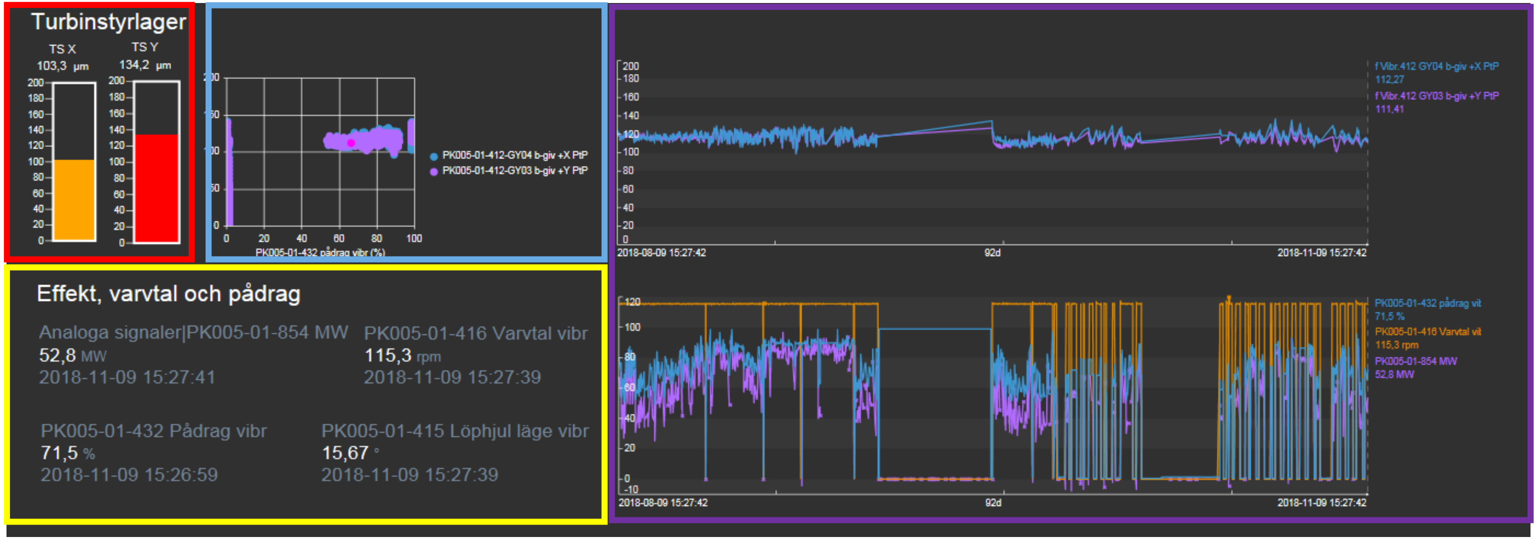
OSI PI

All large scale hydropower units are connected to OSI PI (> 30.000 sensors)



Visualization of vibration status

Ongoing development regarding vibration visualization (independent of supplier)



Red box – Present shaft displacement (X and Y direction)
Yellow box – Present ”production” properties
Blue box – Shaft displacement as a function of guide vane opening
Purple box – Shaft displacement for the last 3 month (at “stable” operation)

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VRD - Activities related to vibrations

Measurements at commissioning of refurbished units

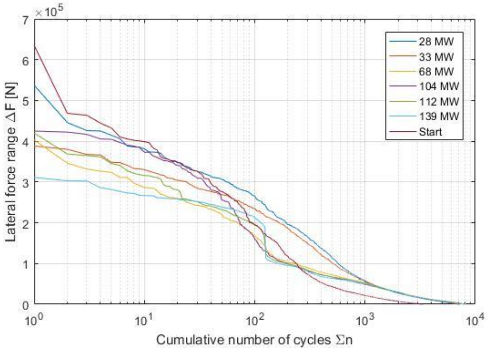
Problem solving (measurement and analysis)

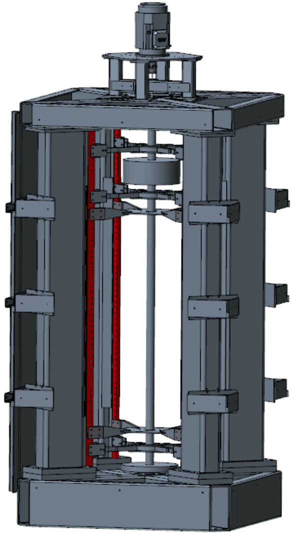
Identification of load spectra

- Analysis and measurement on site (displacements and strains in rotating structure)
- Modification of turbine test facility to enable transient turbine tests

Excitation and damping

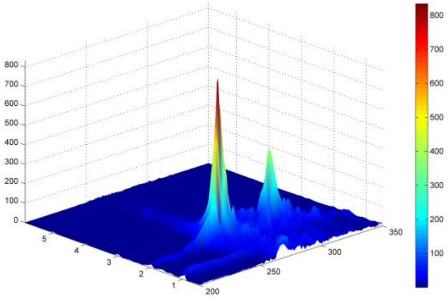
- Identification of excitation characteristics from model tests and site measurments
- New rotordynamic test rig to identify/evaluate methods to increase damping in hydropower units

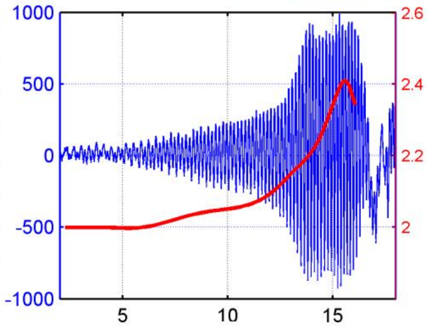


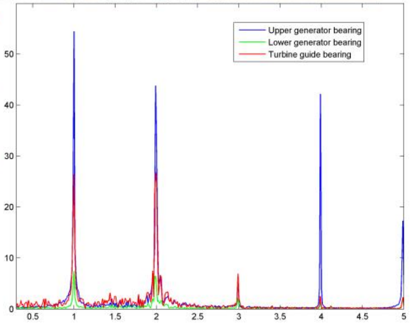


Thank you!

Questions?







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