The crux in problem finding:

Method & example from root cause investigation

Claes Fredö

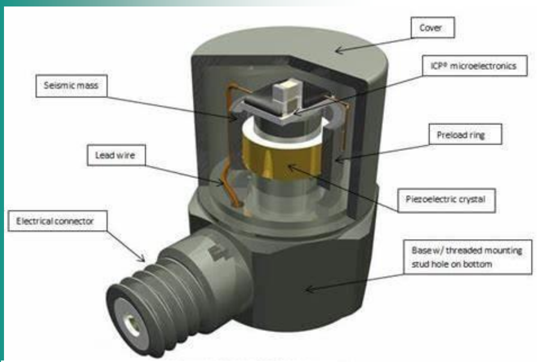
An approach that completes, not competes with condition monitoring

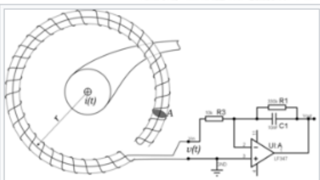
Topics

- Observability
  - Transducers
    - Rogowskiscoil
    - Accelerometer
    - Torsionlaser
  - Measure
    - Long time
    - Controlled
- Practice
  - Measure, how? – philosophy & Canary birds
- Physics
  - DC to MHz
  - Electromagnetic waves & potential
  - Rotordynamic
  - Aero acoustics
- Example – 1.7 MW flue gas fan

Transducers

- Accelerometer
  - Measures vibration from inertial load on piezoelektric cell in transducer.
  - Measures amplitude correct upp to ~1/3 of its internal mass-spring resonance frequency.
  - ICP accelerometers have built in electronics that can be *effected*.
  - Transducers differ in sensitivity to external *disturbance*.
- Rogowskiscoil
  - Flexible core that encircles the wire and provides an output proportional to dI/dt, ie the electric current time derivative.
  - An integrator circuit provides a phase accurate AC current signal output.
  - Typical range is from a few Hz to a number of kHz. Versions that measure up to MHz are available.
- Torsionlaser
  - Two laser beams are reflected by special tape on the shaft to provide a signal proportional to the AC rotation velocity, ie the shaft rotation speed variation.





A Rogowski coil is a toroid of wire used to measure an alternating current $I(t)$ through a cable encircled by the toroid. The picture shows a Rogowski coil encircling a current-carrying cable. The output of the coil, $v(t)$, is connected to a lossy integrator circuit to obtain a voltage $V_{out}(t)$ that is proportional to $I(t)$.

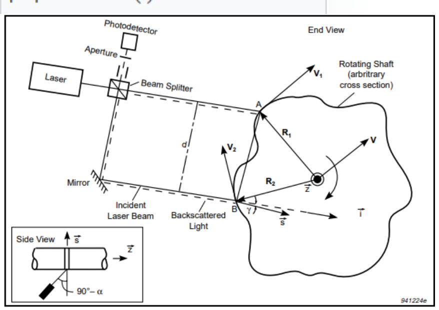


Fig 1 Optical geometry of the Torsional Vibration Meter Type 2523

Philosophy

Law of the instrument:

"I suppose it is tempting, if the only tool you have is a hammer, to treat everything as if it were a nail."

Abraham Maslow

Instrument whatever is relevant for the problem at hand.

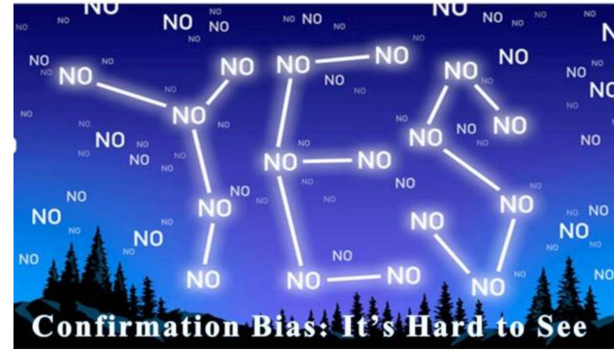
"If the result confirms the hypothesis, then you've made a measurement. If the result is contrary to the hypothesis, then you've made a discovery"

Enrico Fermi

Strange measurement data may contain the key to solving the riddle.

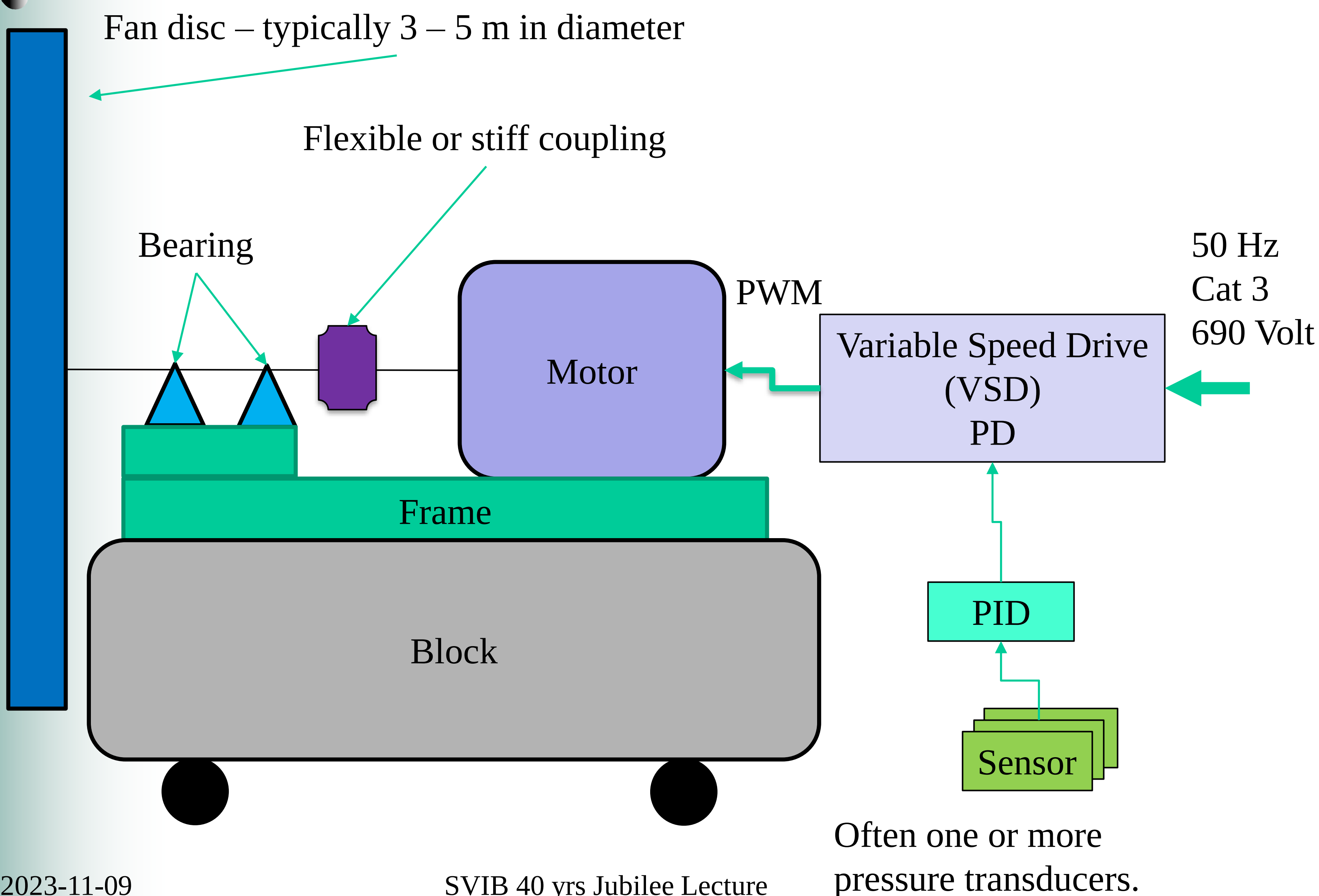
Do not shy away from such data.

Confirmation Bias



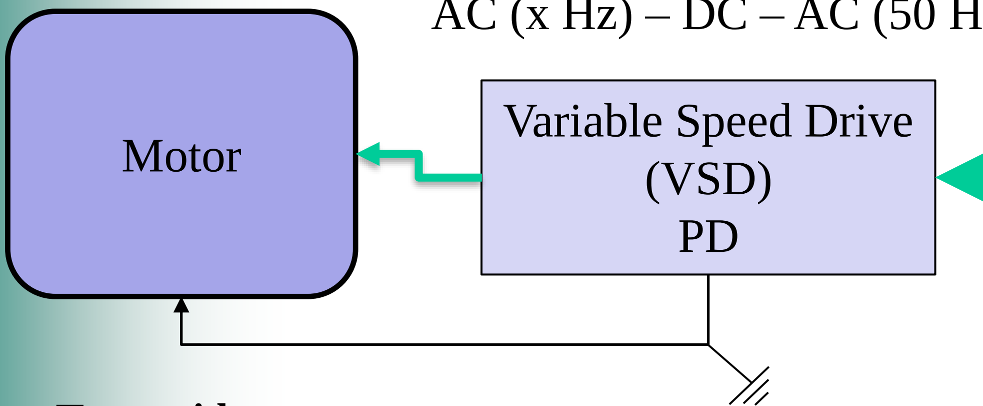
- To capture the unknown
  – Use different kinds of sensors to improve observability.
  - Transducers of different type and manufactury, eg accelerometers, laser vibrometer, proximiter, etc.
- Collect & structure DATA
  - Log data 24/7 – measure it all – also to be able to exclude.
  - Automatic processing to handle large amounts of data
- Structured analysis process
  - Start with an overview (helicoptervy)
  - Do not dive into data without first formulating a theory, i.e a way of reasoning that can be falsified (proven wrong).
- Hug & squeeze *'errors'* for information
  - Ascertain that the transducer is in a working condition.
  - Next, ***explain why***, it may behave erroneously – such insights might solve the problem – ***cherish your Canary birds***

Flue Gas Fan with Variable Speed Drive



Pulse Width Modulation (PWM)

AC (x Hz) – DC – AC (50 Hz)



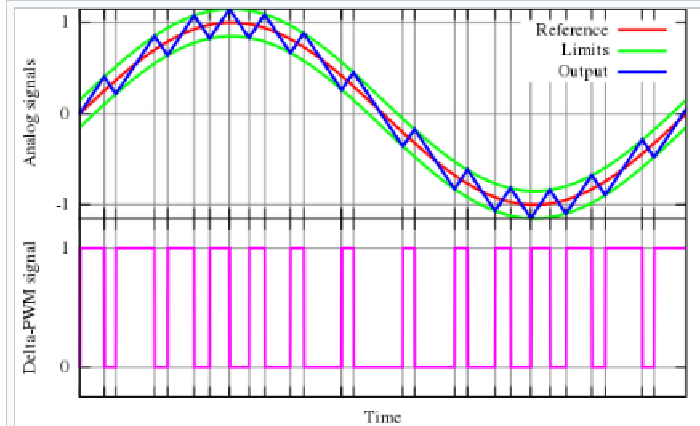


Fig. 3 : Principle of the delta PWM. The output signal (blue) is compared with the limits (green). These limits correspond to the reference signal (red), offset by a given value. Every time the output signal (blue) reaches one of the limits, the PWM signal changes state.

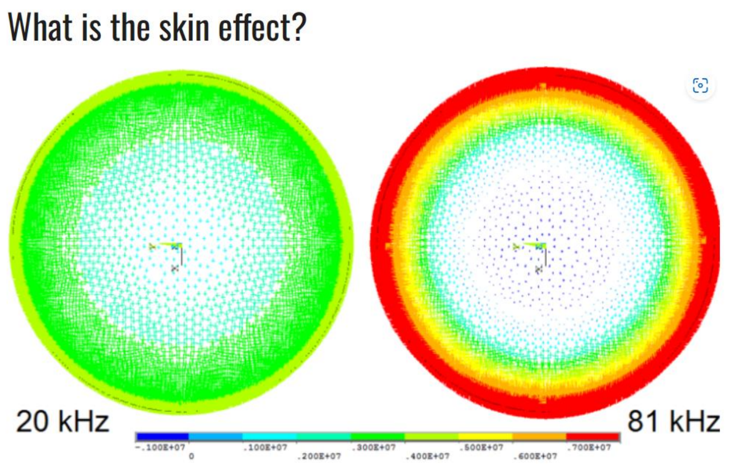
To consider

- Electromagnetic resonance
  - The electromagntic wavespeed in 3E8 m/s in vacuum, in a cable ~80%-50%. The rectangular pulse rise time excite up to ~5 MHz.
  - First cable resonance i.e cable is a quarter wave length => L = 1.5E8/5E6/4 = ~10 m
  - Long cables may increase the motor/cable peak voltage ~5x if pulses are not filtered.
- Electric potential
  - Skin effect
  - EDM (Electro Discharge Machining)
- VSD software
  - Motor model
  - S-ramp or Linear (Z-) ramp?

Electric potential

A thick conductor concentrates
the current density to its surface
which increases its effective resistance.

Therefore, we use for grounding,
cable, harness (drain wire) & a thin screen.

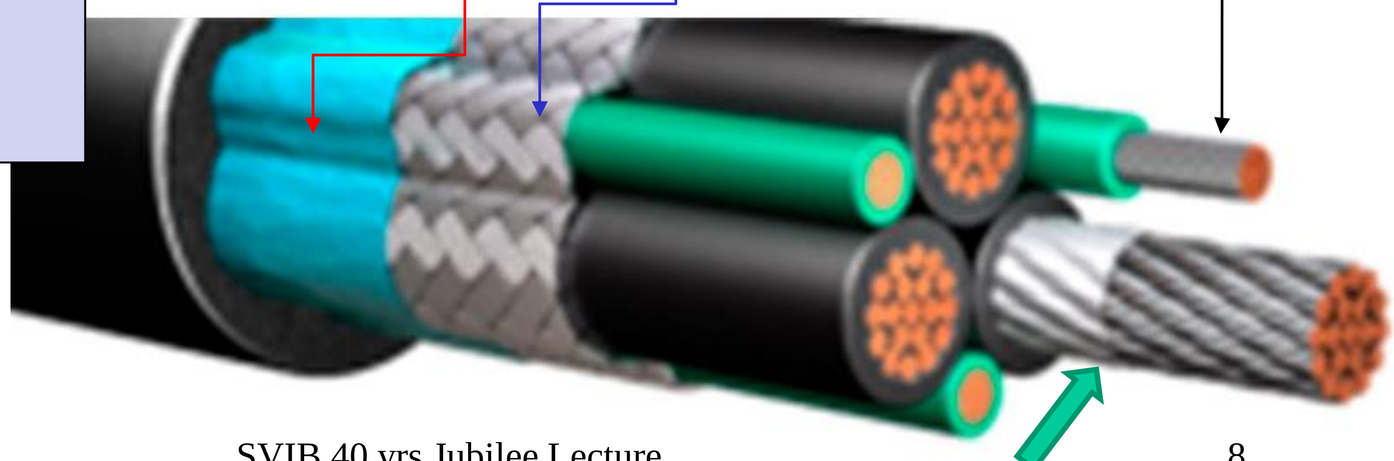


Grounding & EMF shielding

- 50 Hz cable
- Mid freguency harness
- High Frequency screen

Use of VSD demands

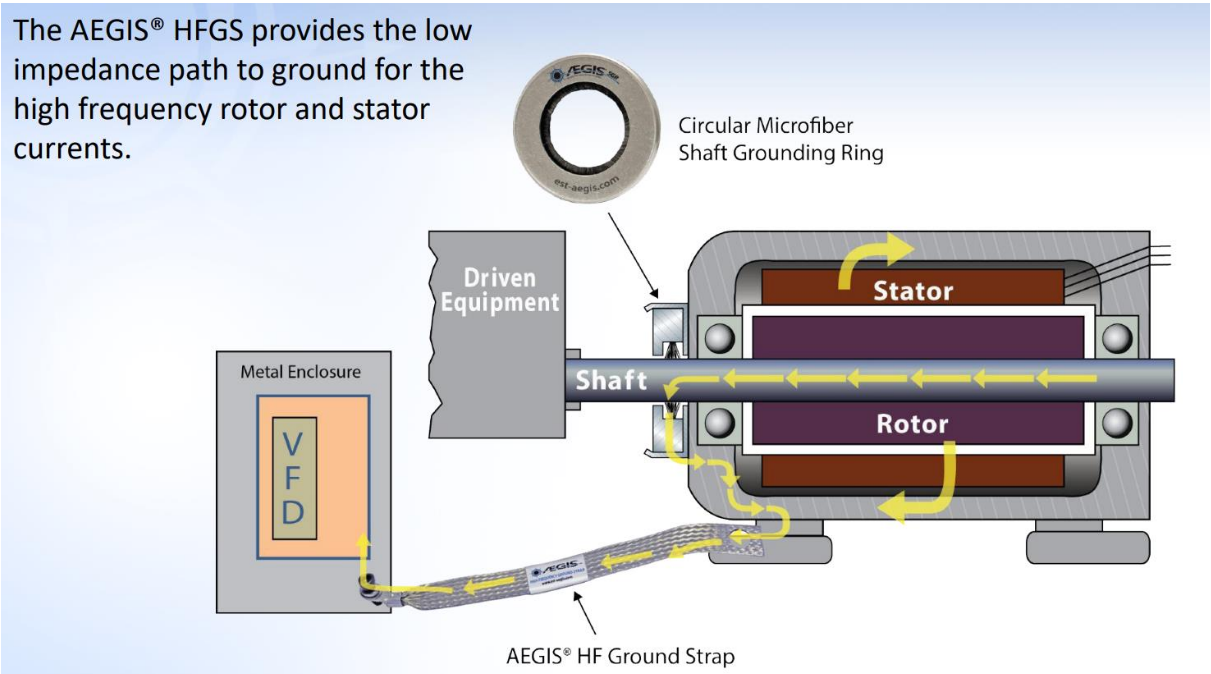
- Motors with improved electric isolation.
- VSD Cable.



Thin wires + screen

Motor + Consumer

The **skin effect** causes the potential to vary across the machine.
⇒ Sparks are prone to fly to our measurement gear – not even battery operated gear is exempt.
Differences in potential evidence even with state of the art grounding



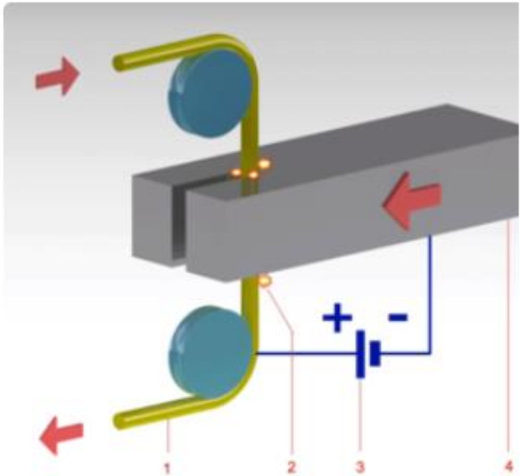
Comments: State of the art grounding

- Connect VSD ground from motor connetion box to position to be grounded, i.e to connect VSD power cable cable, harness & sheating to the grounded position in a star pattern.
- As best pratical, grounding to be applied as close as possible to.
  - Both motorbearings
  - Both fan bearings

When it vibrates, sparking is more prone & vice versa

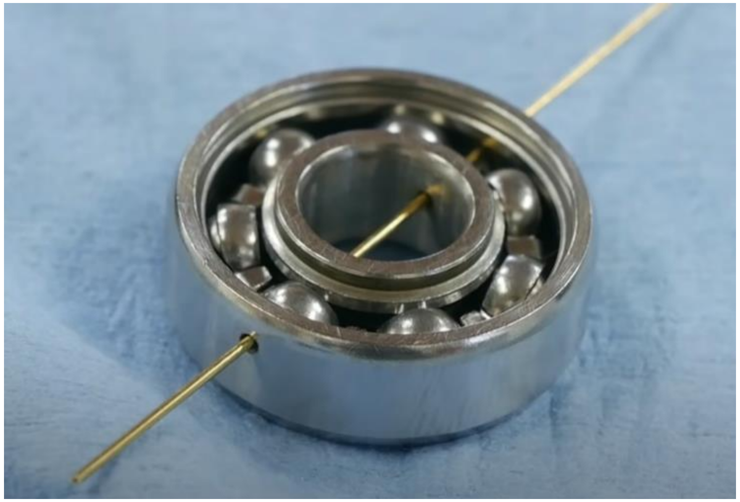
Electro Discharge Machining

EDM a machining method as well as a phenomenon



1 Wire. **2** Electrical discharge erosion (Elec arc). **3** Electrical potential. **4** Workpiece

EDM drill



Rule of thumb

- 3.3 Volt potential difference required for EDM
- Discharging draws metal from the surface
- The higher the current, the higher the material flow

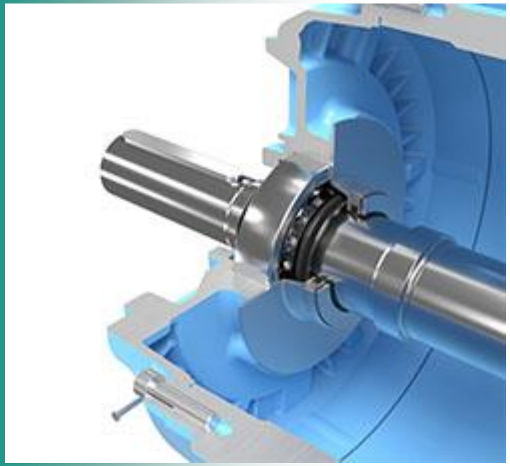
QRING Bearings & EDM

A bearing can be viewed as a capacitance where the impedance is *1/(j2πfC).*

Exciting at MHz frequency requires MΩ DC-isolation

Cables, motor winding & bearings must have a higher degree of isoletion that what's required for a a 50 Hz suncrnous motor.

Grounding brush



Bearings isolated at both ends

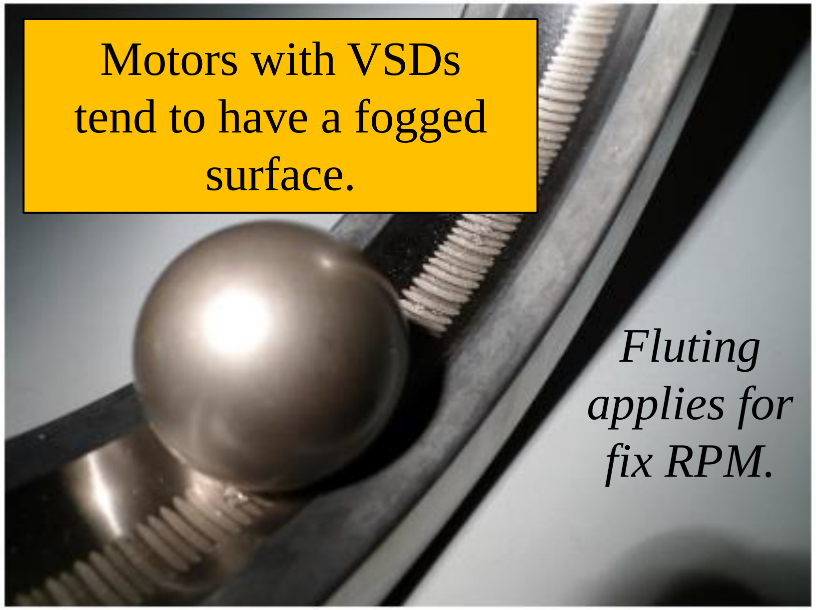
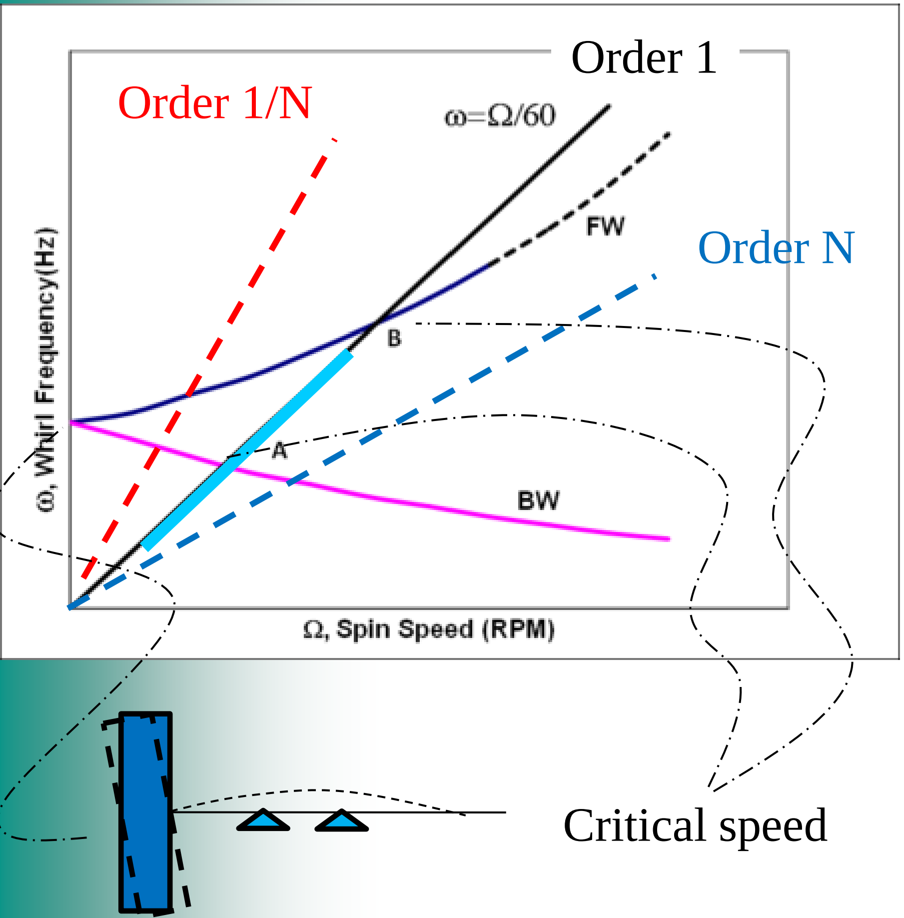


Figure 1: This bearing has been exposed to a bearing current. Note the EDM damage to the race track and bearing elements. Photo courtesy of SKF.

Comment – The power electronics guru I have spoken with state:

- Shafts are thick conductors.
- Apply grounding at every bearing

Rotordynamics



Forward propagating (FW) modes form as waves travel with the rotation direction and hence, increase in frequency with the RPM.

Backward propagating (BW) modes fall in frequency with increasing RPM.

The Operable Speed Range (SR)

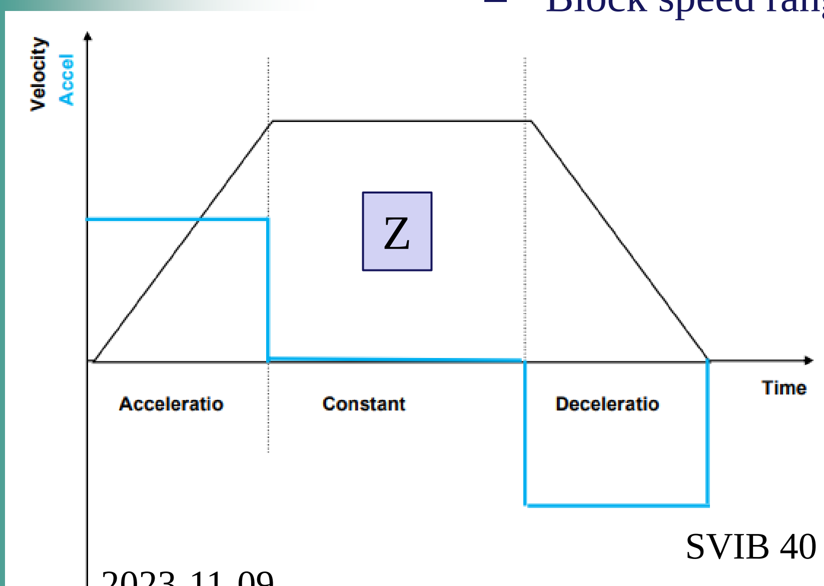
1) BW modes – tend to fall into the SR.

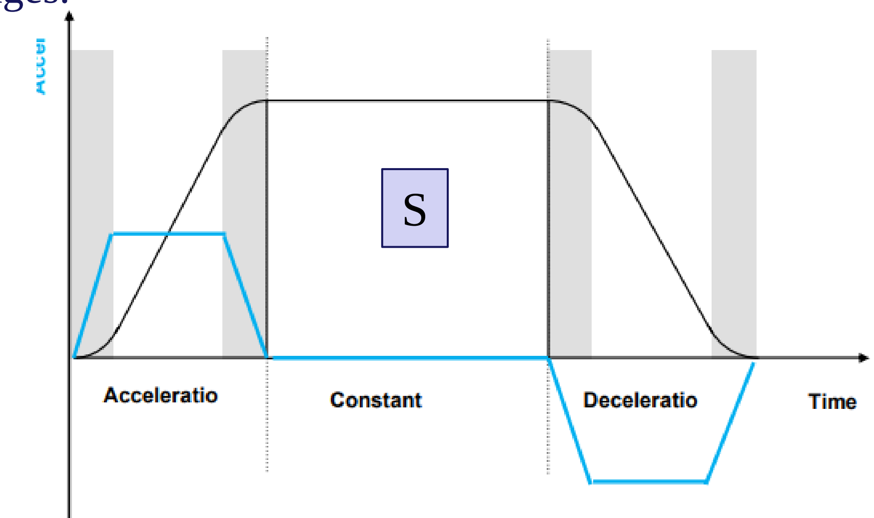
2) Order 1/N – uneven operation may interact with or instigate critical speeds.

3) Fan operation involves high flow speeds, which cause wide band excitation, ie such excitation may drive whatever resonance there is in the system.

VSD software

- The VSD drives the motor based on its (theoretical) motor model
  - The motor model understands RPM, but not shaft (key)phasor angle.
  - Motor models tend to be defined without the fan blade attached or, even, with the motor in its actual position.
  - A motor model is incapable of recognising dynamic phenomena, eg rotor modes.
- The VSD can
  - Adjust PD parameters
  - Operate using a Linear (Z-) ramp or a S-ramp
  - Block speed ranges.





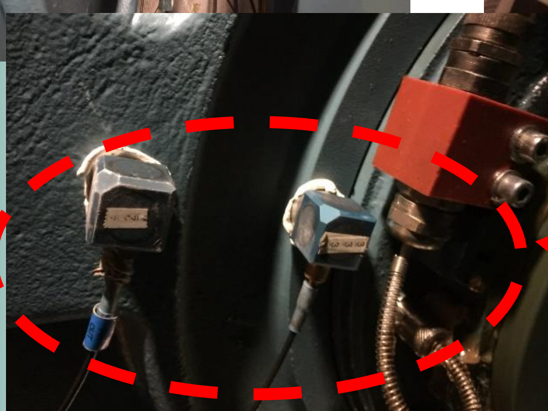
Example: VSD controlled flue gas fan

Large generators and wind mills may experience similar physical phenomena.

Accelerometers

Acc Motor NDE

Acc Motor DE



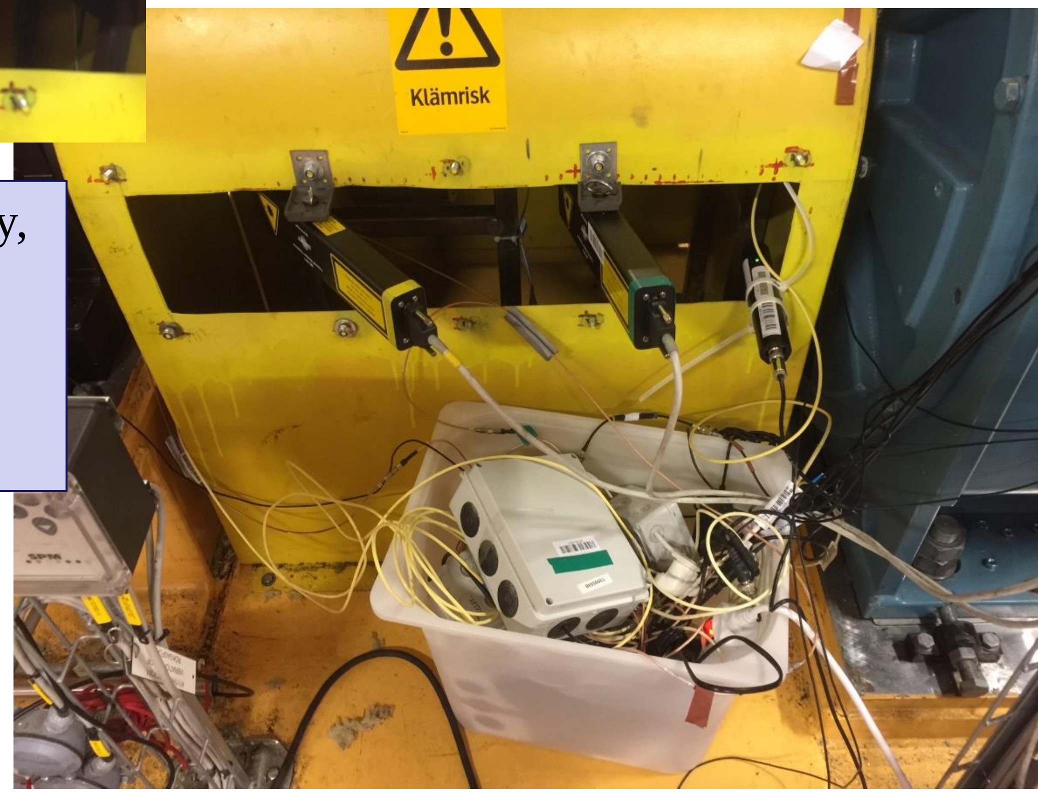
Discussed

Acc Bearing Fan DE

Acc Floor

We instrument also to allow things to be ruled out

Torsionslasers, Tacho & Proximiter Sensors inside the Cover



A torsionslaser measures rotation velocity, ie the RPM AC komponent.

Proximeters measure the relative support-shaft distance.

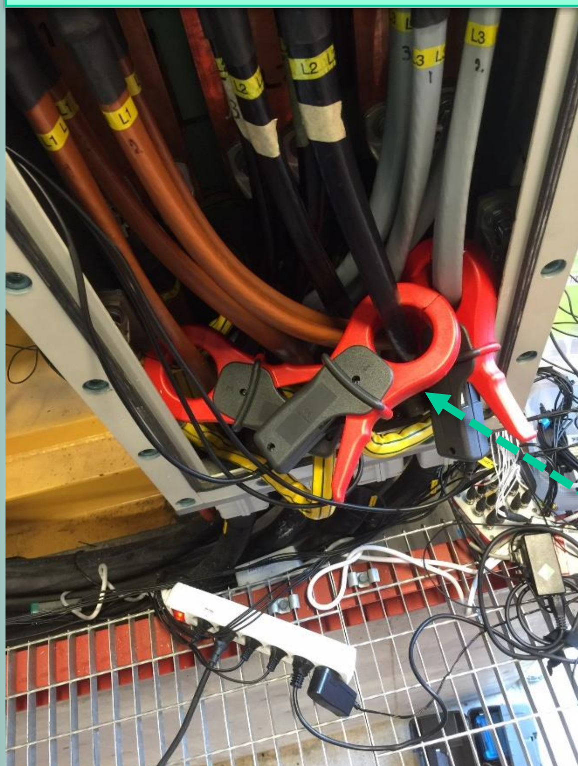
Current

Electricians tend to doubt its use.

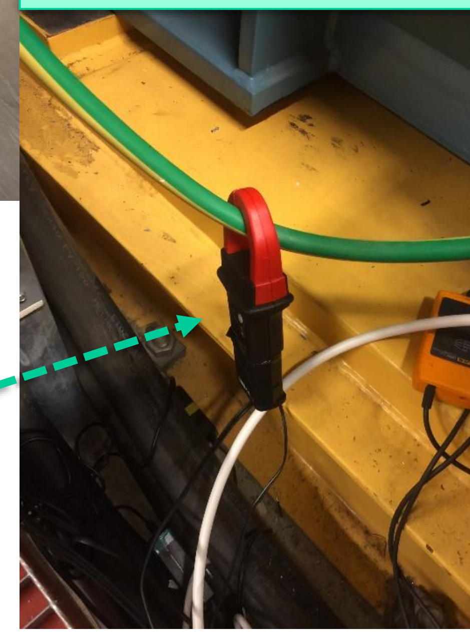
Rogowskicoil

Summed current@Motor (L1+L2+L3+N+Gnd)

L1-L3 Motor current

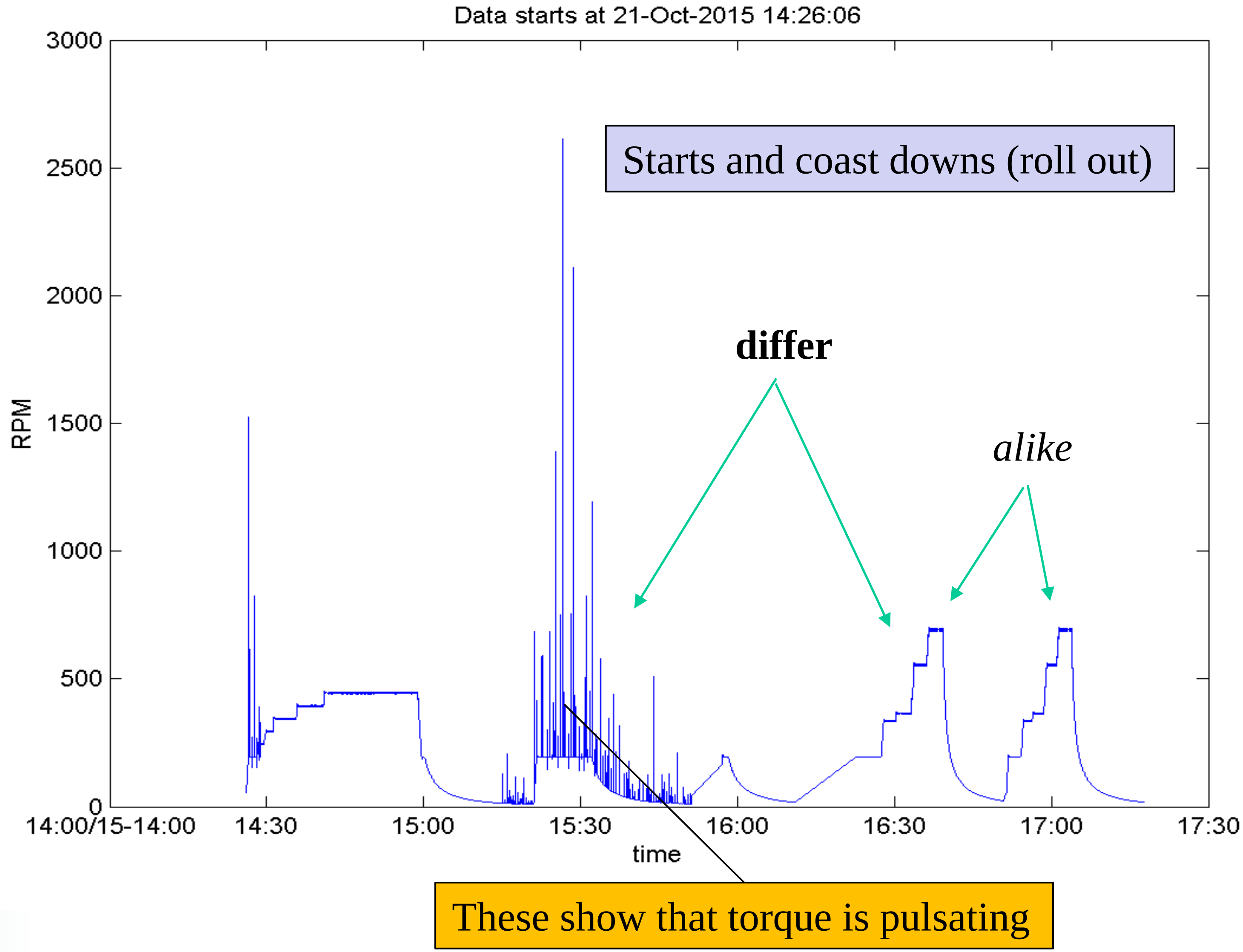


Ground current



Current clamp (transformer)

Cold Operation

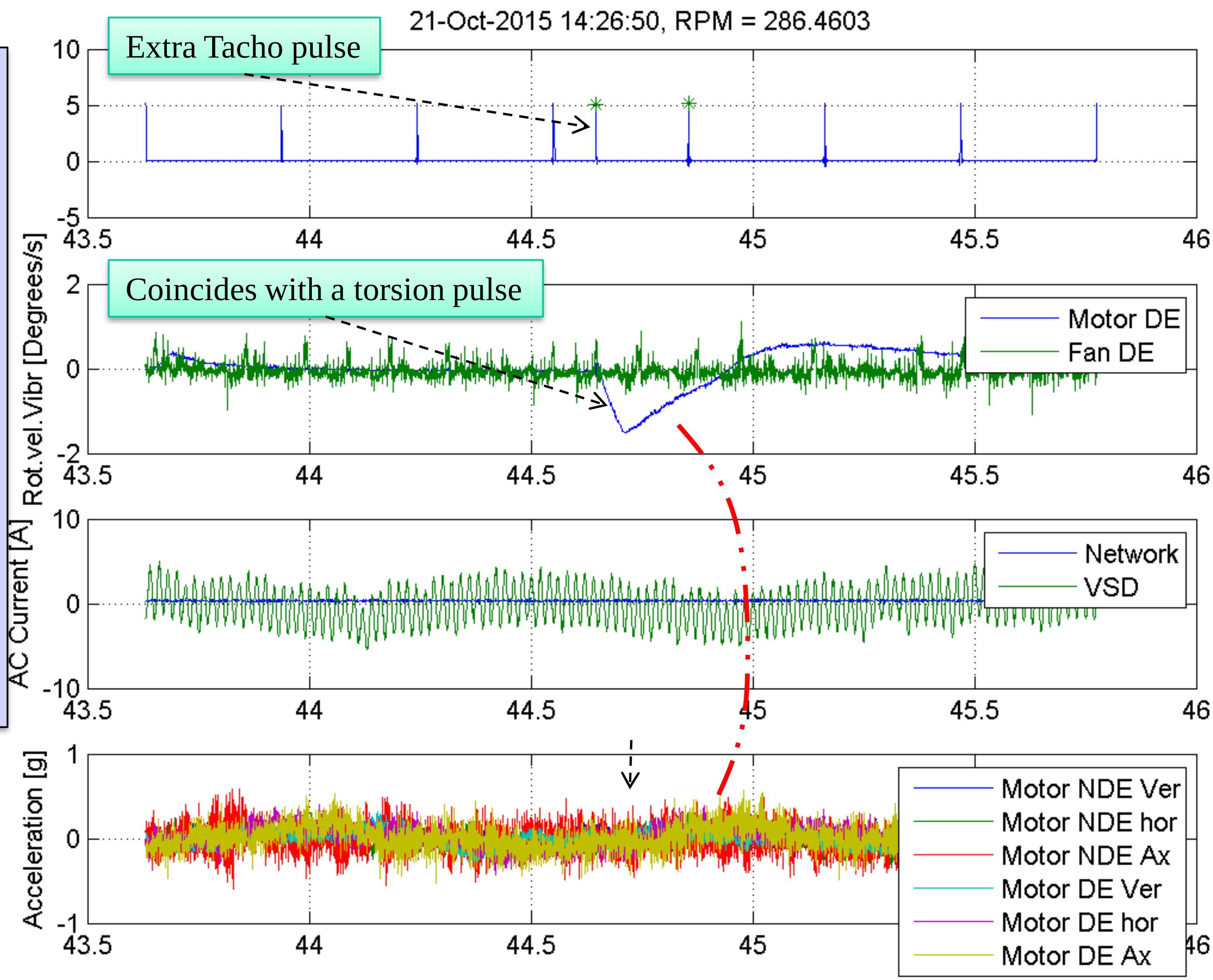


Cold Operation:

Speed Transients?

- *A torque pulse tensions the flexible coupling, which snaps back.*
- *The optic tacho on the motor shaft can then see the reflex tape multiple times per revolution.*
- *As the machine alignment is good, we do not see much linear vibration, ie not much acceleration.*

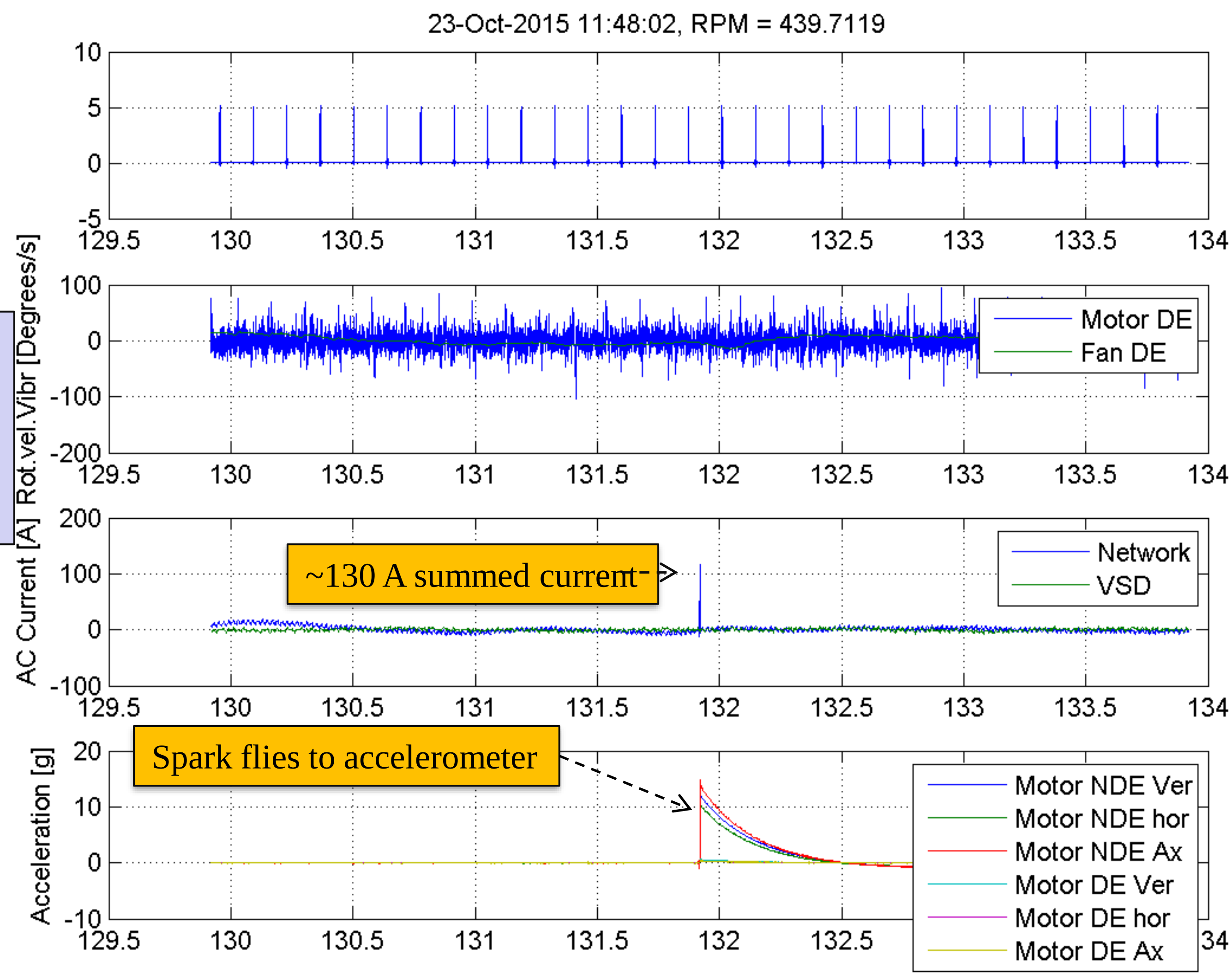
The VSD Z-ramp creates the pulse in the case shown



Cold Operation

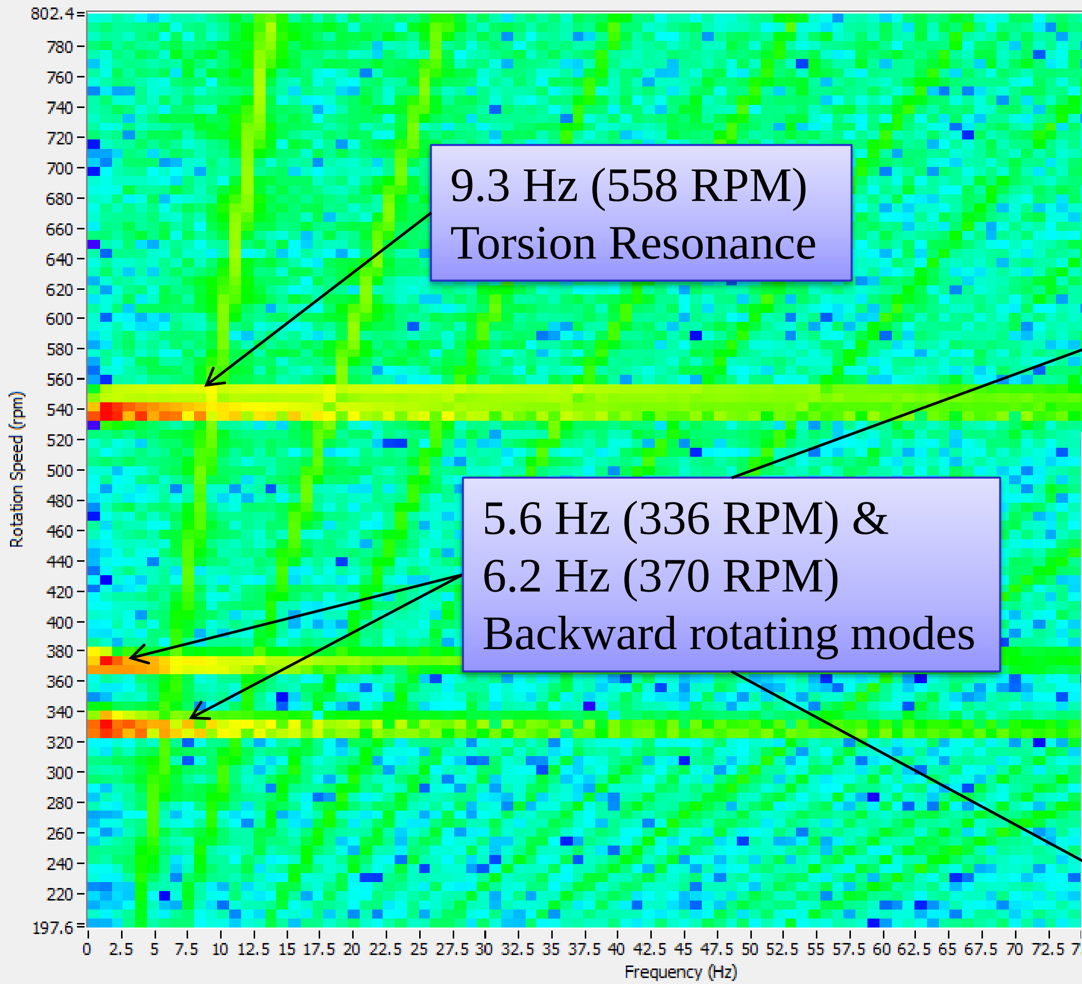
Current can cause vibration

Does vibration/discharge cause current?



Rotordynamics & Cold Operation

Torsionlaser on fan shaft



9.3 Hz (558 RPM)
Torsion Resonance

5.6 Hz (336 RPM) &
6.2 Hz (370 RPM)
Backward rotating modes

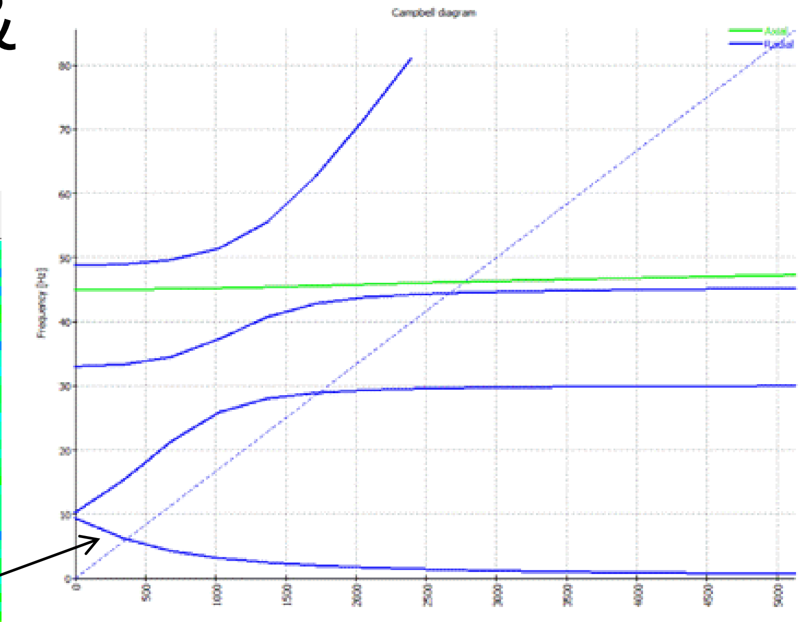
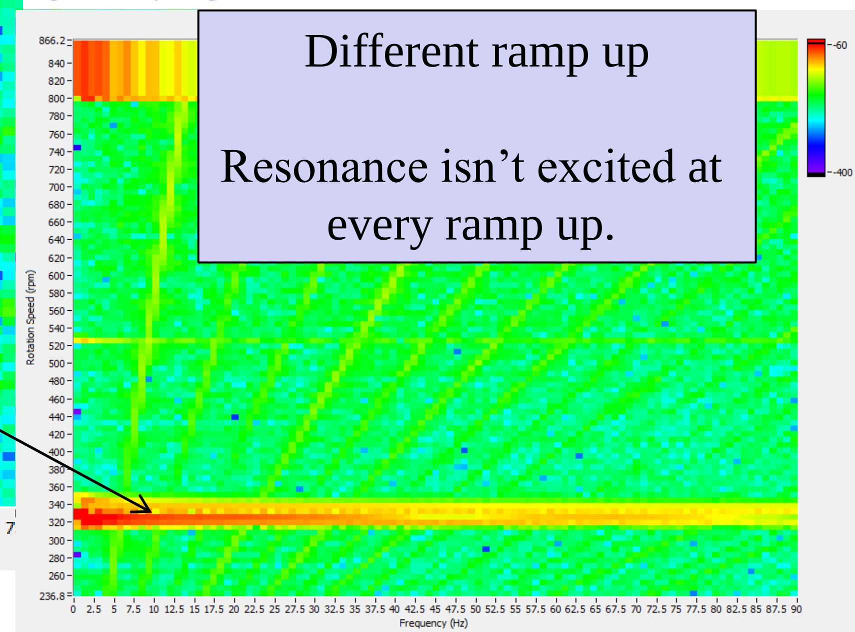


Figure 2: The Campbell diagram from MESYS



Different ramp up

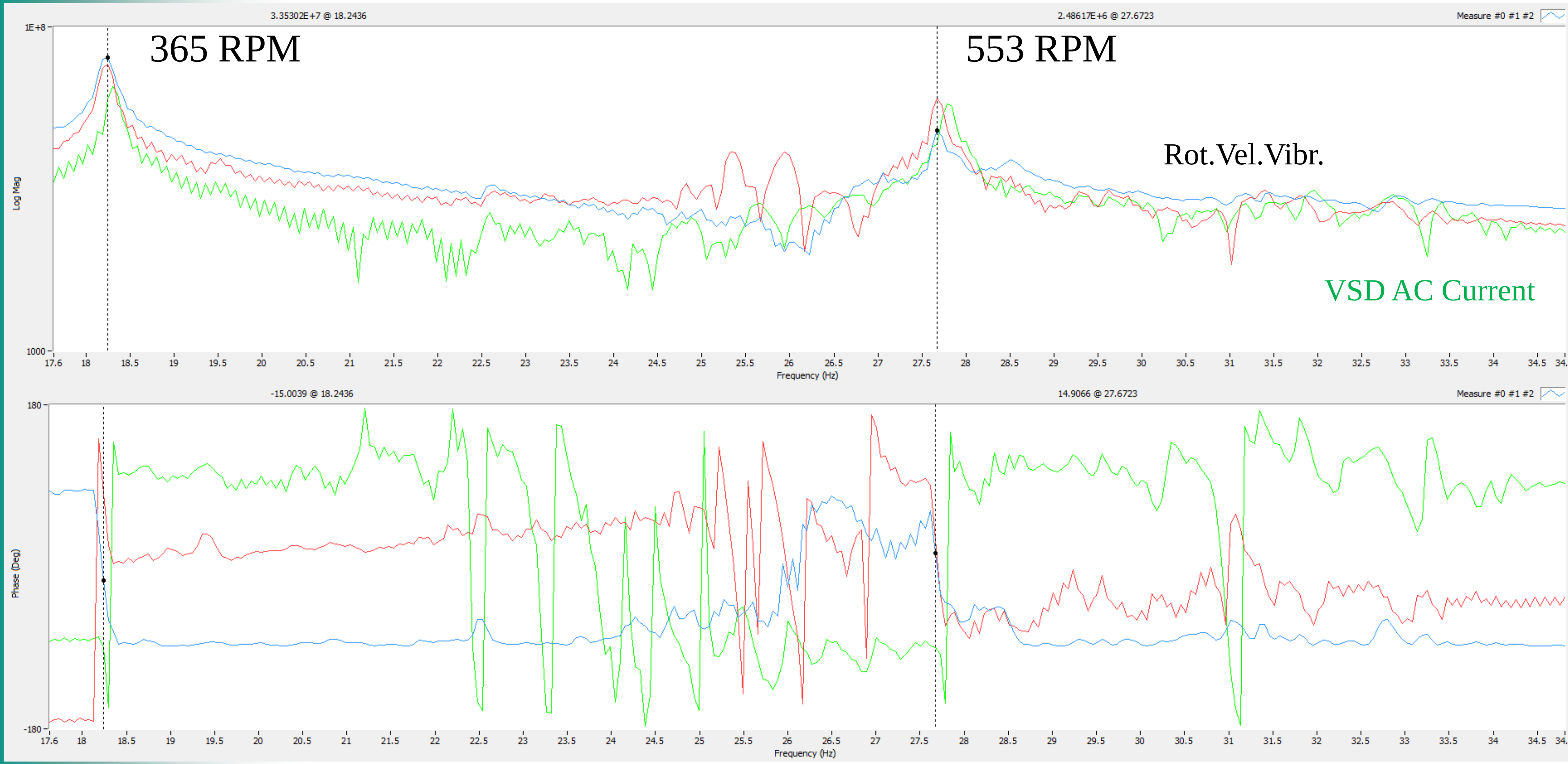
Resonance isn't excited at every ramp up.

Order FRF

Current phase shifts 180 degrees for each resonance that modulates the motorn speed, ie vibration modes turn the motor into a generator.

The Order FRF uses the motor shaft reflex tape as keyphasor.

=> The motormodel acts *N/2*-rotation too late when *N* modes are excited.

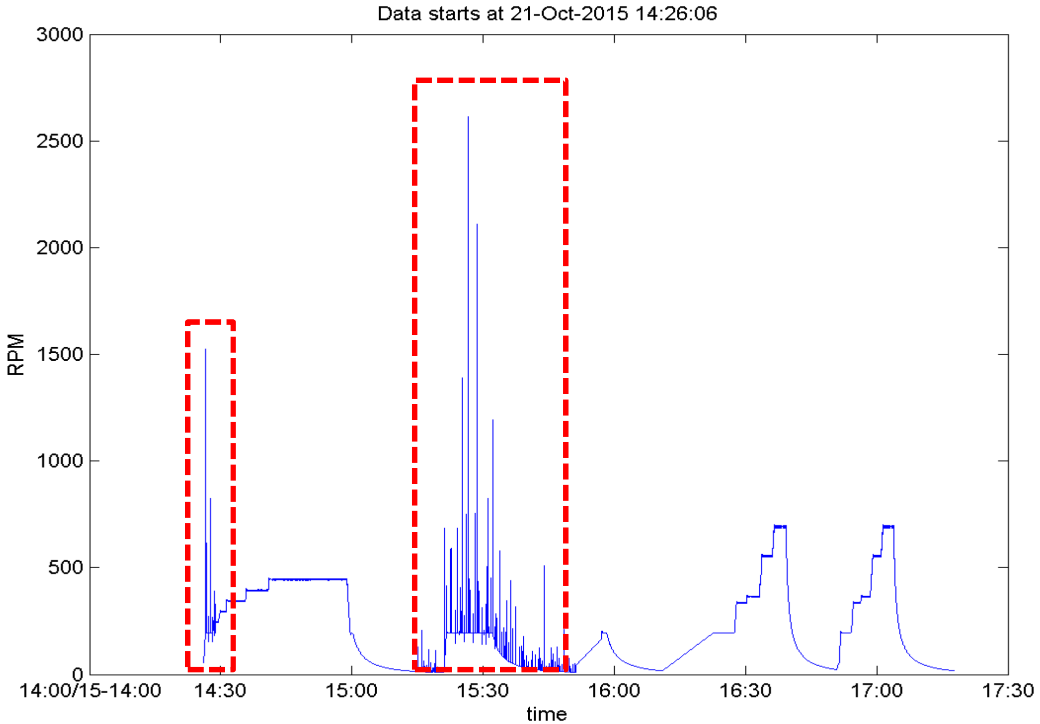


Feedback

A flexible couplings bottom out by it twisting a few degrees.

The fan blade is rotationally inert. As the fan blade loads the motor shaft, the motor RPM is effected.

Using a Z-ramp, the VSD immediatly react to compensate.



Countermeasure

Reduce P & increase D values and shift to a long S-ramp. Control becomes imprecise and thus, robust against this kind of occurence.

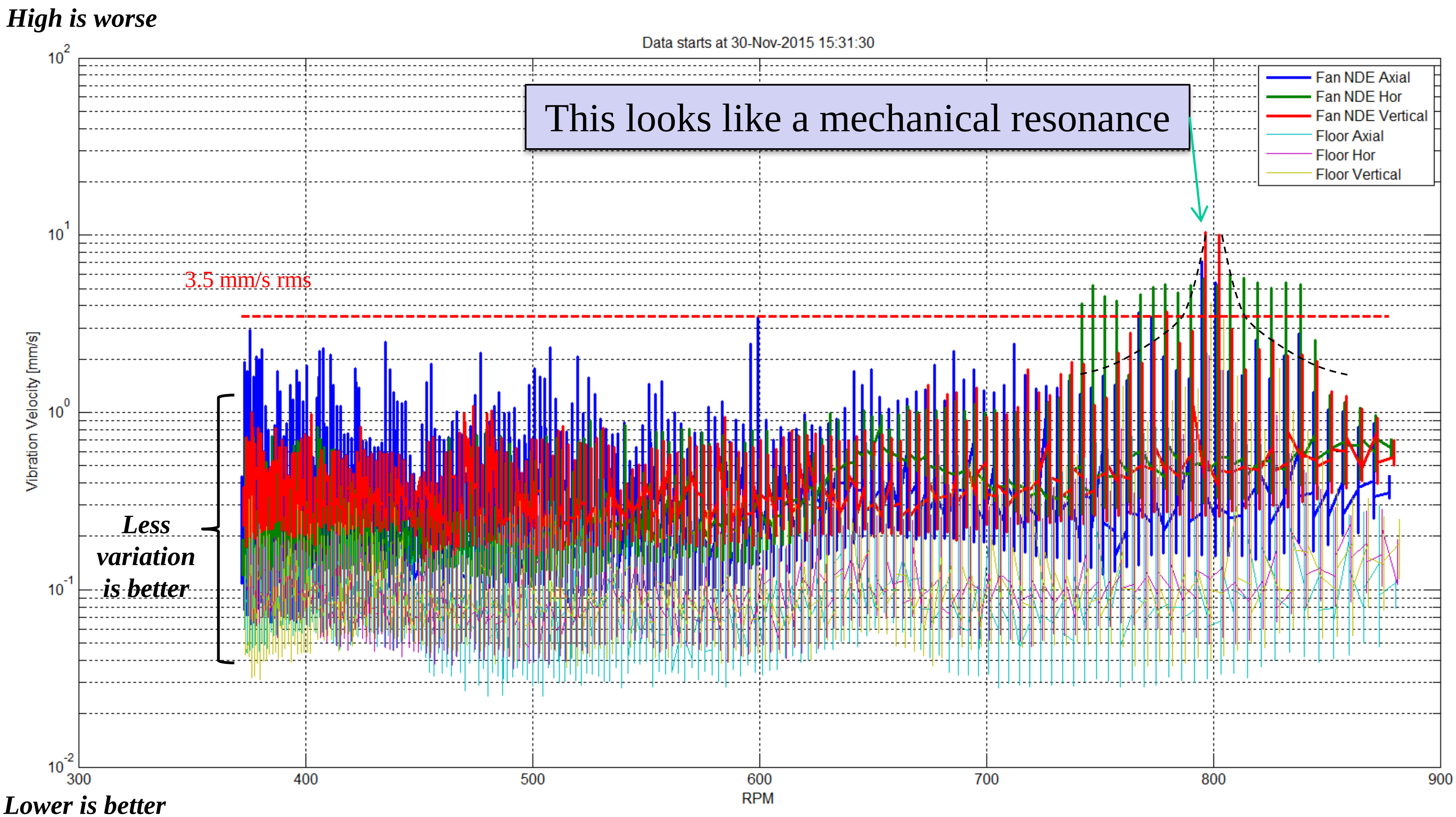
In the case shown– the coupling bottoms out every 10th rotation, ie Order 1/10 is the driver of this critical speed.

Rare Events– from Operation

Important as they may cause overload, initiate cracks, etc.

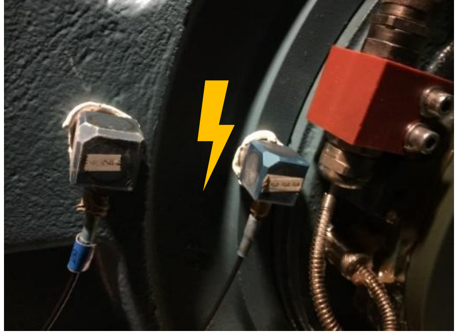
Sampled at 1757 S/s/Channel
24/7 for a few weeks.

Motor and Floor

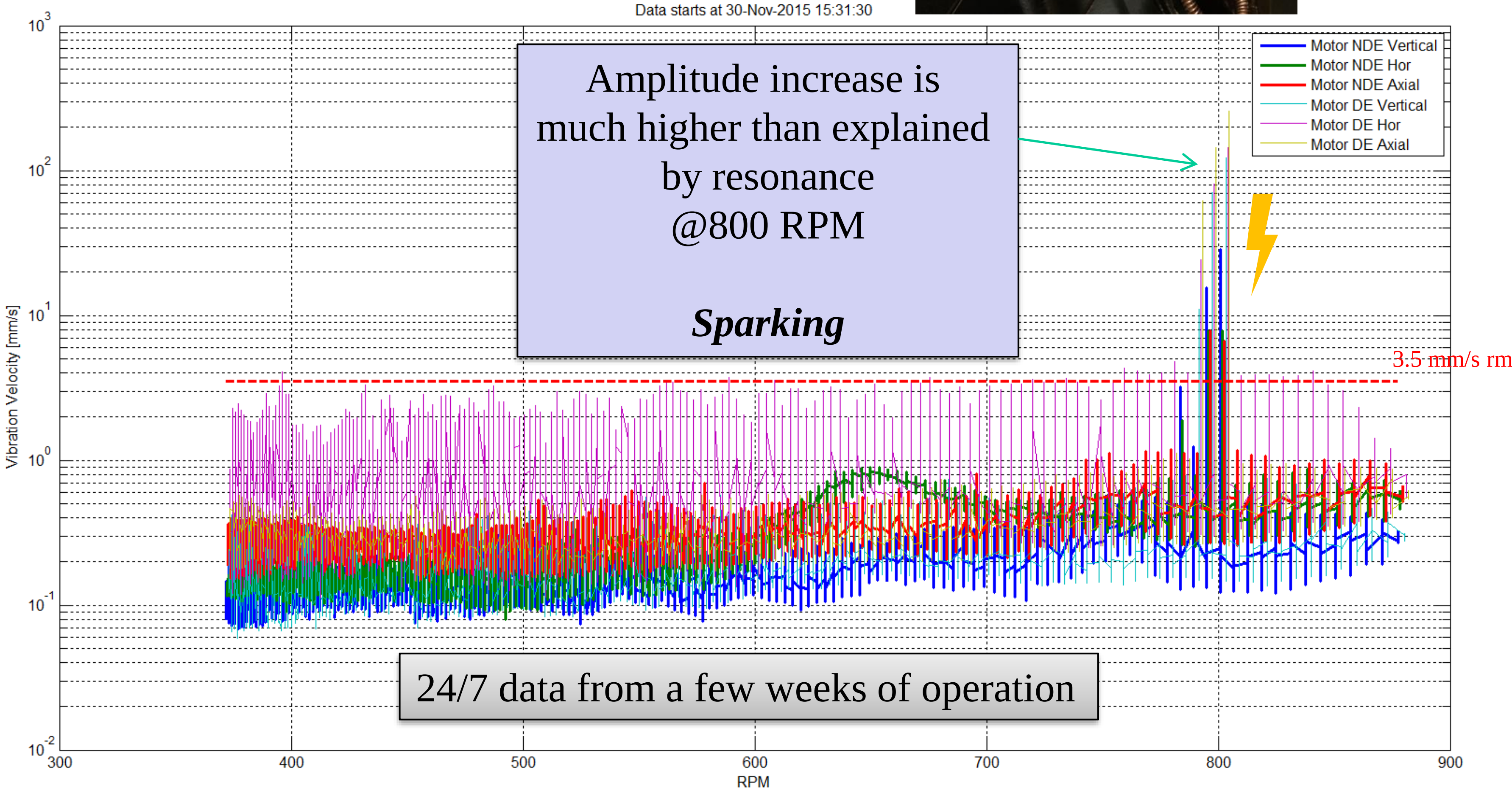


Motor bearing

Motor-
house



Isolated
bearing

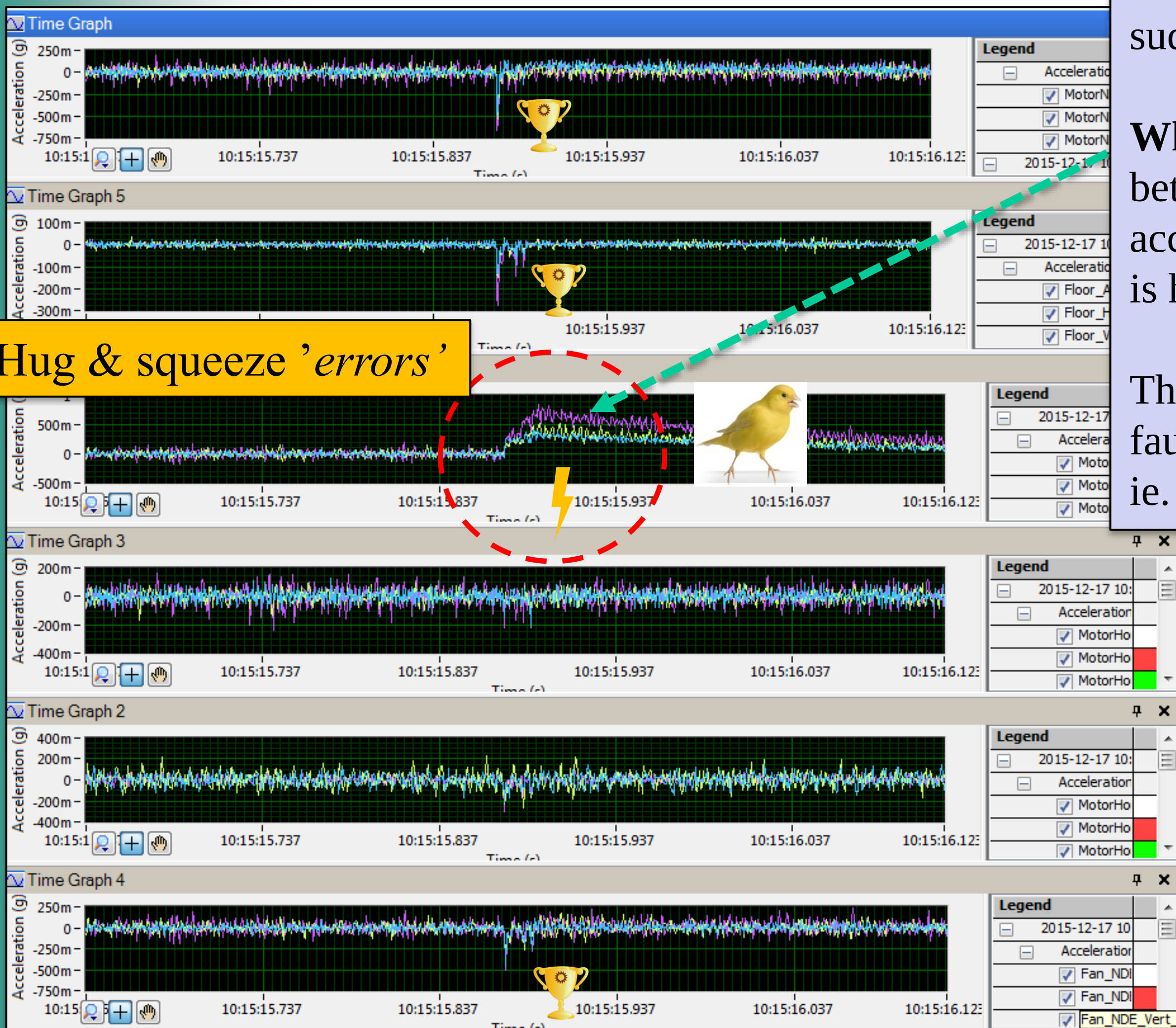


Amplitude increase is much higher than explained by resonance @800 RPM

Sparking

24/7 data from a few weeks of operation

Canary Birds?



Hug & squeeze '*errors*'

The acceleration signal shows a sudden DC-shift

Why? The electric potential difference between motor ground and accelerometer ground (which is floating) is high enough for a spark to occur.

The vibration measurent value clearly is faulty, the information is **highly** usable, ie. ***a Canary bird***

SMARTNEWS *Keeping you current*

The Story of the Real Canary in the Coal Mine

Used until just 30 years ago, the humble canary was an important part of British mining history

Mining foreman R. Thornburg shows a small cage with a canary used for testing carbon monoxide gas in 1928. (George McCaa, U.S. Bureau of Mines)

By Kat Eschner
SMITHSONIAN.COM
DECEMBER 30, 2016

Multidisciplinary:

Sudden torque jolts from faulty installation/control

AC current

Vibration

Relativ position

(B-givare)

Torsion

The torsion laser shows motor shaft torque to jolt

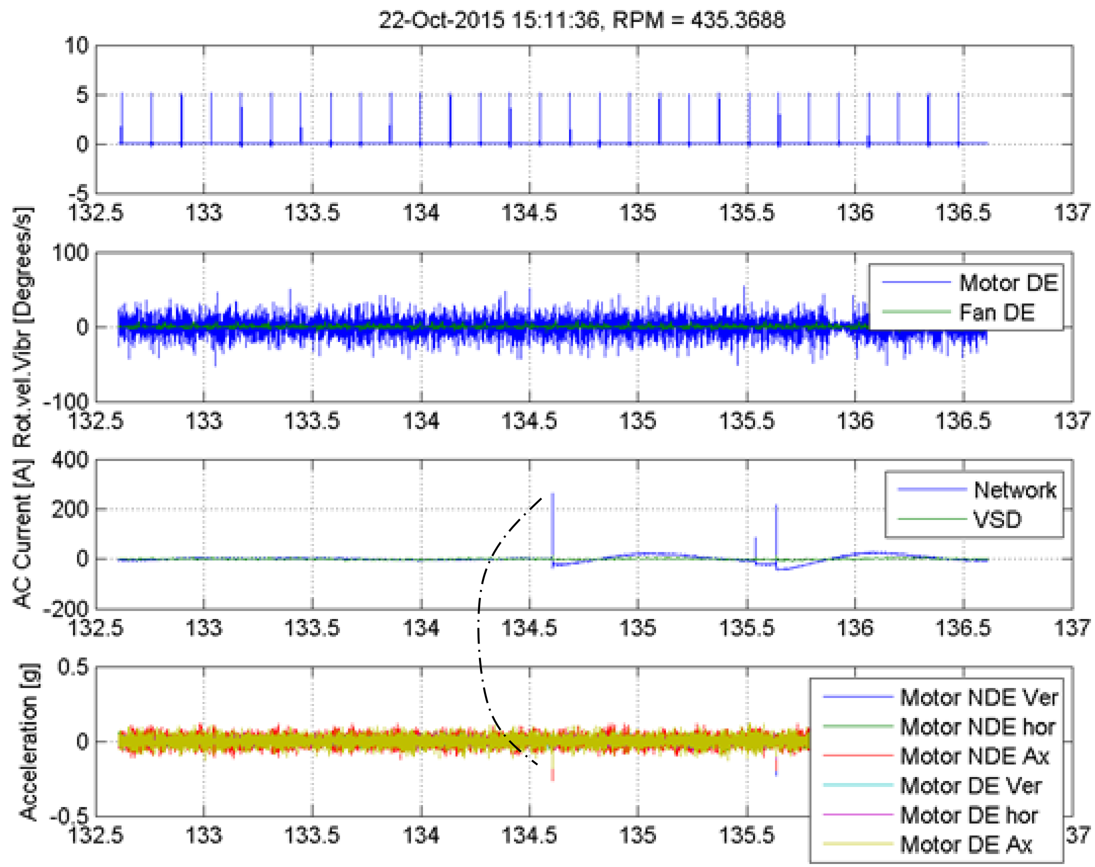
Staff reports strange bolting and cracking sounds from the machine

Disturbance on the 50 Hz power grid can be seen to transmit and effect motor vibration.

Assymetry in the power feed causes vibration.

Improved grounding may reduce such disturbance.

The investigated machine had a faulty 360 grounding connection between the motor power cable and the VSD.



(A) Enskilda störningar med mekaniskt slag där det momentant knäpper/dunkar i motor. (knäpper i detta fall eftersom g-stöten är svag)

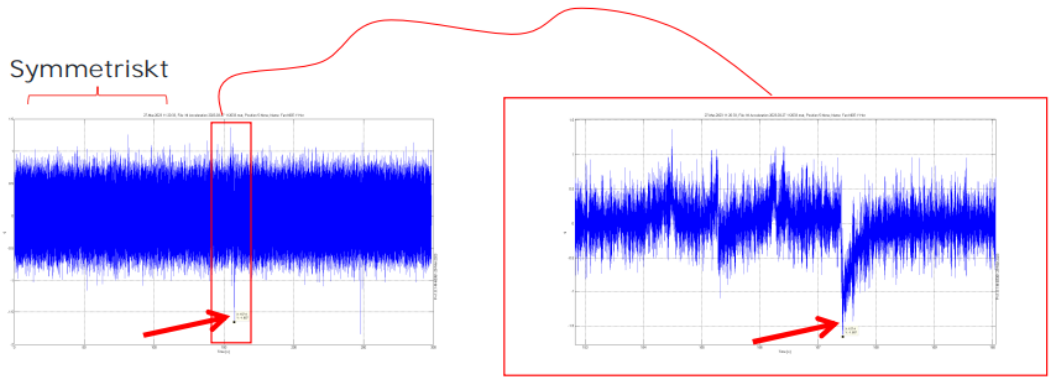
Aero Acoustics

Sound power scales with flow velocity, *U* m/s, as

- Flow across sharp edges ~U^6
- Turbulence ~U^8

Systems with high power and high flow can excite vibration up to <u>very</u> (100+ kHz) high freqency. Such excitation may excite sensor internal resonance(s) and saturate the built in electronics, which behaves poorly. The sensor may clip well below its amplitude range.

Example for a 50g accelerometer

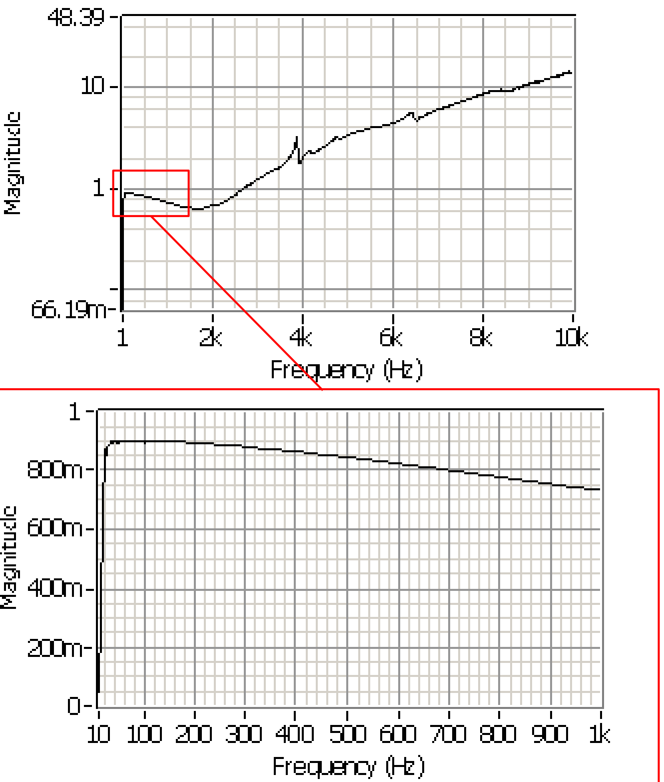


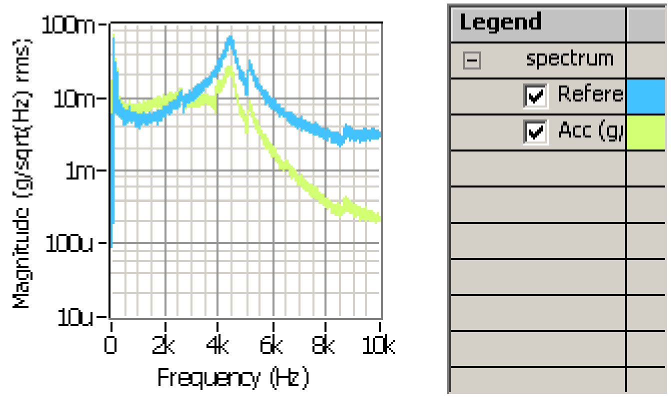
Tidssignal – den markerade toppen ser suspekt ut.

Zoom in visar att accelerometersignalen DC shiftar några gånger.

Sensor internal resonance & built in amplifier saturation

Mechanical filter





Exciter with calibrated reference accelerometer.

Example with typical ICP industrial accelerometer.

Industrial 4-20 mA accelerometrers typically operate up to ~1000 Hz and have sensor internal resonance at 25+ kHz.

This kind of sensor is amenable to mechanical filters.

Countermeasure

Mechanical filter (with pin for torqueing inserted)

DIY
Furniture pad

Conclusions

- Use a shotgun approach, i.e. high observability
  - Problems are costly as compared with measurement, i.e. don’t try to save on cost in the investigation.
  - Use as many channels/transducers as practically reasonable.
  - Use existing signals from built in transducers, e.g pressure, etc.
  - Collect as much data as practical and for as long as practical to locate the needles in the haystack and/or be able to find trends.
  - Use control room data, figure out the machine’s history & listen to every piece of information.
- Automatic evaluation
  - Evaluate, sort and filter information.
  - *Turn odd transducer behaviour to your advantage.*

“The unnatural, that too is natural.”
Johann Wolfgang von Goethe

Component Assembly or System?

Flue gas fan

Observation
A single supplier may sell the complete value chain.

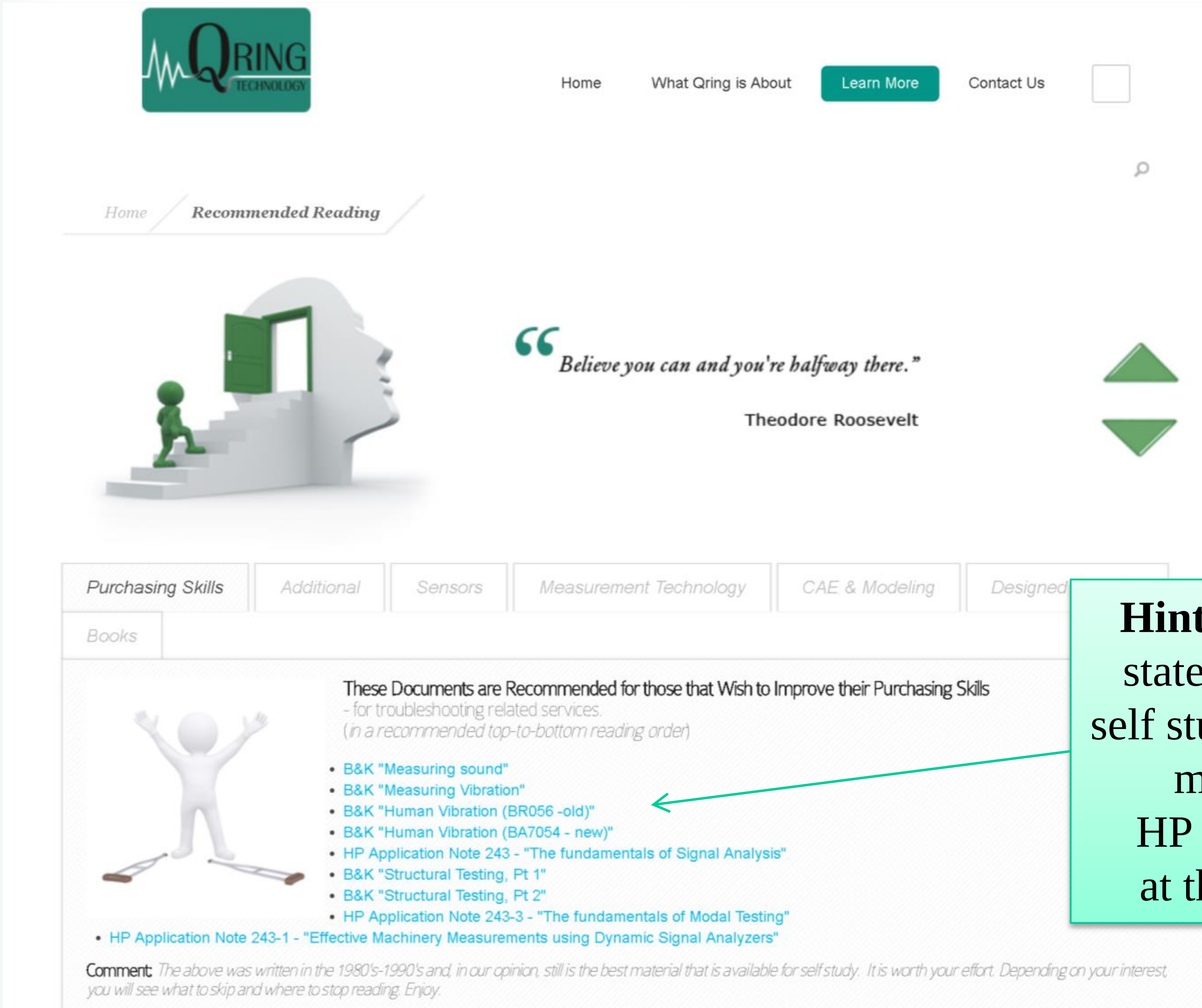
However, a single company that manufactures the whole chain does not exist.

This means that the responsibility to get the system to work falls into the lap of the end user.

- Pressure transducers – boiler underpressure
- PID regulator or via software
- Variable Speed Drive wih PD regulator
- Fan
  - Electric motor
  - Fan blade with shaft
  - Coupling – rigid, flexible or with gap
  - Frame
  - Block
- Vibrationtransducer on fan bearing (4-20 mA RMS)

Learn More: *Recommended Reading*

http://qringtech.com/learnmore/recommended-reading/



Hint: Links to state of the art self study material made by HP och B&K at their peak.