VIBRATION MEASUREMENT PITFALLS

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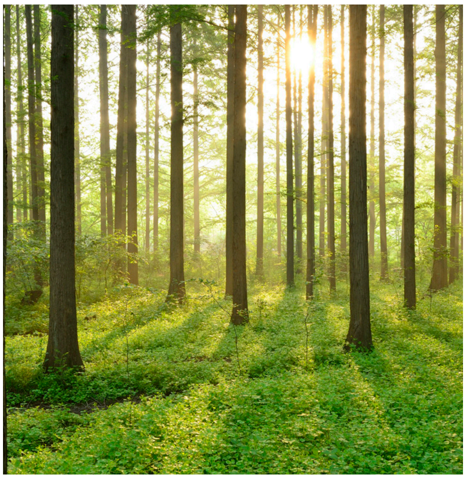

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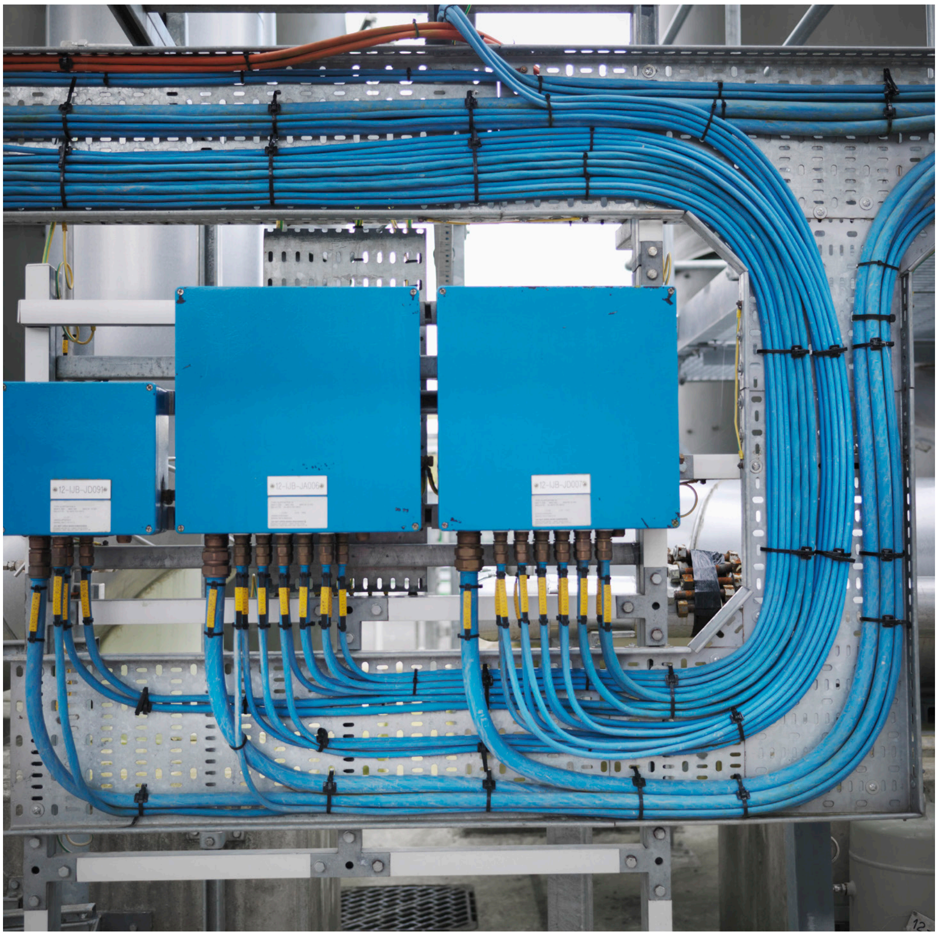

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VIBRATION MEASUREMENT PITFALLS

Experience from vibration measurements and in Nordic nuclear power plants

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Foreword

The project "Vibration measurement pitfalls" assembles knowledge and experiences in the area of vibration measurements and specifically what pitfalls one might encounter and how to avoid them. Problems and pitfalls encountered that are related to vibration measurements and how they were examined and mitigated are gathered. Furthermore, experience from vibration measurements and pitfalls in the Nordic nuclear power plants are summarized.

This project has been carried out by vibration consultant Åsa Collet, Jessica Fromell and Krister Larsson at Efterklang within the Energiforsk Vibrations research program. The stakeholders of the Vibrations program are Vattenfall, Uniper, Fortum, TVO, Skellefteå Kraft and Karlstad Energi.

These are the results and conclusions of a project, which is part of a research programme run by Energiforsk. The author/authors are responsible for the content.

Summary

This report is dealing with vibration measurement pitfalls. If you are an experienced user you are often aware of all the common pitfalls which are well-known for you. You have already made them, or are aware of them, so they can be avoided. If you fall into a pitfall at an experienced stage it's often very difficult and time consuming to detect, investigate, analyze and to solve the mistakes. An unpredictable measurement pitfall will often end up with severe costs and prolonged project planning. However, if you encounter new pifalls you should not be afraid to share and document your mistakes with others so they can be avoided for the future!

The work in this project is based on the collected experiences from five Nuclear Power plants, NPPs, and the experiences from Efterklang's vibration measurement history originated from 1956. All NPPs have highly experienced experts that have worked for more than > 20 years. They have mostly mitigated the types of pitfalls made by unexperienced personnel, such as 'simpler' mistakes in cabling and connections etc., by careful planning and documentation routines.

The main results from both unexperienced and experienced NPP vibration measurement personell are presented in a short format overview in chapter 2 with references to chapters 3-7 for a detailed view.

Report chapters 3-7 have been enhanced to address more practical application measurement pitfalls than theoretical handbook measurement issues. They cover major topics together with a technical overview to help readers understand the reason to why the measurement pitfall occurred during the prevailing measurement circumstances.

Vibration measurement pitfalls which can be found in text books or literature are often easy to mitigate and cure. When you work in a group with a mixture of different project disciplines, suppliers and/or change of instrumentation nothing should be taken for granted. Often a tight time table and/or lack of resources requires a longer and extensive pre-investigation before project startup to achieve reliable measurement information when the project is running.

Keywords

Vibration noise, Electrical disturbances, Charge Accelerometer Noise, Piezo-Element, 1/f-noise, RC-noise, Thermal noise, Sensor cable noise, Non-linear oscillations

Sammanfattning

Den här rapporten handlar om fallgropar med vibrationsmätningar. Om du är erfaren användare är du ofta medveten om enkla fallgropar som är välkända för dig i din yrkesroll. Du har redan gjort dem eller är medveten om dem, så att de kan undvikas. Om en erfaren användare råkar ut för en mätteknisk fallgrop är det ofta mycket svårt och tidskrävande att upptäcka, undersöka, analysera och åtgärda misstagen. Ett oförutsägbart mättekniskt problem kan innebära höga kostnader och innebär ofta förlängda projekttider. Det är därför viktigt att dela med sig och dokumentera nya misstag så att de kan undvikas för framtiden!

Arbetet i detta projekt bygger på den samlade erfarenheten från fem kärnkraftverk, NPP (Nuclear Power Plants), och erfarenheterna från Efterklangs vibrationsmätningar vars historia sträcker sig till 1956. De flesta yrkesmässiga vibrationsingenjörerna är erfarna experter som arbetat i mer än > 20 år på varje kärnkraftverk. De känner väl till de flesta enklare mättekniska fallgroparna, t.ex. misstag för kablar, kontakter, givare etc., och har rutiner för att undvika dem genom t.ex. noggrann planering och dokumentationsrutiner.

De viktigaste resultaten från både oerfarna och erfarna vibrationsmättekniker presenteras översiktligt i kapitel 2 med hänvisning till kapitel 3-7 för en detaljerad genomgång.

Kapitel 3-7 ska ses som en mer omfattningsrik beskrivning med t.ex. svåridentifierade fallgropar som ofta är svåra att hitta i litteraturen. En teknisk genomgång görs för att hjälpa läsarna att förstå orsaken till varför mätfallgropen inträffade tillsammans med en beskrivning av de mättekniska principerna.

Fallgropar med vibrationsmätningar som kan läsas i läroböcker är ofta lätta att identifiera och hitta en lösning på, men när uppdraget kräver samarbete med olika projektdiscipliner, leverantörer och/eller byte av instrumentering bör ingenting tas för givet. Ofta kräver en stram tidsplan och/eller brist på resurser en längre och djupare förundersökning innan projektets start.

List of abbreviations

ADC	Analog Digital Converter
A/D	Analog/Digital
α	Strength of the Nonlinearity
AWG	American Wire Gauge
CMV	Common Mode Voltage
DTC	Discharge Time Constant
C	Capacity
EMC	Electromagnetical Compability
EMI	Electromagnetical Interference
ESD	Electrostatic Discharge
F	Forsmark
f	Frequency
FAT	Factory Acceptance Test
FE	Finite Element
FEM	Finite Element Method
FEMA	Finite Element Modal Analysis
FKA	Forsmarks Kraftgrupp AB
FRF	Frequency Response Function
ICP	Integrated Circuit Piezoelectric (IEPE)
IEPE	Integrated Electronics Piezo-Electric
L	Loviisa
LAN	Local Area Network
LTO	Long-Term Operation
LVDT	Linear Variable Differential Transformer
NPP	Nuclear Power Plant
O	Oskarshamn
ODS	Operational Deflection Shapes
OKG	Oskarshamns Kraftgrupp AB
OL	Olkiluoto

PWR	Pressurized Water Reactor
RC	Resistance Capacitor
RFI	Radio Frequency Interface
Q	Amplification factor
R	Resistance
RAB	Ringhals kraftgrupp AB
SAT	Site Acceptance Test
RG	Radio Guide (coaxial cable)
rpm	Revolution per minute
SSM	Strålsäkerhetsmyndigheten
TVO	Teollisuuden Voima Oyj
Ω	Electrical Impedance

List of content

1 Introduction

1.1 OBJECTIVE

The objective of this project is to assemble knowledge and experience in the area of vibration measurement pitfalls. The information is assembled in this report and can be used to increase awareness of which pitfalls one might encounter doing vibration measurements and how to best avoid them when working with maintenance and quality assurance in a LTO perspective.

The nuclear power plants participating in the project were:

- Oskarshamn (abbreviated O or OKG)
- Ringhals (abbreviated RAB)
- Forsmark (abbreviated F or FKA)
- Olkiluoto (abbreviated OL or TVO)
- Fortum Loviisa (abbreviated L)

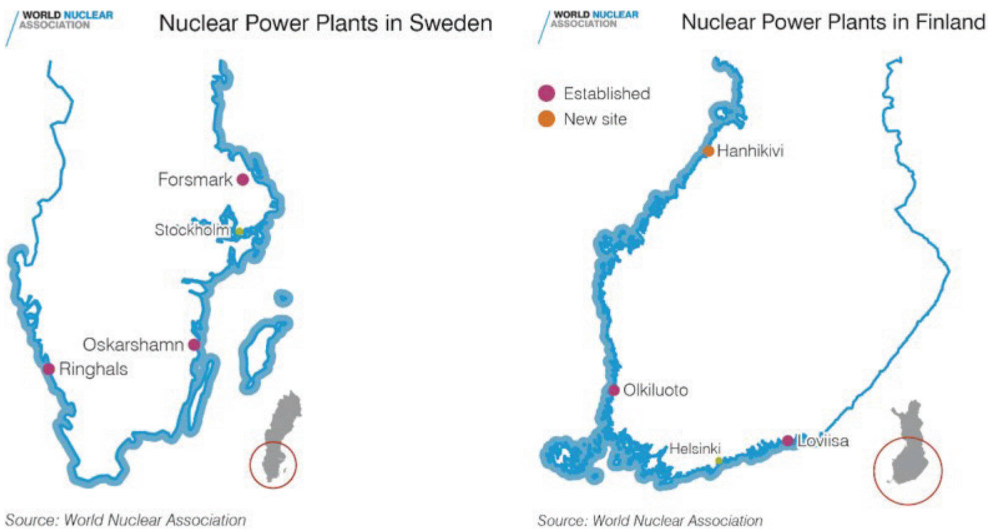


Figure 1: Nuclear powerplants located in Sweden and in Finland 2020.

In the project there is a reference group and a steering group. The members of the reference group are:

- Paulus Smeekes (TVO)
- Petri Lemettinen (Fortum Loviisa)
- Kent Andersson (OKG)
- Magnus Adolfsson (FKA)
- Lena Skoglund & Björn Severinsson (RAB)

1.2 METHOD AND STRUCTURE OF REPORT

The work in this project is based on the collected experience from the five Nuclear Power plants, NPPs, and the experiences from Efterklang's vibration measurement history originated from 1956.

A questionnaire, see Appendix A, was distributed prior to each interview in order for the NPP's to be able to prepare and collect historical information and data on their experience of vibration measurement pitfalls.

The interviews were, due to pandemic restrictions, performed in digital meeting rooms such as Teams.

The interviews have been anonymized and the responses have been categorized into common areas following the vibration measurement chain. The responses of the questionnaire and the interviews are summarized in the examples and stories reported in chapter 2, and further analysed and reported in detail in chapter 3-7.

2 Summary of interviews

Interviews of each NPP's (Nuclear Power Plant's) vibration specialists has been undertaken during the period February-May 2021 in order to collect the experience and know-how of the possible pitfalls one might find when doing different types of vibration measurements in all five NPP sites.

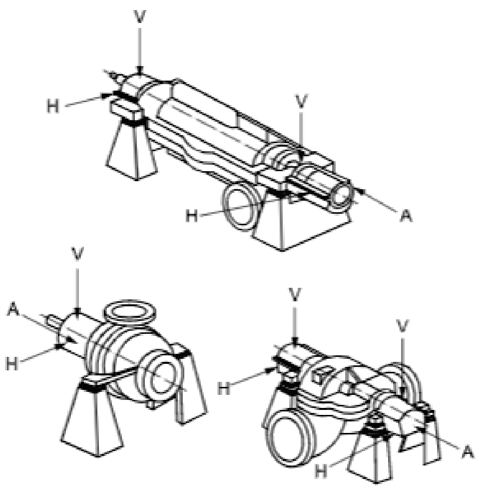
This chapter is a summary of these interviews and reflects the examples of pitfalls, mistakes and how to measure or behave in order to avoid pitfalls retold by the NPP experts interviewed. The amount of pitfalls and mitigation methods presented for the different sections below are just short and overbridged described. Further detailed pitfall stories can be found in this report. Table 1 below shows where to find them.

Table 1: Identification table of common pitfalls described in the report

Found fault	Possible pitfall 1	Possible pitfall 2	Possible pifall 3	Possible pifall 4	Possible pifall 5	Possible pifall 6	Possible pifall 7
Unexpected DC component/ ski-slope	ICP acceler-ometer, section 3.1.5-3.1.6	High frequen-cy overload, section 3.2.2	Steam pipe measu-rement Section 5.1 and 2.3	Section 2.1.2, 2.3. Eg. Faulty cables, wrong sensors, tempera-ture and radiation sensitive-ty	Integrat-ion issues section 2.4 and 3.1.5		
Unexpected 50 Hz component or other disturbances	Impact testing, section 3.1.4	Interfe-ring potenti-als, Section 5.2	2.2 impact testing during parallel work	2.3 and 5.2 Groundi-ng issues. Transien-ts due to cabling section 2.3	Not galvanic-ly separate-ed channels section 2.6		
Unexpected vibration magnitude/ frequency	Sensor malfunctio ning, section 3.2.1	Selecti-on of measur-ement points, Section 4.3	Inconsiste nt align-ment, Section 4.4	Section 2.1 Standar-ds and Vibration criterias, alarm levels	Section 2.1.1 Fixture points and resonan-ces of fixtures	2.1.1 and 2.3 using filters and amplify-ers.	Sensor sensitiv-ity, section 2.3
Unexpected phase shift	Disturb-ance of high freque-ncy vibrati-on, section 5.1	Amplifi-ers, section 6.2 and 2.3 and 2.6	Operat-ing over long cables (> 30m) with ICP sensors, Section 6.3	Book keeping and selection of points sections 2.8 and 2.9			
Missing project information	No rotor-dynamic model availab-le, section 4.2	Prepara-tion, section 7.1, Section 2.1.2	Section 2.1.1 and 2.1.2 Unable to access before or during meas.	Underes-timation of constru-ction changes Section 2.1.2	Book keeping section 2.8		
Malfunctioning Equipment or poor signal quality	Sensitivity to radiation section 2.1.1 and 2.3 and 6.3		Using wrong Filters and sensors, eg section 2.3		Poor/ wrong attach-ement section 2.3	Cabling and connect-ion, section 2.3	
Something breaks but root cause is hard to find.	Section 2.1.1 Not enough measurement time to find actual issue						

2.1 MEASURE RESPONSE VIBRATIONS ON A MACHINE/PIPE/FOUNDATION ETC

Measurement standards frequently used are for example ISO 10816-3 & 17, ISO 14694, ISO 20816-1,3,6 & 7 and Finnish Standard PSK7709 and PSK7707. These last two give great tools with respect to vibration measurements and at some extent also to acceptable vibration levels. However, a common pitfall is that, when blindly following standards, one might over- or under estimate the severity of a machine vibration level and for example believe that there is a problem when in fact there is not, or that levels are fine when it could be an indication of a severe problem. Standards are mostly used as a guideline both for measurements, for example for choosing measurement positions see Figure 2, and for procurement of new equipment. The vibration experts at the plants use their own internal experiences, standardss and acceptance levels first. These are often based on a combination of experience and simulations.



NOTE H, V (horizontal, vertical) are the two orthogonal radial measurement directions; A is the axial measurement direction.

Figure 2 — Measurement locations on horizontal pumps

Figure 2 Example of measurement locations specified in ISO 10816-7 for horizontal pumps

The acceptance levels in the ISO-standards are often too high for the NPP application, and the NPPs have, for many components, decided for their own acceptance criteria. The requirements are highly dependent on the machine speed, e.g. low speed machines often require lower acceptance levels than the standards recommend. One example is the emergency diesel generator requirements where the levels in the standard are too high which might cause difficulties when discussing levels and acceptance criteria with suppliers.

When comparing acceptable levels for example for a NPP turbine the standard is not applicable since the turbine acceptance levels are much lower than the standard. For example the standard ISO 20816-2 states that the limit is 2.5 mm/s for a machine at 1500 rpm, but that would be a too high vibration level for this turbine, which has a normal vibration level of around 1.5 mm/s at maximum speed that is seemed feasible. One has to use the standards as a guideline and adapt the levels for each individual machine.

The standard’s levels are usually not directly applicable and a pitfall regarding using the standards would be to only rely on those levels and to set too low and lenient vibration criteria's and alarm levels. However, some machines have also shown that levels above the standard's levels can be acceptable in some cases and these machines have functioned properly with higher vibration levels for forty years.

Table A.1 — Zone limits for vibration of non-rotating parts of rotodynamic pumps with power above 1 kW, applicable for impellers with number of blades $z_i \geqslant 3$

Zone	Description (see 5.2 for details of zone definitions)		Vibration velocity limit r.m.s. value mm/s			
			Category [a] I		Category [a] II	
			⩽ 200 kW	> 200 kW	⩽ 200 kW	> 200 kW
A	Newly commissioned machines in preferred operating range		2,5	3,5	3,2	4,2
B	Unrestricted long-term operation in allowable operating range		4,0	5,0	5,1	6,1
C	Limited operation		6,6	7,6	8,5	9,5
D	Risk of damage		> 6,6	> 7,6	> 8,5	> 9,5
Maximum ALARM limit (≈ 1,25 times the upper limit of zone B) [b]			5,0	6,3	6,4	7,6
Maximum TRIP limit (≈ 1,25 times the upper limit of zone C) [b]			8,3	9,5	10,6	11,9
In situ acceptance test		Preferred operating range	2,5	3,5	3,2	4,2
		Allowable operating range	3,4	4,4	4,2	5,2
Factory acceptance test		Preferred operating range	3,3	4,3	4,2	5,2
		Allowable operating range	4,0	5,0	5,1	6,1
For all acceptance tests in the preferred operating range (see 3.4), each of the filtered values [c] for rotational frequency (f_n) and blade-passing frequency ($f_n \cdot z_i$) should be			⩽ 2	⩽ 2	⩽ 3	⩽ 3

[a] For definition, see 5.1.

[b] Recommended values. The vibration magnitudes should be above these limits for about 10 s before an ALARM or TRIP is released to avoid false alarms and trips.

[c] For acceptance tests in the allowable but outside the preferred operating range, the filtered values for rotational frequency (f_n) and blade-passing frequency ($f_n \cdot z_i$) may be expected to be higher (1,3 times) than the values for the preferred operating range.

Figure 3: Example of acceptance criteria defined in standard ISO 10816-7

One example was a couple of water pumps that broke down after a while when allowed as high vibrations as the standard recommended and for these pumps the levels had to be adjusted.

SSG3030 has a clause specific for machine alignment which is easily forgotten when procuring new machines.

To not measure enough points might be a pitfall when following a standard. It is important also to measure axially on the driver and driven machine, pumps and fans, compressors when the machine has a specific type of coupling and foundation.

For specific components where the long term trend has low level of vibration, a correction action can be done even if the vibration level does not exceed the specific alarm level.

2.1.1 Some examples of pitfalls

All sites are in unison that before performing a measurement it is important to take a lot of external factors into account. For example investigate the environment before installations so that, if there is high radiation levels or high temperature levels etc., proper measures to protect the equipment can be made.

Examples:

- A vibration engineer spent quite some time investigating a bearing problem that turned out to be an electrical problem due to electrical disturbances interfering with the transducer due to its positioning.
- For a more permanent measurement installation some of the measurement equipment needed intermediate equipment that was installed inside the containment. They were mounted inside shielded cabinets (shielded with led). After a year, the equipment just stopped working and it was found that the shielding was not sufficient. The lesson here was to always try to get the signal out of contained areas and do the processing and or amplification (charge amplifiers) outside of the containment.
- The equipment's sensitivity to radiation vary a lot. Some charge amplifiers are very sensitive to radiation and might work for a while before they deteriorate. Some ICP accelerometers have shown to work only one year in radioactive environments and some have worked fine for ten years. It is therefore important to check the measurement environment and the sensors used so they are possible to use for the purpose at hand.

One of the most difficult type of measurements is the one where you cannot visit or perform a test measurement beforehand. For example one that you install in a room e.g. in the turbine chamber, and you cannot access it during operation. That is, if you discover some issues with your signals you cannot go in and check the equipment. Then it is especially important to check as much as possible when installing it e.g. how cabling are drawn and were the connectors or intermediate boxes are positioned and if they need any type of protection.

Another example of a pitfall from a NPP was that after a rebuilt some valves started to emit a whistling noise. 98dB at 640Hz. 8 valves were whistling like a choir. One supplier responsible for the rebuild made a lot of measurements using a pipe clamp with a small rod protruding were the sensors were attached. Very high vibrations were measured but it was found that these rods were way to weak and that they had a resonance at the same frequency as the valve resonance frequency. This was deduced using an impact test of the pipe clamps and rods. Before being able to validate that this was indeed the case and not dangerous vibration levels of the system, the NPP had to operate at a lower load for quite some time due to access restrictions to the pipes and valves during operation. The consequence was losing a lot of production capacity for quite some time.

FEM calculations of the piping and pipe clamp rod resonances were made. However, this was not validated before startup which could have saved a lot of time and production capacity for the NPP.

Another measurement pitfall example with small pipes, 250 mm in diameter, anchored against the wall where both mounting plates and pipe support were released from the wall. The bolts had fallen out of the mounting plate and there were also cracks in the pipe support. This was not a place you are usually looking for this kind of error. It was discovered by studying the time signal of a continuous monitoring measurement that high shock levels occurred at midnight between Friday and Saturday every week. It turned out that a small valve was opened in the system when it was tested once a week during the night shift between Friday and Saturday +- 15 minutes.

It turned out that the whole pipe made a whip-flick movement when the valve opened. It was first assumed that the issue was caused by starting of a pump pair or a larger valve, and not this small valve. Partly because the damage was upstream of the small valve.

Since then the valve is tested once a month instead. The levels are not critically high but a high enough number of repetitions could cause fatigue failure of the pipe supports.

The lesson learned from this example is that long term measurements and monitoring is needed to detect certain types of errors. Doing cold condition testing alone cannot identify problems when the plant is in operation.

An example of a pitfall using accelerometers when measuring on low-speed machines like water cooling pumps. The vibration engineer used a handheld system to do vibration measurement rounds. On a low-speed machine he got very low levels and did not react until the machine broke. It turned out that the accelerometer used was an industrial accelerometer with a built-in high-pass filer at 5 Hz, and the machine, when running at 300 rpm, had its first order at 5 Hz (accelerometers are usually not the best choice since for example, an industrial accelerometer often has a high-pass filter built in at 5Hz. It is in those cases better with non-contact sensors or proximeters). If performing the measurement with a handheld system, you may not use the same sensor every time and it is important to keep track of what settings and filters that are available. A standard handheld monitoring instrument normally has a high-pass filter of 5 Hz.

2.1.2 Preparation of tests

It is important to prepare your measurements well in order to avoid as many pitfalls as possible. To secure that you get the data and measurement quality you want you might want to leave the equipment in place and measure a while beforehand to secure that the measurement is possible. The availability to the machine or system to be measured might vary and the timing of measurements might change last minute so it is good to be able to have the measurement equipment standby.

For example, the blow-off system that blows down steam from the main steam line to the condensation pool. The measurement purpose was to see how conservative the calculations were. Preparative measurements were done mounting sensors on the reactor wall and then repeated during the regular test campaign. Also, beforehand it was compared with similar tests performed by another NPP, to ensure that the results obtained were valid/reasonable and they were consistent. Lesson learned to always keep a reference point and sensor to ensure that each blowing is the same.

It is rare to know exactly what is expected in advance and what to do and which of the results is required. You must consider when planning, to have a little more information and have planned for extra time so you have time for any modification if necessary.

When preparing measurements it is important to know the purpose of the measurement, what one want to measure and to include a FEM engineer if the results are to be used together with simulations and/or to verify simulations for example so that one knows what the FEM engineer expects of the results.

One typical pitfall is that the receiver of the requested vibration test data has not considered the practical things around the planning of the measurements like measurement points, directions, frequency range etc. Instead they give a request to measure as much as possible which might lead to an overwhelmingly amount of data. It is therefore important to plan the measurements together and to clarify what results that are expected and other expectations and limitations that might affect the measurement at hand. A walk-down with all included personnel are also preferred to clarify for example what is possible to reach and where to attach the sensors etc.

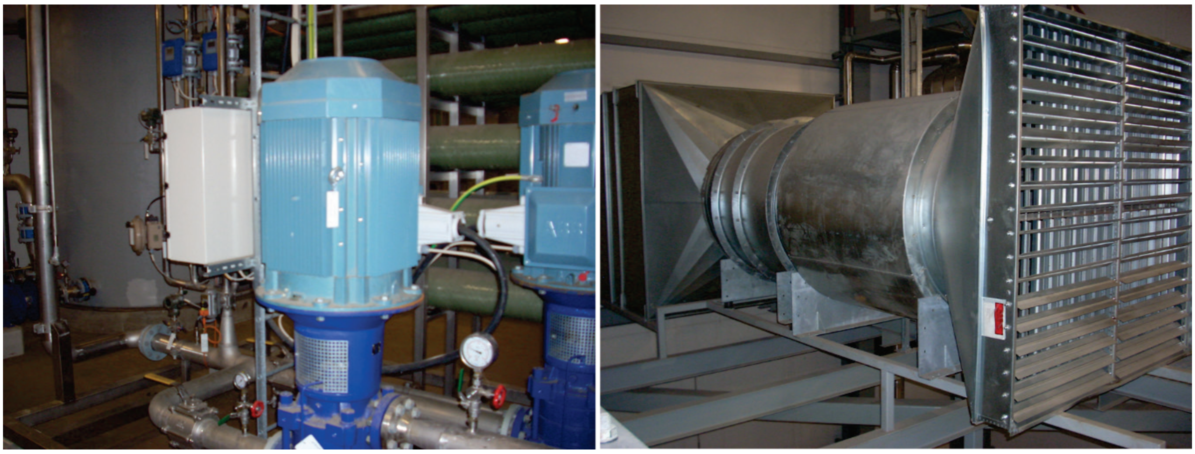


Figure 4 It might be difficult to access the bearing positions due to for example isolating materials, protective plates, cooling flanges, fan coves, pipes, cables etc.

Sometimes there are several systems crossing each other when comparing as-built with drawings and it might be difficult to plan the measurement. There are several examples from the interviews where measurements have been planned using a isometry of a system, but the fact of crossing systems are missed and some of the planned measurement points are not accessible.

Another part of the preparation phase is to discuss a plan of how to handle any last minute changes to the measurement, e.g. if the load conditions change from say 100% to 80%.

When planning for example impact testing it is essential to inform the mechanical supervisor and control room that such testing is going to be performed, so they do not start up or stop another component near the ongoing vibration test. Also, they should not change any valve position during the test.

An example of a planning pitfall: Pumps were planned to be measured at one NPP and different operational conditions were discussed. A few floors above the pumps there was orifice plates, and depending on the operational conditions of the pumps a cavitation problem occurred. The orifice plates were too close to a T-pipe branch and this caused cavitation at a pipe wall which in turn caused high vibrations and a crack in a welding. This problem was due to mistakes done by several different areas of expertise, for example the construction department that placed the orifice plates, the vibration experts were not involved early enough in the process and focus was put only on the pumps and not the piping and flow conditions. Vibration experts were involved to verify pump vibrations. Lesson learned is that all construction changes affects eigenfrequencies etc. and they need to be verified. If something is altered the modification needs to be verified and how the changes affect the system as a whole need to be understood, see 3.2.2 .

Prior to measurement, vibration specialists had not received all the information about the problem and therefore had the wrong sensor sensitivity with them. the vibrations were so high that the accelerometers fell off and the ordinary sensors used was overloaded. The vibration felt like someone downstream were 'loading gravel into the pipes'. The vibration engineers therefore focused on a small bore instead of the choke disc.

Another example of a pitfall. The NPP had too few people who would monitor and measure too large areas, it made it difficult to walk around and get an idea of the problem and how the pipe behaved why troubleshooting took much longer than necessary.

Lessons learned from these pitfalls is for example that if you know that have high frequency vibration/information then you should consider a reliable filter and if possible choose a less sensitive sensor to have margin so as not to overload the sensor, see 5.1. Overall experience when one has strong high frequency vibrations is that lab tests make it possible to see how many filters (digital and/or mechanical) that solve the overload problem best out at the site.

Another experience of pitfall may be that you plan to measure in a place you may not have found out the 'reality' of what is actually possible. That you cannot get your cables laid out properly, see 6.3. This can usually be solved on site. However it can be a little stressful and many other personnel waiting for etc. Then there are often problems with many other technical disciplines working in the same area at the same time and then equipment can break by mistake and important to think before about what can happen and who else will be here and what can happen? For examples if cables are located against hot pipes and can melt apart, etc.

One experience of pitfall is regarding emergency diesel generators. Historically they have vibrated a lot and there have been many efforts with measures by trying to stabilize the machines and one typical pitfall was that one of the measures shorted the vibration isolation of the foundation by adding pipe support. These kind of mistakes needs to be identified first before additional vibration measurements can be done and new measures developed. To compare changes with ''as-built'' is good practice that might avoid many hours of vibration investigation and troubleshooting.

2.2 MEASURE REFERENCE SIGNAL (S) FROM FORCE INPUT

Typical errors when doing impact testing are related to the signal quality and the processing of the signals. It is important to be careful when performing and analyzing the data. Measurement equipment and systems have become much more easy to use and more automatic during the last decades. At the same time this sometimes makes it harder to avoid pitfalls, because one might not be in control of, or fully understand the signal processing made by the software and how different settings affect the result. Low frequencies are in some cases harder to excite and one might miss important information about the structure. For some structures it is not possible to get good impact test results due to soft clutches, tolerances etc.

A common pitfall during impact testing is to measure when other work is going on at the same time and there is a lot of disturbances. Then it is important to try to focus on what you are looking for and what quality you can obtain from your work at that specific time with those conditions. If you cannot avoid disturbances, make sure to document everything carefully. If possible, try to plan for measurement when you won't be disturbed and plan for enough time so that the measurements can be performed even if some disturbances interrupt the measurement and affect the measurement quality.

As always, it is important to keep track of the measurement positions and directions. Often you have your regular measurement running and do a simple impact test without force sensor and just want to know which frequencies are being excited. Repeat this several times to see if the results are consistent.

Typical mistakes are the choice of measurement positions, sensor mounting, sensor resonances, etc. It could also be that not enough points are included, or that cabling has chafed against each other and resulting in disturbances of the signals.

2.3 VALIDATION OF MEASURMENT CHAIN

At the NPPs participating in this project many different types of sensors are used. Piezoelectric accelerometers, Velocity sensors, Proximity probes, Pressure sensors and Displacement sensors. The sensitivity of the accelerometers are chosen for the task at hand, however 100mV/g has proven to be a common choice for many applications e.g. heavy structures.

Choosing the right transducer, amplifiers and cabling for the measurement is a task where there are many different types of pitfalls one might fall into. For example when messing up the cabling or installation there are often disturbances in the signals. For instance a 50 Hz ground loop tone or a DC-offset of the signal and when using very long cabling the cable and connector quality might affect the signal quality, see 6.3. The equipment might be sensitive to temperature, radiation, magnetic fields etc. and therefore it is important to know when to use which sensor, as well as what cabling to use that can withstand the environment for example high temperatures.

Another typical pitfall is electrical grounding issues, which are not simple at all, see 5.2. Different phenomena can be obtained for a standstill and a running machine for example. There are no school book examples but one must learn case by case and gather experience on how to handle the issue and how to install and prepare measurements in different rooms and on different machines.

When the proper transducer is chosen for the right purpose, which is often made based on experience, there is usually no issues with the sensors themself. However, as an unexperienced measurement engineer there are several pitfalls one can end up doing and some of them are described below. However cabling are something that often might cause problems. These problems are often identified by disturbances and transients in the measured signals. One example is the type of sensor cable called microdot. If the connection is wired too tight to the sensor the connection can be lost. Also the pin of the connection can get worn out and that might cause glitch and therefore disturbances in the signal. This can also be seen and tested during calibration.

Typical pitfalls that have been encountered at the NPPs and shared in the interviews are listed below:

- Charge amplifiers
  - × Using charge amplifiers that phase shift the signals, see similar example in section 6.2. This might cause great confusion when performing a modal analysis or an ODS. Wich is a typical pitfall made by an unexperienced user.
  - × In the mid 80s some valves were rebuilt following the same schematics as another NPP site and there were high vibrations after this. Accelerometers were mounted on the valves in order to monitor the movements and the amplifiers were connected and places outside a concrete wall and after that the signals were sent to the control room. It was then discovered that the amplifiers got overloaded and that there was a lot of high frequency content that caused this. Mechanical filters were installed as well as another type of sensor to double check the signal quality and get indications of the best settings for the amplifier. However changing amplifier settings did not solve this problem but a mechanical filter or another type of sensor was needed.
  - × Regarding charge amplifiers a common pitfall is also not placing them correctly and not considering the prerequisites for the measurements. Avoid long cabling and put the amplifier in a cupboard or similar to protect it and the connections from e.g. radiation but also consider mechanical wear, water leaks, steam leakage etc. Lead carpets can be used to additional protection against radiation .
  - × An example of measurement pitfall inside the containment when two charge amplifiers were put one after the other when the supplier had said that one was a filter, like analog filter for the signal and not an amplifier. Very strange results were obtained and the signal made no sense. It is

important to verify what equipment is installed and what specifications it has.

- Transducers and Faulty sensors.
  - × Example where a velocity transducer after a while got a DC offset. The spectrum looked okay when the transducer was calibrated but the amplitude was wrong and the transducer was found to be sensitive to radiation and broken.
  - × Low frequency errors on accelerometer signal causing severe magnification of low frequencies, see section 3.1.5.
  - × When finding a faulty sensor there are different ways of investigating. For example:
    - For velocity transducers – measurement of impedance Ω between conductors and between conductor and screen (so no grounding problem). One of the NPP's test the damping of the transducer signal.
    - Mounting the accelerometer on a calibrator and send in a known vibration signal and check.
    - For modal testing – checking coherence and transfer function – and how it looks, checking frequency signal.
    - Looking at the frequency analysis, spectrum and time waveform, then one can judge if the signal is OK or not OK.
    - Checking that the transducer is mounted correctly – not loose- not on a resonant bracket etc..
    - Checking with the calibrator that one have correct signal from the transducer. Depending of type – measuring the impedance of the transducer between conductors and between conductor and screen
    - If there is a fault in the transducer – change to a different transducer
  - × Other pitfalls with respect to sensors might be:
    - The sensor powering not being turned on
    - Using wrong sensor powering when using an external power supply
    - Using the wrong sensitivity in the measurement setup
    - Mixing sensor direction/orientation when using X/Y/Z
  - × One NPP once found in a measurement that the shock was higher than what was possible for the transducer. The transducer was then changed to an accelerometer with sensitivity 10 mV/g instead of 100 mV/g ,which solved the problem. In some cases there is a frequency content that can excite frequency peaks near sensor resonance.
- Examples of attachment of transducers.
  - × Using magnets on surfaces where it is not preferable. E.g. when a magnet have poor contact to the structure or the structure is not flat. Poor attachment can influence the signal quality. Always check the signal quality before starting the actual measurement.
  - × Changing attachment point or transducer might cause differences between measurements. For example when first using a larger industrial accelerometer and the next time changing to a small accelerometer with a magnet foot on a painted and quite rough surface caused a loss of information and frequency content in the signal. Changing the position again to a flat and unpainted surface caused questions regarding the difference in signals between the measurements.

- The manufacturer had mounted transducers on too weak brackets on the piping and had a grounding 50 Hz noise problem during commissioning in the 1980´s. The transducers and cabling were exchanged for permanent new ones with rigid brackets (around the pipe and a bar sticking out of the isolation with no problem).
- Also, a manufacturer mounted a sensor on a motor flange with a flexible shims desk which gave high frequency content, interpreted as noise from the bearing condition.

Figure 5 Vibration measurement on a steeam pipe – pipesupport – with velocity sensors and accelerometers. Hole drilled at bottom side of the support with a M10.

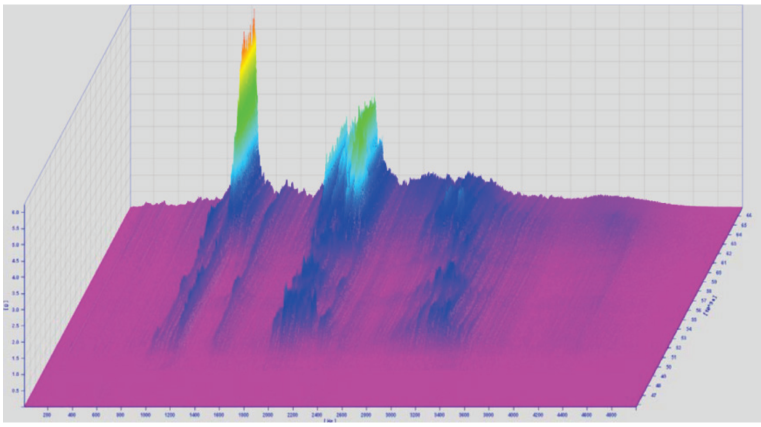


Figure 6 Vibration measurements in a steam pipe. Measured vibration level is dependent on the placement of the sensor on a pipe support. The pipe support have eigenfrequencies at the high peaks exaggerating the vibration levels on the pipe, that can clearly be seen in the results.

- Cabling (see also section 3.1.1 and 6.3)
  - × Example broken cable with a loose contact.
  - × To avoid mistakes with connectors it is good to use a standard connector that can match for most of the equipment.
  - × Regarding online cabling and cables used for mobile units one NPP have tried to use/install a cable with area between AWG20 to AWG24. Normally AWG 22 is well suited for most applications. However, for mobile cabling it is preferable to use a thicker cable like AWG 20. For online cabling over 100 meters, it can be an advantage to use AWG 24. On the other hand, it can be tricky with a thinner cable with different types of connectors and screw terminals (plinths).
  - × Some cables with Teflon (high temperature) where the cable is AWG 24 or less it can happen that the cable easily be damaged, it depends on the softness and hardness of the material.
  - × Typical pitfalls with regards to cabling are
    - – Cable material, hardness, softness
    - – Selection of cable diameter to match the application and length
    - – Selection of type of cable against radiation, oil, environment
    - – Using untwisted cable without shield for long distance.
    - – Cable tags/wire numbering for easy online installation.

Figure 7 Example of cable routing to avoid outer disturbances and broken cables due to other work. However, routing all cables together like this might cause another pitfall, the one of over-hearing between cables or grounding issues.

- Grounding issues creating electrical disturbances like 50Hz tone (see also section 3.1.4 and 5.2). Might be mitigated for transducer using an isolating material called Bakelite between the sensor and the machine/pipe.
- Grounding issues are a type of pitfalls that constantly occur. For example, if you want to measure on one of the fixed sensors, you often have to galvanically isolate yourself to avoid grounding issues to destroy your data signal. However, it depends on what you are supposed to measure on. For example, if measuring using extra sensors on turbines where 50 Hz is the most interesting you should really be certain of that the grounding is secured, otherwise a small signal levels earth faults can be devastating as illustrated in Figure 8.

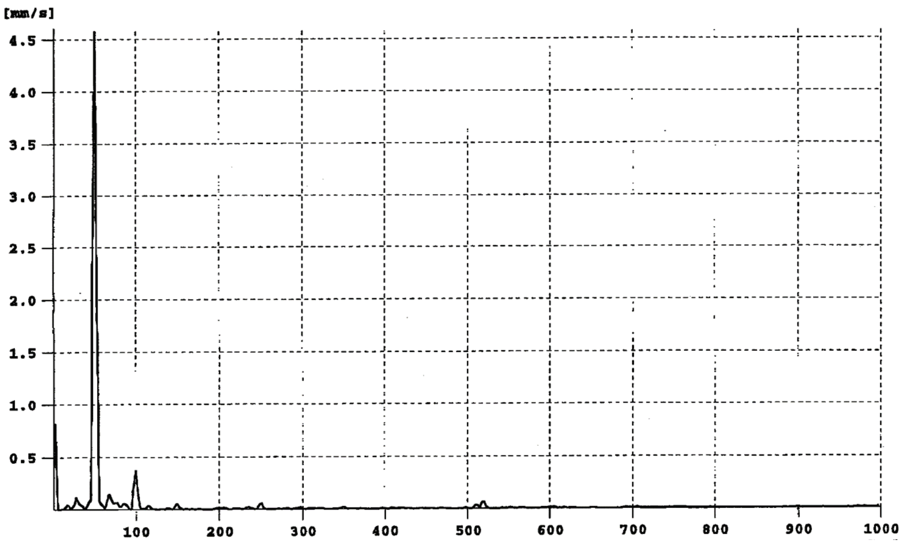


Figure 8 Vibration measurement on a turbine bearing. Disturbances at 50, 100, 150, 250 Hz that ''hide'' increased vibration levels at approximately 525 Hz.

- × NPP experts have experienced examples where a supplier has cut out 50 Hz with notch filters even though in this case it was not a disturbance.
- × A pitfall can be that you think it's a disturbance even though it is not. E.g. measurements of pipe vibrations from a pump with speed of 50 Hz where you can get pulsations with 50 Hz and then you do not want to remove it. It is important to do a background measurement run and test for any noise, etc. and look at the signal and measurement chain before starting.
- × A typical pitfall is when using strain sensors and using very long cables. Then it is easy to get a lot of grounding issues disturbing the measurement.
- × Another example is a fixed sensor setup on a turbine at one NPP. The connectors and amplifiers were put in a box outside the turbine chamber. At that time ground was often connected in the box and up in the control room to always be able to access the cable screens if problems occurred with grounding issues.
- × Pitfall using the wrong cable for the measurement at hand. Getting signal disturbances and grounding issues etc. For example when using a multichannel cable with single signal-cables and common ground. Best cabling according to some NPP experts are a paired and twinned cable with individual screen. That is individual and common screen as well. If you try to measure close to electrical appliances/machines it is important to be careful with cabling in all ways. Example of cabling that work are RG174 and Cat5e.
- × An example of pitfall one NPP expert encountered was that the input channels on a frontend had the ground connected between channels so when the contact of one channel got connected accidentally to ground it got disturbances. Not only that channel got disturbances, but all channels since they were not galvanically separated.
- × One NPP conditioning monitoring system for flow sensors showed strange transients now and then on the signals received. When investigating the cabling no error could be found. It turned out to be due to a rebuild project of the system were a major effort was made to connect the different station earths. The flow sensors with very small voltage changes were affected by this rebuild. Also the accelerometers mounted on the turbine had a lot of issues and since the expert on this monitoring system did not work there anymore and the support of that specific system is quite mediocre. Many efforts were made to try to eliminate the transients on the vibration signals. When changing two cables to new identical cables, the problem disappeared. The problem was caused by two sensors out of one hundred. The conclusion of this was that one should not attach the cable screen at both ends to earth. Experience of NPP experts are that it usually is best to connect to earth at sensor side, see section 3.1.4.
- × Another example. NPP experts had problems at one specific place, where they had extremely sensitive equipment together with other equipment in a cabinet. When the alarm test button was pressed on the other equipment, the sensitive equipment started to sound the alarm. This was due to interference in the cabinet via the wiring shield. The NPP experts solved it by pulling the cabling of one equipment on one side of the cabinet and the other on the other side of the cabinet and this problem was despite

shielded wiring, etc. That is, a cable screen can act as an antenna and receive the error that way. It is typically easy to see if you have this type of issue, earth loops, etc. It is not always obvious that this is the case but when you have problems with sporadic disturbances and transients, you can suspect poorly laid wiring.

  - × A new monitoring system was installed and it had a lot of strange things and transients, intermittent problems that appeared maybe once every two months and these kinds of sources of error can be hopeless to detect. Needed to show that there was a real signal and not a bug in the systems and the problem was solved by rebuilding the grounding.
  - × Another system had errors that occurred once a year. Could not find the cause but eventually switched the wiring to another route and has not had the problem for three years.
- Intermediate boxes:
  - × When installing intermediate boxes there should be an instruction that cables are to be fixed and ''look good''. In some boxes there can be BNC connectors for manual measurements and the access to those connectors should be simple to avoid grounding issues. Also, it should be clear how to connect the shield from the box to earth as well as from sensor shield to earth.
- Sensor sensitivity
  - × Selecting the incorrect sensor sensitivity. For example, the excitation is too high for a standard 100mV/g transducer and a less sensitive transducer needs to be used. This is mostly discovered by looking at the measurement system and the signal quality. It is mostly better to choose a lower sensitivity to be sure not to overload the sensor or of possible, do a quick test measurement to ensure that you have chosen the best sensor sensitivity for the purpose.
  - × Example from NPP. The sensors (accelerometers) in question were located on a construction that was quite high and therefore the sensors and sensor positions were very difficult to access. To still be able to check the vibrations systematically, fixed sensors had been mounted and the signals could be accessed through a breakout box. At some point, the machines were renovated and the sensors were changed at the same time. At that time, the NPP used a system where the original accelerometers had a sensitivity of 50 mV/g but the new accelerometers had sensitivity of 100mV/g. When controlling the vibrations with the system, the settings were not changed due to lack of communication/documentation of the change and the vibrations achieved was twice as high as before the replacement. An investigation of the root cause was deployed and it was soon discovered that the accelerometers had been changed and that the new sensitivity differed from the old sensors. Lesson learned for this pitfall is to be observant for any changes in equipment as well as the settings of the measurement systems.
  - × Another example from a supplier doing tests using many sensors (accelerometers) with different types of sensitivities and if not properly/enough documented it can take quite some time to deduce what sensor belonged to what measurement point etc.

- Temperature sensitivity
  - × Using a sensor that is sensitive to temperature fluctuations and impacts, see section 3.1.5 and 3.1.6. This can create ‘ski slopes’ (high low frequency content) in the signals and there is a need of extra high pass filters and/or the sensor need some time to stabilise.
  - × One specific example of this is a sensor used with the handheld vibration monitor system, where one sensor is extremely sensitive to temperature changes and impacts. E.g. if there is a temperature difference between the measurement surface and the room temperature. It might be enough that the surface is 40-50 ˚C to get this effect. For some applications there are always disturbances of the signal and for some it is more sporadically present.
- High frequency vibration might excite accelerometer resonances and largely exaggerate the vibration levels measured. This is a typical pitfall encountered when measuring on system involving steam pipes, see 5.1. Using accelerometers on high pressure steam pipes is a typical and common pitfall that most NPPs have encountered. It is often discovered due to that the accelerometer overloads or that the signal get a ski slope effect with very high low frequency content or that the rms values, especially when integrated (see 3.1.5), are unreasonably high.
  - × The pitfall to insert accelerometers at the steam flow systems where high frequency vibrations influenced the accelerometers was made because the engineers did not have experience measuring with accelerometers at the high pressure turbine were there was high steam flow and steam howls.
  - × The same pitfall can be made on steam pumps where acceleration becomes overloaded. Mechanical filters from supplier were tested, but these are too soft and feel too weak according to NPP and maybe not adapted for industrial sensors. That is, they worked as filters but did not work assembly-wise since the rubber became very weak and did not feel robust enough to permanently be assembled in the plant. The NPP tested a little harder filter, filter made of Bakelite. Unfortunately this ended up to passed too much high frequency vibrations. Also for this case the solution was to switch to a velocity sensor.
- Magnetic fields.
  - × A non-contact eddy current vibration sensor was replaced to measure vibrations on a rotating disc, see section 3.2.1 for detailed description. The environmental conditions for the sensor was tough due to the steam was highly saturated. That is the water content was very high, and there was a high occurrence of water droplets that had a blasting/corrosive effect on the surroundings. This set high demands on the vibration sensor with respect to temperature (temperature variations between T=60-160 ˚C) and humidity. The new sensor was tested for all kinds of disturbances but missed the tolerances against magnetic interference noise.
- Radiation.
  - × NPP experts experience show that it usually is not the sensors that age due to radiation but the cables that get brittle.

- × Charge amplifiers has shown to be affected. Protect in lead enclosed cupboard or similar. The problems are usually discovered when the system shuts down and no signals can be obtained.
- × Distance from radiation is the best way to protect oneself and the equipment.
- × Always check with manufacturer specifications regarding radiation sensitivity before using the equipment in radioactive areas to avoid this pitfall.
- × Regarding radiation, there are sensors classified for this use however there is rarely any specification on how long they work in radioactive environments. Some kind of stress test is made by the suppliers. However to avoid any pitfalls one has to be distinct with the suppliers what materials must endure radiation, such as Teflon and materials used in semiconductors, because not all suppliers are aware of this. Additionally, it is preferable to put the electronics outside of the containment and use the correct cables for the purpose. Check the sensors/signals on a regular basis and do not count on more than a couple of years of lifespan. Degradation can be observed e.g. that the signals loose high frequency content, see section 6.3.
- × A big amount of cabling with Teflon should not be allowed in the reactor enclosure.

- Pressure sensors
  - × When performing dynamic pressure measurements a common pitfall is getting very high pressure pulsations due to acoustic resonances in the installation most of the time, the sensor is installed in a small bore of the main pipe and the length of this small bore could coincide with the acoustic resonance in the main pipe and then one might get ten times higher pressure pulses in the measurement. Therefore it is important to try to avoid this and to know how to quickly calculate the acoustic resonances (roughly) to get an indication if the high pressure pulsations are due to actual pressure pulsations or due to an acoustic resonance caused by the installation dimensions.

2.4 VALIDATION OF MEASUREMENT CHAIN – SIGNAL

- Another pitfall is when using high pass filters and one does not chose a high enough cut-off frequency. Often 1 Hz is not enough and up to 5Hz might be needed. Otherwise, when integrating the acceleration signal to get the velocity this might cause problems.
- Integration issues are enhanced by the frequency resolution used, see section 3.1.5. For example, if one have a resolution of 1 Hz one often get a ‘clear’ frequency component at 1 Hz and the signal can look healthy even if it is not. This is a typical pitfall made by unexperienced personnel.

2.5 VALIDATION OF MEASUREMENT CHAIN – CONNECTIONS AND CABLES BETWEEN TRANSDUCERS

- Heat and oil might cause large problems since many materials tend to become brittle after a while of exposure, for example cables and the cable isolation. To avoid this issue, it is important to do visual inspection of the equipment on a regular basis. One typical area where this is important is for the emergency diesel generators at some NPPs where the environment is quite harsh with heat and oil. Additionally, it is important that the construction engineers make sure that the correct materials are used.
- A pitfall regarding cabling is to choose the cheapest cables which might not last one season, this could easily be avoided by experience.

2.6 VALIDATION OF MEASUREMENT CHAIN – FRONTEND AND INTERMEDIATE BOXES

When validating the complete measurement chain it is sometimes easy to forget the measurement system, the frontend and also any intermediate boxes. The frontends need to be checked on a regular basis and it is important to know and understand the limitations they might have. If they are sensitive to electrical disturbances, if the channels are galvanically separated, if they give the raw data signal or if they have a built in filter function (analog or digital) that might affect your data and your analysis. Intermediate boxes might be for example a charge amplifier.

Typical errors are:

- Phase shifts originating from some charge amplifiers.
- Using frontends or other intermediate boxes where the channels are not galvanically separated and not making sure that the ground is connected properly on all channels, then you get disturbances on all channels in that system.
- Connecting pressure sensors incorrectly by connecting the plus signal to the wrong connection which then might also affect the rest of the measurement chain. This might take a while to find and sort out. Take care when connecting different types of sensors/signals and try to have galvanically separated inputs especially when connecting to the plant process equipment so that the pant process is not disturbed. E.g. galvanic insulator amplifiers.

To avoid pitfalls it is important to carefully check when new systems are installed – for example by measuring parallel with old system. Compare both vibration amplitude mm/s rms and μm peak and also the phase angle – so they show the same amplitude and polarity.

2.7 VALIDATION OF MEASUREMENT CHAIN – APPLIED SOFTWARE AND SYSTEMS

One of the pitfalls regarding software and systems are all the different measurement systems used, and all different versions and data formats obtained. How do one secure that old data is readable in the future or in other software versions? This is something that most sites consider and struggle with at some extent. Some NPPs have had routines that all data is converted to text (.txt) format and saved in a specific data archive. However, lately the files obtained has become larger and larger and saving everything in .txt format is no longer viable and most data is saved in the original format of the actual measurement system and software used.

However, it is important to consider how data may be used in the future. Data should be stored and how to access it in the future since this could add to future pitfalls for instance stored to wrong format. Clear documentation of the data is essential in order to avoid as many mistakes or wrong assumptions as possible.

Another problem, or pitfall, with using many different types of software is that most of them take some time to learn. If one has to learn too many systems one might not become trained to any of them. To focus on one or a couple of measurement systems and software's might be a great way to avoid so called ‘easy’ pitfalls made when the operator is not completely used to the software at hand.

One way for the NPP’s to mitigate this pitfall is to limit the amount of different software's and systems, and make sure that all operators have proper training in using them.

When it comes to backward compatibility of data and software this can be a pitfall if one installs an updated version and does not check beforehand that old data or projects can be opened and accessed properly in the new version.

A typical pitfall might be compatibility issue due to change of IT platform or newer hardware, or servers.

2.8 VALIDATION OF MEASUREMENT CHAIN – BOOK KEEPING

All NPPs agreed that book keeping is one of the most essential aspects of avoiding measurement pitfalls. Taking clear and specific notes of measurement such as of the setup, the load and operating conditions, the positions and directions of the sensors, what equipment that was used, how the cabling was done etc. using both written notes as well as sketches and photographs is the best way of avoiding many pitfalls. Both during a measurement campaign or investigation, as well as after during a follow up. For example if a colleague has to follow up your measurement in some way, or when a sudden equipment failure occurs or something in the process changes and the signals are suddenly very different.

Common mistakes are:

- When for instance doing a follow up measurement, that the sensor directions or positions have not been properly documented and then makes it difficult to compare the new measurement with the old one.

- Another pitfall is when searching for root cause of vibrations or transients and one measures at a lot of different positions when searching and forget to have a good reference point to be able to validate that the levels are comparable and not due to changes in either structure or operational load.

It's a great strength if you can show afterwards what and how you have measured. To show ''This is what we have done and this is what we have thought'' etc. otherwise a measurement result can create more questions than it answers.

Most of the pitfalls due to documentation are due to inexperience's and/or carelessness due to for example lack of time or a very tight measurement schedule/slot. This is mostly discovered during the report phase and the documentation of the data and how to store the data.

One example was when one NPP had changed sensors several times and different personnel did measurements at different times. The directions of the sensors were different for each measurement and therefore it was very difficult to afterwards go through the sometimes insufficient documentation, and to compare the different measurements with each other. Some of the mistakes regarding bookkeeping can be mitigated by performing most measurements together with a colleague.

Another pitfall is not documenting a measurement enough and when a follow up is to be made, say a year later, most details are forgotten and it is difficult to know what was done and how to repeat the measurement or how to use the results.

2.9 SELECTION OF MEASUREMENT POINTS

When selecting measurement positions there might be many pitfalls. For example due to lack of instructions on how to measure. In some cases, such as when measuring amplitude and phase, an easy mistake to make can be to place the sensor in a different direction than intended or another position. Also when preparing and planning measurements it might be that one plans for using some specific points but then finds that these are hard to access either by being hard to reach or by being covered or otherwise blocked, whereas the pitfall is to not check the accessibility of the points before doing the planning.

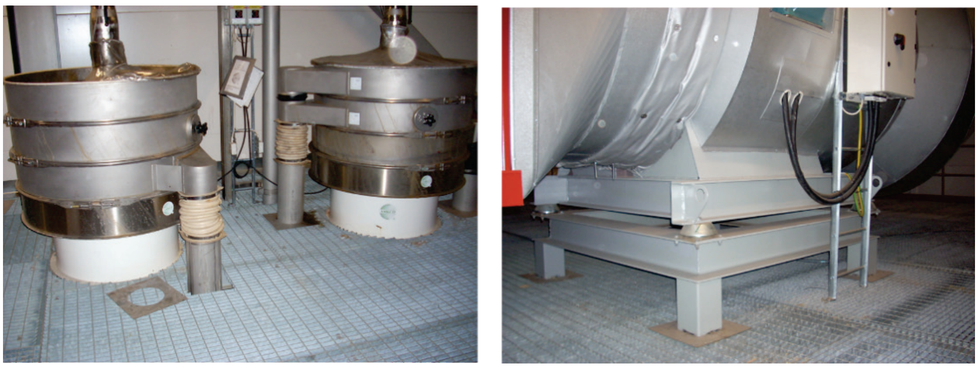


Figure 9 It might be difficult to access bearing positions due to isolation, protective plates, cooling flanges, pipes, cables etc.

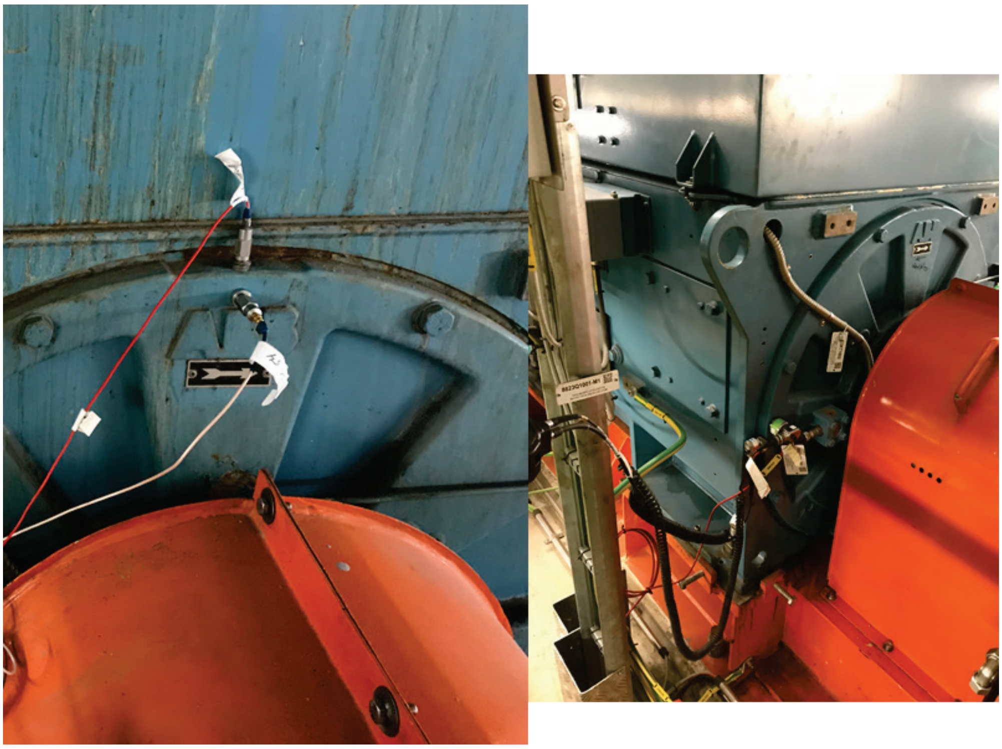


Figure 10 Measurement in axial direction can produce different results depending on the senor placement. To simply assume that only the unbalance of the machine is of interest one might miss that the cause of the bearing degeneration is that the machine foundations is to weak.

To mitigate these pitfalls, it can be preferred to visit the place for the measurements before doing planning and to follow or have common instructions on how to measure and how to select the measurement points. Selection of measurement points depend on the object to be measured. A systematic approach for the selection of measurement points is needed.

The following is an example of a systematic approach to how to select points in order to avoid pitfalls and confusion:

- For vibration measurements on machines – e.g. a horizontal motor-pump – one example is to start with Mp 1 (measurement point 1) on the motor outboard bearing horizontally, then vertically, then axially, after that the motor drive end Mp 2 in the same directions, then the pump drive end Mp 3 H/V/A and finally the pump outboard non drive end Mp 4 H/V/A. This approach is actually the same as MIMOSA ISO and also according to the vibration standard ISO 10816/20816 for example.
- Always start with the motor non-drive end – also on vertical machines. For pipes measure in 3 directions R/T/A or H/V/A or X/Y/Z.
- For a resonance test – enough points and selection of points are important to be able to evaluate all degrees of freedom parallel, both rocking mode and axial.

To select an adequate co-ordinate system for your structure one needs to have an understanding of how the machine operates, the machine components, and knowledge about the expected failure pattern. Most NPPs have practical instructions for those who perform the measurements on site.

Some NPPs require additional measurement point at specific positions on reciprocating machines, like suction and discharge valves. Also, on diesel engines e.g. on the cylinder top, fuel nozzle pipes, pipes and the foundation.

For complex objects it is good practice to mark the measurement position. Some NPPs do use a metallic glued plate on the machines for safety reasons as well as for practical reasons when doing maintenance or replacing the components.

Another example of a mistake or pitfall made in one NPP, some fixed points where the sensor was delivered on the machine show different results to temporary measurement sensors due to different sensitivity or sensor position and fixture method, the measurement position showed either higher or lower levels comparing to hand held measurement. This could be avoided with a systematic approach to choosing points and fixture method etc.

In some cases, like for axial fans with the motor inside the pipe-duct, there may be a damped signal-attenuated when placing the sensor on some positions.

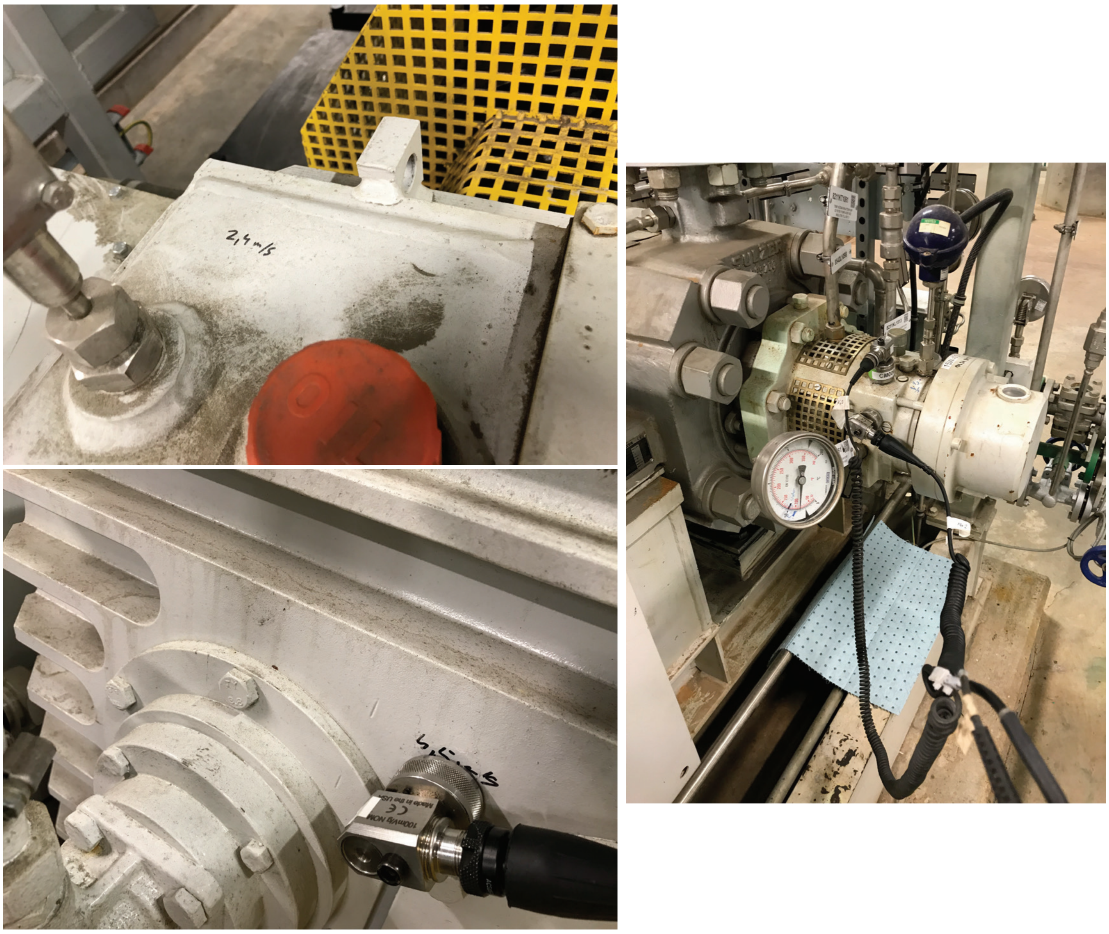


Figure 11 Vibration measurement on equipment with unidentified measurement positions – simple markings from earlier meassurements might be a good guidance for follow up mearurements. The figure shows a gearbox for a diesel generator set.

2.10 VALIDATION OF RESULT

Many pitfalls can be made when measuring vibrations and therefore validating the results are very important in order to avoid them. Some examples to mitigate pitfalls described by the NPP experts are as follow.

For ODS measurements it is necessary to measure both amplitude and phase information to verify mode shapes during running conditions. Some systems have a default setting to always measure auto power spectrum which just gives amplitude information. This is often forgotten to change to spectrum function instead to both get amplitude and phase information.

When preparing a resonance test using impact hammer on a new structure, most NPPs test with different force tips (soft to hard) to see which frequency range is excited and if the hammer is of correct weight in order to excite the structure sufficiently.

If a new structure/machine is tested – it is sometimes necessary to test with different trigger settings. Also, it depends on the selected hammer and response sensor sensitivity. The analyzer has its own default setting that normally should match the trigger level. In some cases, it depends on the structure and there may be a need for a slight adjustment of the trigger.

To avoid measurement pitfalls and to ensure good measurement and data quality it is recommended by NPP vibration specialists to bring reliable cables and spares with you. The transducer mounting is also important so that it is not loose. Choose proper equipment depending on the object and use the same type of sensor with similar sensitivity and properties in case there is a need to compare with another object.

A key factor to consider to avoid pitfalls when validating the results is signal integration. The acceleration signal is converted to a velocity signal by time domain integration. Normally no double integration should be used, i.e. converting acceleration to displacement. The signal can have a ski-slope shape at low frequencies, which destroys the pattern of the time waveform, see section 3.1.5. To trust these signals or to not investigate them further and/or to validate their reliability is a typical mistake made by both unexperienced and experienced personnel.

Unsteady impacting or any other human factor that can affect the signal is another issue.

A common mistake when validating results is to not measure on the same place each time, especially on some bearing housing with a size between 300-600 mm, (see also section 4.1 for a more detailed example regarding selection of response positions). The result can be different when measuring near the seals or on the free end of the bearing. The same is valid for the horizontal and vertical directions. The result can be different vibration levels, also the content in the spectrum can differ.

3 Learn by doing – Vibration measurement pitfalls

Almost everyone, from a small child to a skilled experienced vibration engineer, has its own experience to vibrations but in different scopes. Sometimes an unskilled vibration engineer can with a very good human sense detect a vibration problem without having any vibration measurement equipment to validate them. The human body has the benefit to sense vibration and interpret vibration as good or as dangerous in a subjective manner. Especially if the person in charge has a long experience of the field he/she is responsible for. Sometimes very small signs of dynamic variations can be judge as somethings is abnormal and should be investigated further.

However, it gets complicated when there is a need to deal with special cases of vibration in specific environments like hot steam pipes with valve openings, vibration measurement in a tough environment due to radiation, magnetic and electrical interference, transients vibrations etc. When things get more complicated there is usually a need to use testing equipment suitable for the task which can deal with the complexity. When the human sense to judge vibration is combined with the output of an instrument the limitations with the instruments must be learned by experienced. In theory you can learn how your instrument work but you need to learn deeply by experience, learn by doing in order to avoid the pitfalls.

Small insignificant source vibrations can excite resonant frequencies of surrounding structural parts where the vibrations often increases so much that they become dangerous. This needs to be investigated with proper instrumentations and methods for verifications and you need to be aware of that there will always be some measurement pitfalls to take care of.

This report is dealing with vibration measurement pitfalls. If you are experienced user you are often aware of all easy pitfalls which is well-known for you. You have already done them or read and aware of them. If you do a pitfall at this stage it's often very difficult and time consuming to detect, investigate, analyze and to cure the pitfall. Hopefully you don't do so many pitfalls when you are experienced since often they often have a big impact on the project you are involved in. However, if you have done them you should not be afraid to share your mistakes.

On the other hand when you are a new unexperienced user it's very important that your working climate allows for doing mistakes because you are in a learning process and will not repeat the mistake to next time. In this stage there is often many mistakes done but to detect, investigate, analyze and to cure them is often not so time consuming. As a note it can be told that the founder to Swedish Consulting company "Ingemanssons Ingenjörsbyrå", Stig Ingemanssson (present Efterklang part of AFRY), strongly encouraged all vibration engineers that it is OK to do vibration measurement pitfalls. Just remember how your thinking was at the time when you performed the measurement.

3.1 COMMON PITFALLS FOR UNEXPERIENCED STAFF

In this chapter it will be describe examples of common pitfalls for mainly vibrations measurements dealing with accelerometer measurements since this is the most fundamental sensor for taking vibration measurements.

It is very common to use acceleration measurement to measure velocity vibrations (followed by an integration of acceleration).

3.1.1 Cable noise

Cable noise is mainly the issue of piezoelectric accelerometers having a high output impedance. These disturbances can result from triboelectric noise or electromagnetic noise. Triboelectric noise is often induced into the accelerometer cable by the mechanical motion of the cable itself. It originates from local capacity and charge changes due to dynamic bending, compression, and tension of the layers making up the cable. This problem is avoided by using a proper graphitized accelerometer cable and taping or gluing it down as close to the accelerometer as possible.

Also, it is critical to maintaining high insulation resistance of the transducer, cabling, and connectors by keeping them dry and very clean. Given these precautions compared with the simple operation of voltage-mode accelerometers, charge mode accelerometers are generally only used in high temperature, high acceleration applications.

3.1.2 Measure vibrations with charge mode accelerometers

Charge mode piezoelectric accelerometers output the high impedance electrical charge signal generated directly from the piezoelectric sensing element. These transducers require an external charge amplifier (better option) or an in-line charge converter to convert the high impedance charge signal to a low impedance voltage signal suitable for measurement purposes. Since the output is high impedance, the charge signal is very sensitive to noise, i.e. cable shaking, from the surrounding environment and several important precautionary measures should be taken for proper measurements.

In Figure 12 there is an example of noise pick-up caused by shaking cable between charge accelerometer and amplifier in frequency level below f=2 Hz. Note extreme maximum level of 60 000 mm/s rms at f=1 Hz.

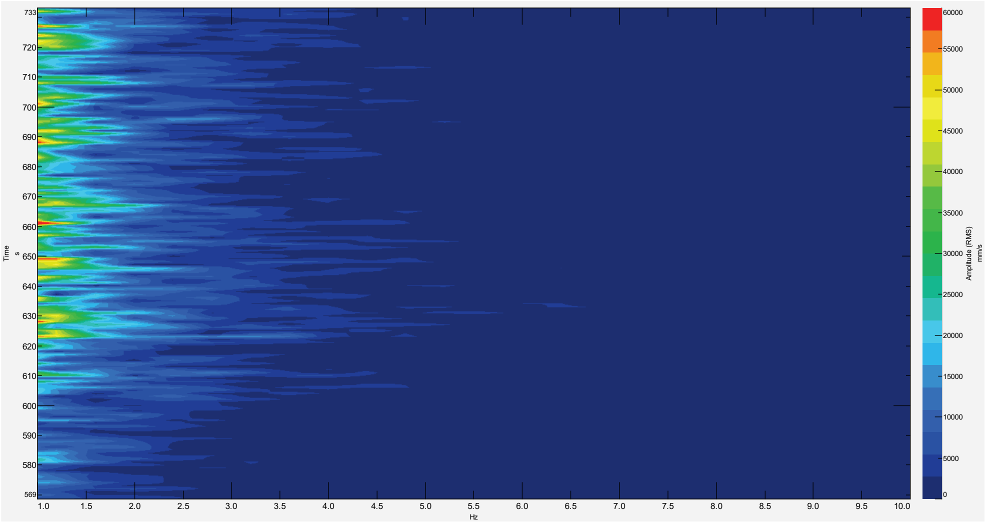


Figure 12: 3D spectrum between f=1-10 Hz showing the response from charge accelerometer which picks up low frequency disturbances from shaking cable

Figure 13 shows the same measurement but in a higher frequency range, f=10-40 Hz, where the expected combustion vibration becomes visible. The vibration at f=18 Hz has an unrealistic high vibration level of 700 mm/s rms and is a result of the low frequency noise from the cables. The cable shaking error declines exponential and then influence even the higher frequency as f=18 Hz when the vibration at f=1 Hz was 60 000 mm/s rms.

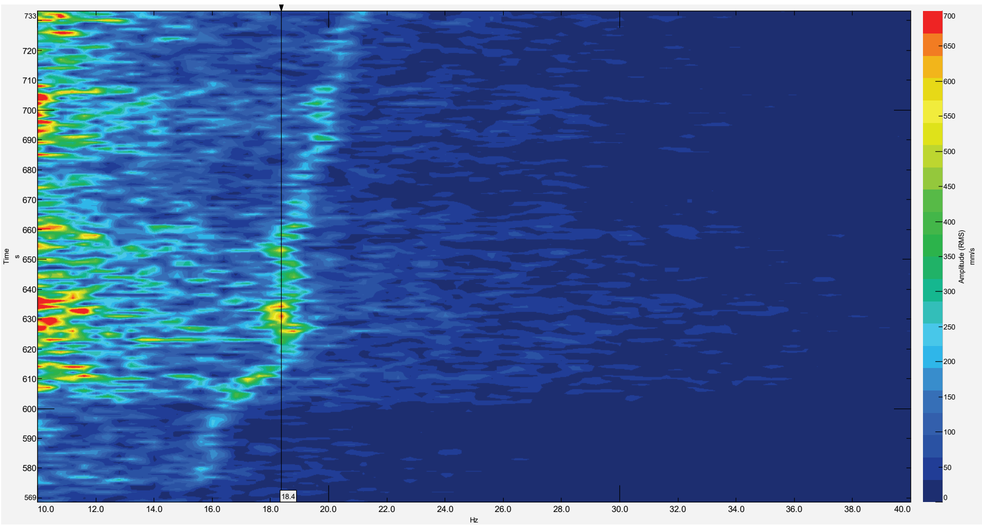


Figure 13: 3D spectrum between f=10-40 Hz showing combustion vibration influenced by the low frequency cable shaking error.

Mitigation to the problem was in the first place tried to secure the cable with tape. However this did not help as the testing place kept an overall high vibration level. The problem was solved by using an ICP accelerometer which allows for a low impedance cable instead, not so sensitive for cable shaking. This reduced the noise from the cable with a factor of approximately 100.

3.1.3 Transvers vibration

Piezoelectric accelerometers are sensitive to vibrations acting in directions other than coinciding with their main axis. In the transverse plane, perpendicular to the main axis, the sensitivity is less than 3 to 4% of the main axis sensitivity (typically < 1%). As the transverse resonant frequency normally lies at about 1/3 of the main axis resonant frequency this should be considered where high levels of transverse vibration are present.

3.1.4 Grounding problems

Electromagnetic noise is often induced in the accelerometer cable when it is placed in the vicinity of running machinery.

In an industrial environment the machine or equipment which the accelerometer is mounted to may be at a different electrical potential (voltage) than the ground at the electronics rack. With the shield connected on both sides to ground we create a so called *ground loop* in which a current will circulate if the ends of the shield are held at different potentials. Because the resistance of the shield along the cable is not zero we will find different voltages along the shield which in turn will couple in the live pole due to the capacity between the shield and the conductor.

It is important that the shield of the cable is grounded only at one end! This is to avoid any *ground loop*. Normally the quality of the ground is better at the electronics end than at the machine. That is why this is the preferable end to ground the shield

Below is an example of a bump test which includes 4 hits between t=0-34 s with two different types of accelerometers (one charge accelerometer dedicated for high temperature and the other ordinary ICP temperatures for room temperature) measuring the responses from the bump test simultaneously at room temperature. When the two responses are compared, Figure 14 and Figure 15, it's obvious that they have different galvanic isolation. Accelerometer in Figure 14 picks up almost all energy into the f=50 Hz like a magnet and the resonances from the bumps are difficult to detect. Additionally the four different impacts can almost not be distinguished in Figure 14 due to vibration energy sink at f=50 Hz. Note also that the f=50 Hz disturbance is not constant in level during the time elapsed. The variation to the amplitude at f=50 Hz is often occurring and reflects the dynamic variations in the surrounding environment.

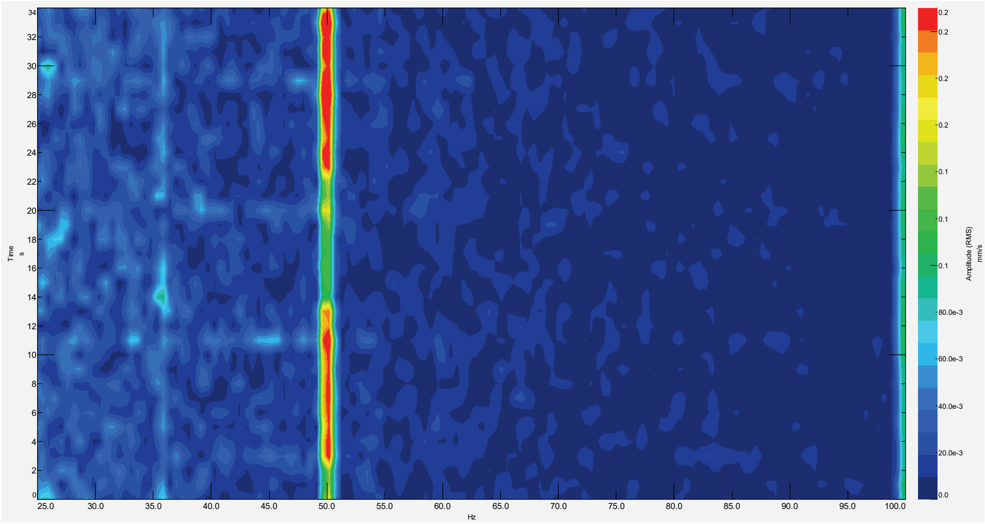


Figure 14: Structural bump test with four impacts measuring with a charge accelerometer (high temp) affected with ground problem at f=50 Hz

On the other hand the ordinary ICP response accelerometer, see Figure 15, detects the response correctly free from f=50 Hz disturbances.

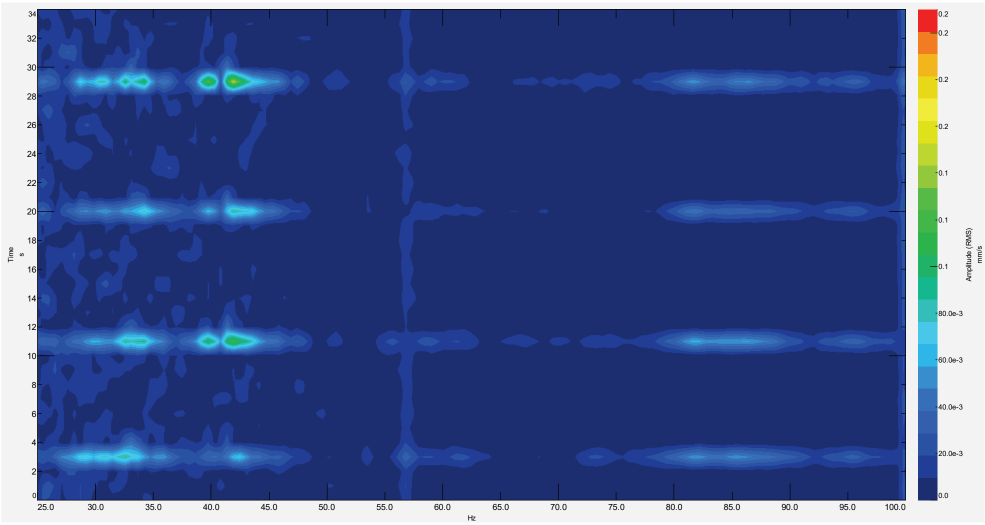


Figure 15: Bump test with a ICP response accelerometer in close proximity to the high temp charge accelerometer. Signal free of f=50 Hz disturbances

The high temp charge accelerometer is equipped with an in-line charge converter which takes the power from the logger instrument to convert the signal of high impedance piezoelectric sensor into voltage signal at a low impedance level. By replacing the in-line charge converter to an off-line battery charge converter, the f=50 Hz problem was solved.

To summarize when there is grounding problem and the measurement chain includes a peripherical devices that gets its power from a 220 V source it's always a good idea to try to replace it to an off-line battery converter to get rid of the f=50 Hz problem.

3.1.5 Low frequency vibrations measured with ICP accelerometer (IEPE)

The charge q on a piezo element will slowly decay to zero when it is left on its own, see Figure 16. This is due to a very small leakage current between the plus side and the minus side of the piezo element. As a result the charges on both sides equal out after a while.

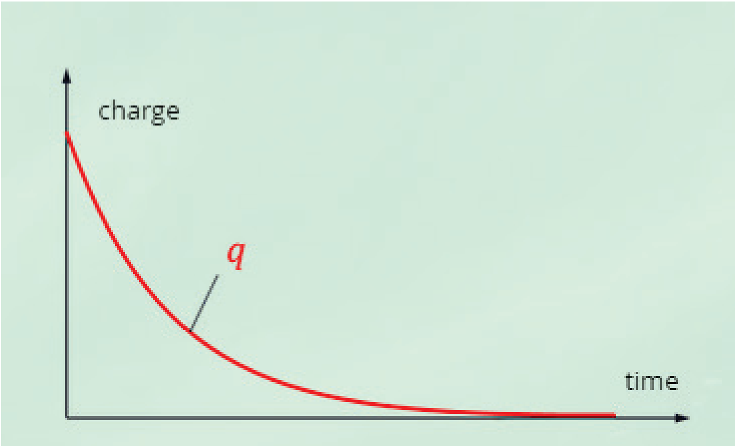


Figure 16: Natural discharge curve of a piezo element

This is the reason why static vibrations cannot be measured with piezo elements. The vibration must be “quicker” than the relaxation of the signal. The self-discharge of the piezo element may lead to a problem at low frequencies. As the discharge happens not only for static charges but under all conditions it’s easy to imagine that the refreshing of the oscillating charge signal must be faster than the discharging otherwise the charge signal will disappear. Although the signal will not disappear suddenly, the amplitude will be reduced more and more when the frequency is decreased.

The duration of this relaxation is governed by the so called **time constant** which in turn depends on the *electrical resistance* between the electrodes and the *capacity* of the piezo-element.

For an ICP sensor there is also a built in charge amplifier inside the sensor which converts the charge to a voltage signal. This establishes the low-frequency response analogous to the action of a first order, high-pass, RC filter as show, see Figure 17.

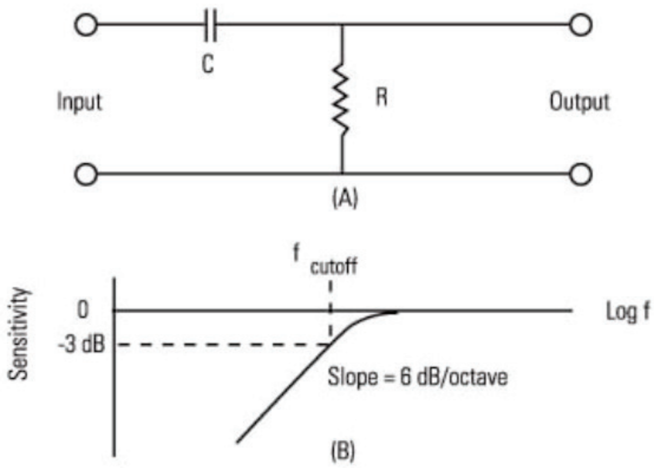


Figure 17: The discharge time constant of an ICP® sensor establishes the low-frequency response analogous to the action of a first order, high-pass, RC filter as show

The high pass filter cutoff frequency, f_{cutoff} , is defined as

$f_{cutoff} = 1/(2 * \pi * R * C)$ **Equation 1**

where R*C = DTC

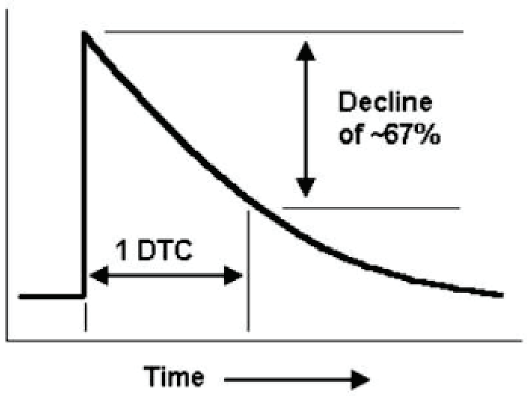


Figure 18: Discharge curve pointing out 1 x DTC time at -3dB reduction

The DTC is the time it takes a signal to decline to ~67% of the peak value of a transient (-3dB). Typical DTC times may vary from 0.1 s – 10 s for general ICP accelerometers. The longer time the better to detect low frequencies but also more sensitive for low frequency noise.

Table 2 shows typical cutoff frequencies for DTC times.

Table 2: Discharge Time Constant DTC: 0.1s-10 s, with corresponding different cutoff frequencies for sensitivity reduction with 5% 10% and 67 % (3dB)

DTC (sec	Frequency (Hz)		
	-5%	-10%	-3 dB
.1	5	3.4	1.6
.5	1	.68	.32
1	.5	.34	.16
5	.1	.07	.03
10	.05	.03	.016

As can be seen from the table a longer DTC time implies that the sensor can measures ideally very low frequencies as long as the sensor has a low noise floor.

The sensor noise floor becomes better with a more sensitive accelerometer. The noise level is natural high in the low frequency range due to the "1/f" spectral noise. By comparing the noise floor in Figure 19 there is almost a factor of 20 reduced noise floor with a 5 times more sensitive sensor for low frequency range.

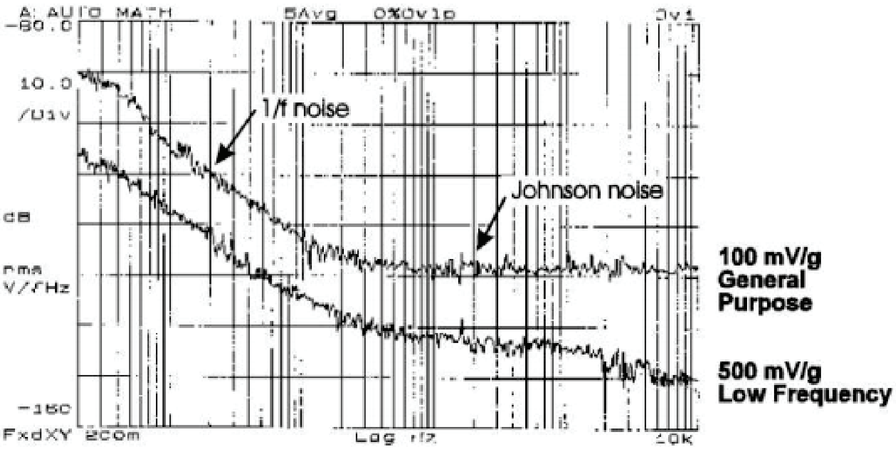


Figure 19: Noise difference between a 100 mV/g and 500 mV/g ICP accelerometer. Note the amplified low frequency "1/f" pink noise level at low frequencies.

This filtering characteristic is useful for draining off low-frequency signals generated by thermal effects on the transduction mechanism. If allowed to pass i.e. a too low cutoff frequency is selected, this could cause drifting, or in severe cases, saturate the amplifier. When the amplifier is overloaded the low frequency amplitude readings will show unrealistic high values. Especially unrealistic values are pronounced when acceleration is converted to velocity by integration or a double integration to displacement. An integration of the low frequency spectral pink noise is scaled as 1/f will by an double integration to displacement be scaled to magnitude of $1/f^2$ instead. Most noise from electronic devices (cables, amplifiers, sensors etc) picks up as pink noise.

3.1.6 Test examples showing common pitfalls for low frequency testing with ICP sensor

A controlled measurement in a test rig excited with a white noise excitation between f=0-100 Hz where the FRF between an LVDT displacement sensor and a double integrated ICP-accelerometer signal with sensitivity 100 mV/g was formed without any external or digital high pass filters added to remove DC component. However the ICP sensor DTC time at -3db was t=0.5 s which sets the HP cutoff frequency at f=0.32 Hz, see Table 1.

The test was taken at different temperature increase from T=30 ˚C up to T=90 ˚C in five steps, see Figure 20, and the aim was to find out how sensitive the ICP accelerometer is for temperature variation and how this influence both frequency and amplitude when using the LVDT sensor as a reference.

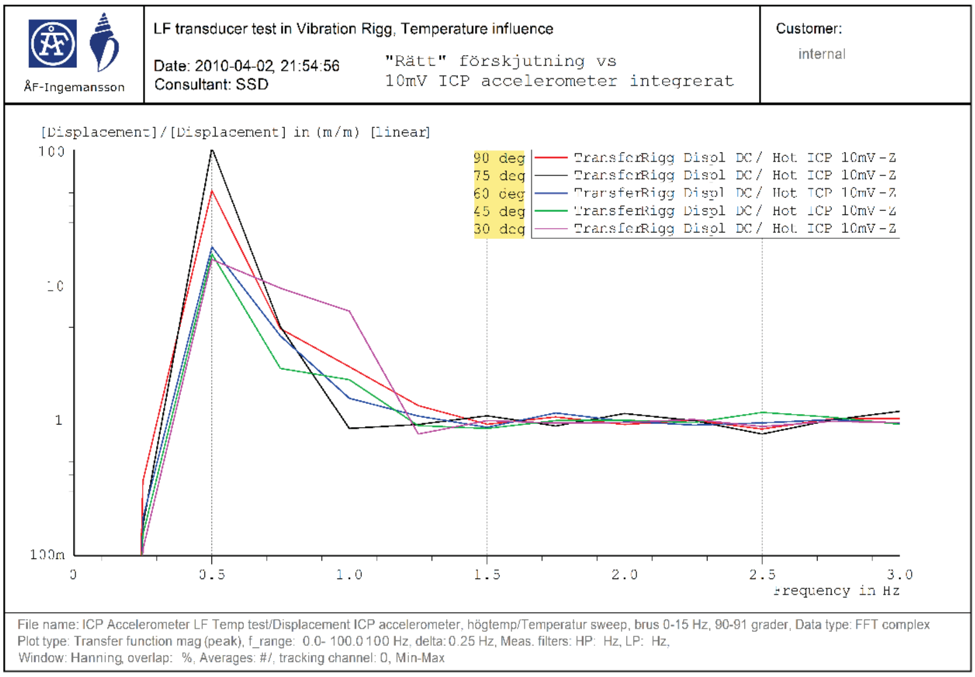


Figure 20: ICP accelerometer 100 mV/g compared with LVDT displacement sensor during a heating process at T=30, 45, 60, 75, and 90 ˚C

As can be seen from Figure 20 the effect of temperature variation up to T=90 ˚C influence frequency range up to approximately f=1.3 Hz. Above f=1.3 Hz both sensors register equal magnitude for both LVDT sensor and ICP sensor (=FRF value is 1). It's also evident that the sensor itself cannot filter out the high thermal noise at f=0.5 Hz with the DTC -3dB HP filter at f=0.32 Hz which is expected. The magnitude is amplified a factor of 100 at T=75˚C (black curve) at f=0.5 Hz. The exaggerated amplification is also occurring during warm room condition, T=30 ˚C , but lesser amplification of approximately 20 instead of 100 at f=0.5 Hz. This can be explained by the double integration of ICP acceleration without adequate HP filtering to remove electrical noise which follows pink noise (1/f low frequency noise) behavior. An integration of pink noise will upscale the low frequency contribution to scale with $1/f^2$.

Another typical low frequency pitfall in judging the low frequency range from ICP accelerometer comes from a measurement taken on motor component to a pump installation. A triaxial ICP accelerometer sensor was mounted on the motor component measuring vibrations in x, y and z- direction according to picture in Figure 21. In the transverse Y-direction the pump registered dominant repetitive low frequency transient shocks in frequency range f=1-10 Hz. Minor shocks in lateral x-direction and vertical z-direction. The pump was mounted with the suction side in wrong plane (horizontal instead of vertical) which might be the cause to the shock problem to the motor.

The measurement showed an overall level of approximately 80 mm/s rms in frequency range f=1-10 Hz after an offline digital high pass filter was applied on the time signal at f=2 Hz. This cannot be a real vibration since no visible vibration was subjectively observed during the measurement.

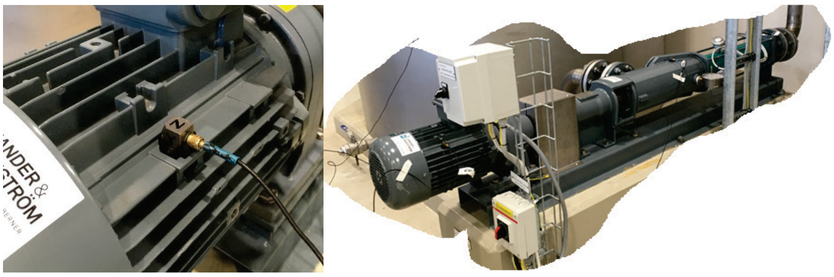


Figure 21: Accelerometer position for motor vibration, Z: vertical, X:lateral, Y:transverse direction

HP filtered time signal with corresponding spectrum at one shock event around t=140 s is shown in Figure 22.

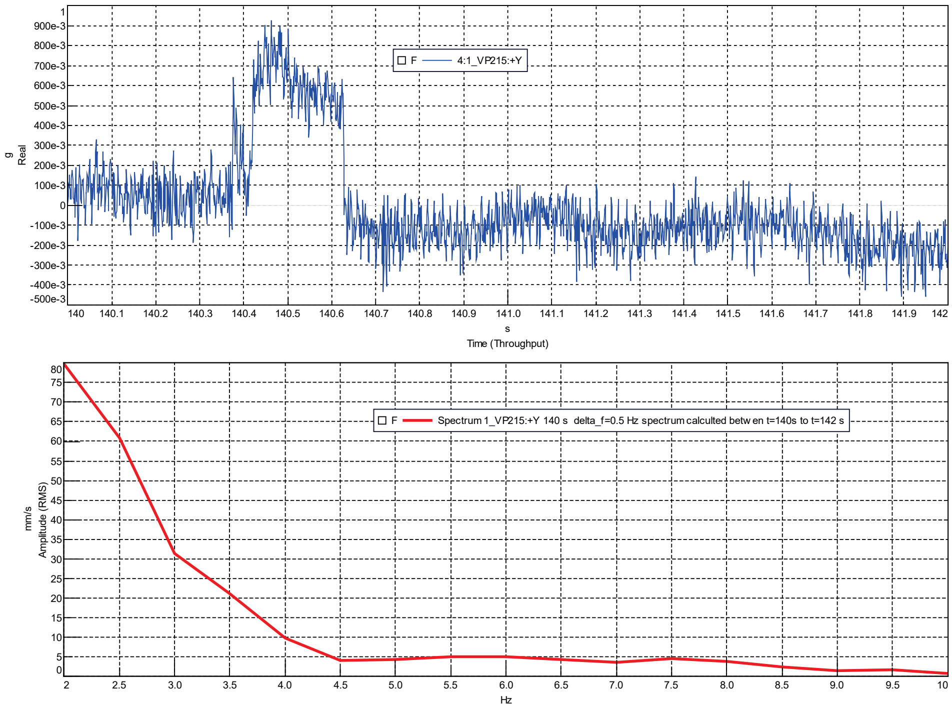


Figure 22: Upper curve - HP filtered time signal at f=2 Hz between t=140-142 s. Note the steep slope at t=140.4 s and at t=140.6 s of the shock.

Lower curve – Spectrum between t=140-142 s with frequency resolution 2 Hz showing the low frequency “ski-slope” error.

As can be seen from HP filtered time signal this still has a trend and is not removed by the filter, i.e. signal is not fluctuating around 0. The sensors internal amplifier is most likely saturated at the moment of the steep rise and fall time of the shock. The ICP’s internal electronic cannot recover fast enough to stabilize the level after the shock. As a result the well-known “ski-slope” due to trend dominates the frequency spectrum in the low frequency range.

Earlier in the measurement sequency at time t=5-6 s there are no strong transient shocks. The corresponding time signal with its spectrum then looks normal with reasonable vibration levels and can be seen in Figure 23.

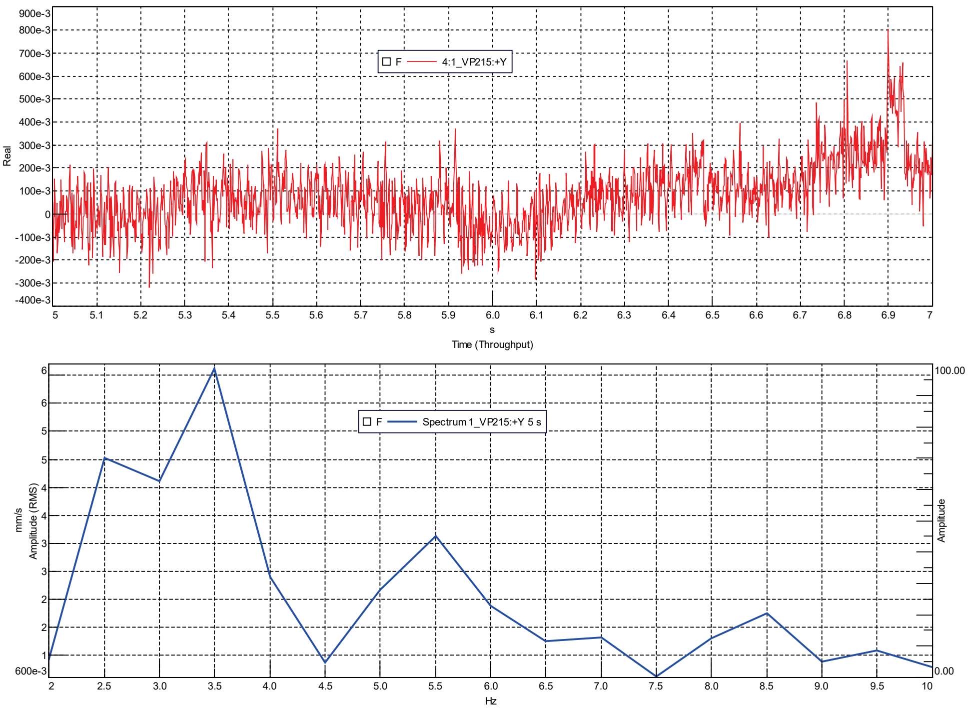


Figure 23: Upper curve - HP filtered time signal at f=2 Hz between t=5-7 s.

Lower curve – Spectrum between t=5-7 s with frequency resolution 2 Hz with normal dynamic response

3.2 DIFFERENT SCENARIOS FOR VIBRATION PITFALLS FOR EXPERIENCED STAFF

In this chapter there will be described two different stories from more complicated vibration measurement where measurement pitfalls prevented the testing to be quick and easy and on time to follow the overall project schedule.

3.2.1 Story 1, measurement pitfalls during turbine testing

Below there is an example of an extensively investigation regarding high pressure radial turbine vibration which took one year to find out with lots of efforts and resources.
This pitfall is related to a non-contactable eddy-current displacement sensors and installed on left and right system sides of a radial HP turbine as described in Figure 25.

As a result of this problem investigation, the energy availability from the block was just 0.7 % delivered to the electrical distribution net during the problem identification year.

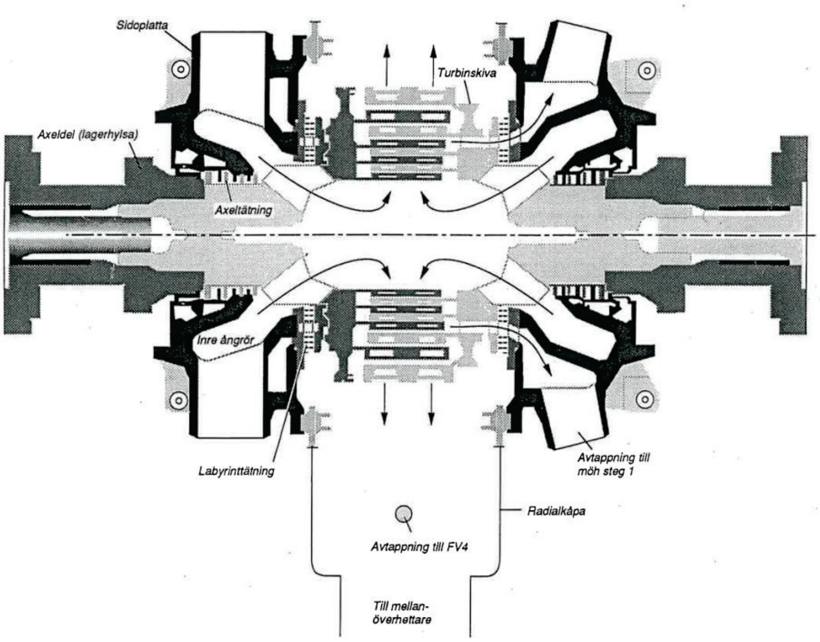


Figure 24: Principal drawing of a radial high pressure turbine

Inside a HP-turbine, see Figure 24, the environment is extreme. The moisture content of the vapor is very high with the presence of water droplets that has an almost blasting effect on the surroundings. This sets very high demands on the vibration sensors. The temperature range varies between T=60-160 ˚C.

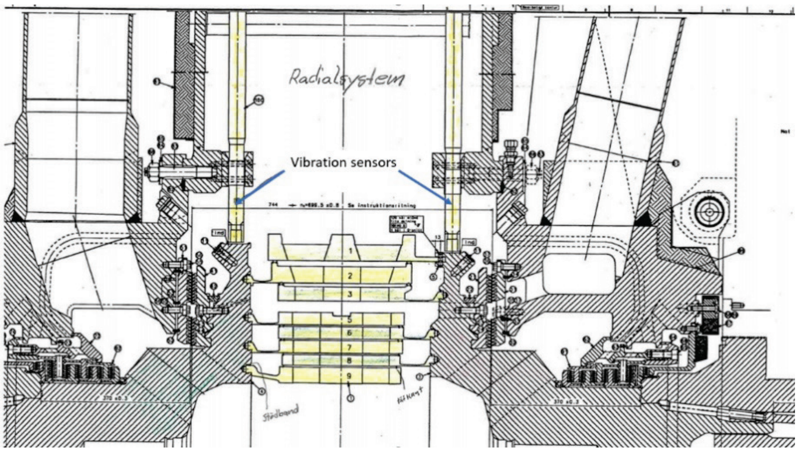


Figure 25: Position of non-contactable displacement sensors mounted on probes with spears

The plant had during several years used eddy current sensors with porcelain housings but due to aging and the blasting effect described above the sensor could not cope with the environment. The choice fell on a sensor that had a metal housing. It was considered capable of coping with the harsh environment. Selected sensors were actually intended for distance measurement in demanding environments. Extensive tests were carried out on the sensor in terms of amplitude, frequency range and impact of temperature and fulfilled the demands.

The newly metal housed eddy current displacement sensors was equipped on left and right radial HP turbine side. At speed 1500-1700 rpm the overall levels increase on and then decrease again. The largest deviation comes in the speed range above 2200-3000 rpm. A detailed spectrum at 3000 rpm shows harmonic components of the speed and half of the speed occurring, see Figure 26 . The highest vibration are above 300 µm which are quite a lot above acceptance level for this component.

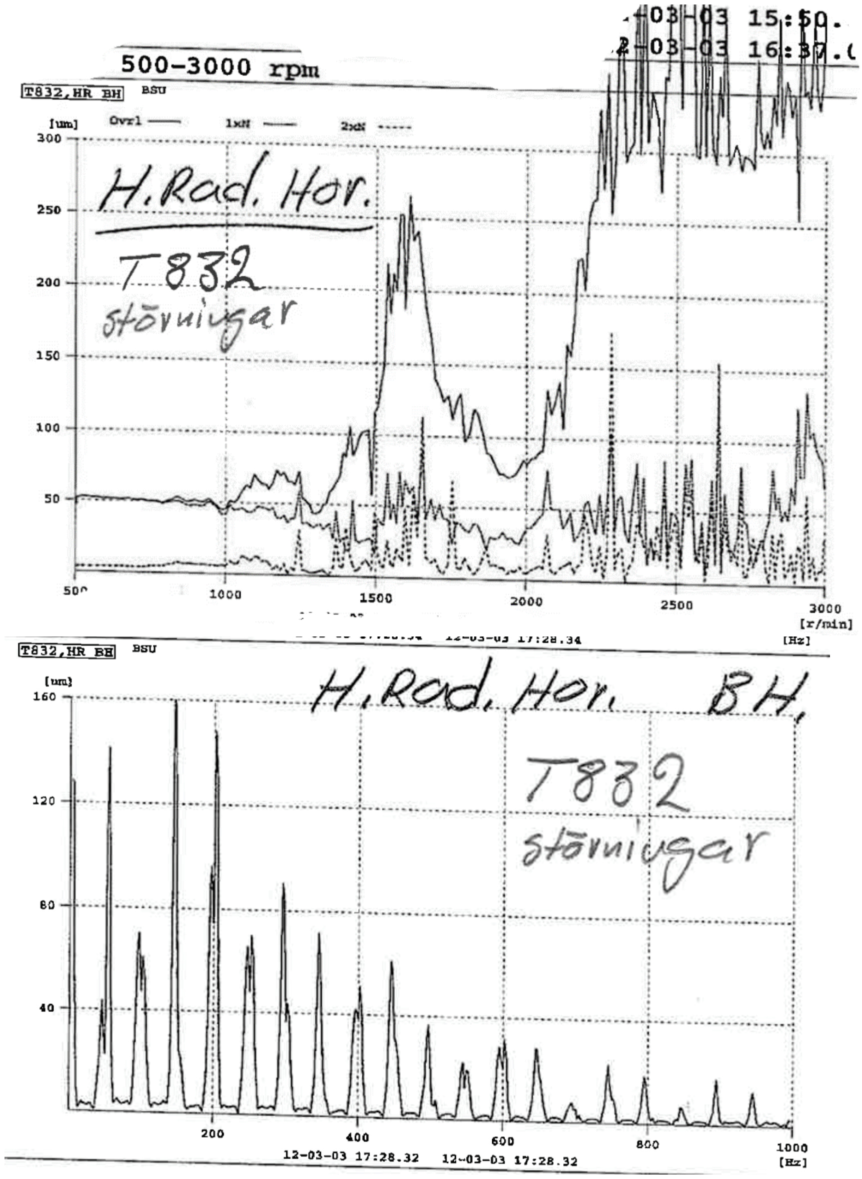


Figure 26: Horizontal displacement measurement from an disturbed eddy current sensor.
Upper diagram – overall level together with (1 x rpm) and (2 x rpm) level between 500-3000 rpm.
Lower diagram – displacement spectrum at 3000 rpm

The cause of the behavior with harmonics could be due to several reasons. If the measuring chain is ok the frequency image (multiples of the speed) indicates that something is loose. The pattern is typical of something that hits the rotor or vice versa.

In the case of the sensor spear, the lower part of the thread is newly manufactured. Gaps here could affect the measurement but are not likely.

The measuring surfaces is turned and polished. The system had not been operational since this was fixed. The surface had been damaged a number of years ago due to a protected sleeve for a vibration sensor that came loose. The older damaged surface caused interference with the measurement signal.

The nature of the measuring surface is less likely to be the cause of harmonics the spectrum shows. It doesn't explain why there is also a similar behavior of the left side sensor.

In the problem solving phase the HP-turbine was installed with temporary vibration sensors on radial cover and in the bearing near the radial system. After a number of roll-ups, it is clear that the vibration sensors pick up interference from within the radial system and not outside on the covers and bearings.

Next the radial system will be dismantled for error examination. All drums were inspected. The measuring surfaces of the eddy current vibration sensors were turned and diamond pressured to ensure the quality of the measurement. No problems were found.

Also, additional balancing tests showed good results but the problem remained after several tries of restarts during the year.

Finally the problem was traced down to be caused by faulty magnetization on the measuring surface of the vibration sensors. The magnetization of the measurement surfaces was contaminated with left over from magnet particle testing which was carried out probably four years earlier for crack detection. The former porcelain eddy current sensors was in- sensitive for these disturbances and therefore no one thought about to test the new metal housing senor for sensitivity against magnetic field disturbances.

The phenomenon of magnetic disturbances on the measuring surfaces could be recreated at Siemens test facility in Finspång. Here, tests were carried out with demagnetization of the measuring surfaces that gave very successful results. The measuring surfaces of the radial HP turbine are demagnetized and roll-up was measured with good results after the finding, see Figure 27.

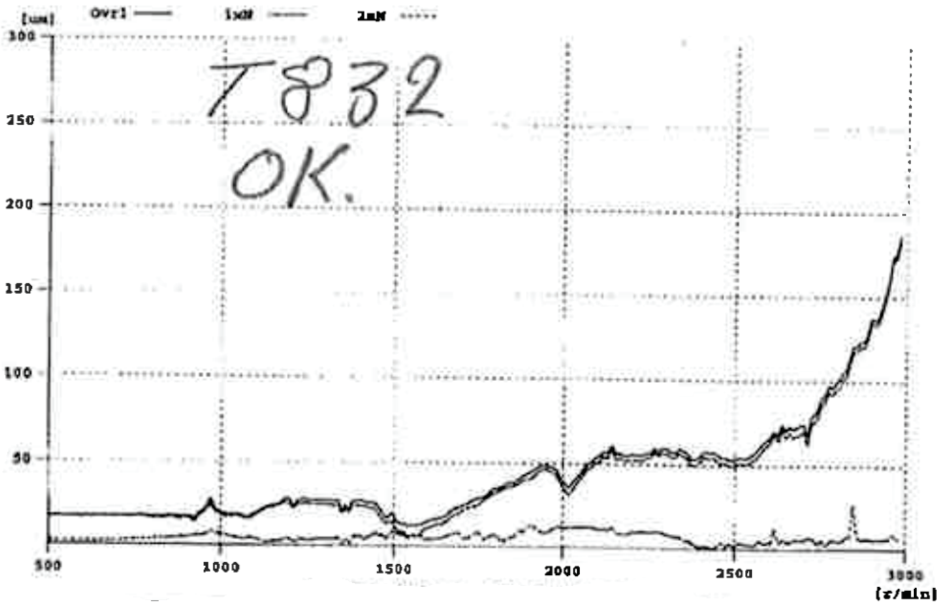


Figure 27: Overall level together with (1 x rpm) and (2 x rpm) level between 500-3000 rpm for an undisturbed eddy current displacement sensor.

3.2.2 Story 2, vibration measurement pitfalls due to mis planning in preparation phase of modification of pipe system

It's well know that a pump system vibration response is mainly determined by the dynamic in the connecting pipe system and the foundation that supports the pump system. If the modification is made on pump system component or the connected piping to the pump, the result of the modification needs to be verified by tests. In first place vibration positions for structural verification are selected on the pump system itself and on the piping in close proximity to the pump i.e. in the same room as the pump is positioned. This may be an appropriate approach if the construction modifications can be neglected to have any dynamic impact. However this needs also to be verified and cannot be taken for granted.

In this case there had been a reconstruction of the pipe system a couple of floor further up from a pump room in the building. This was due to that one component needed to support another component during specific running conditions, start and shutdown. One modification of the piping was that it had been implemented a single hole single stage orifice plate to reduce the flow in the pipe line, see Figure 28.

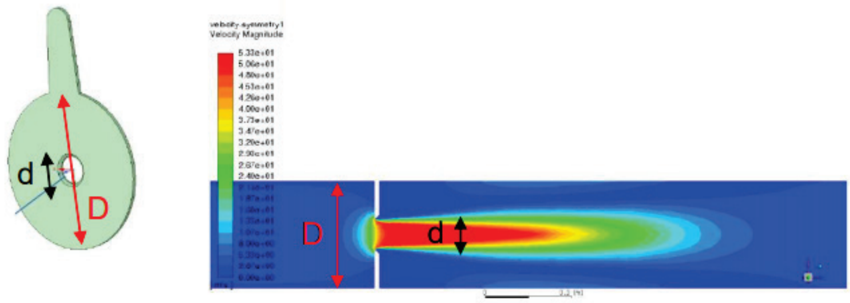


Figure 28: Single hole, single stage orifice plate with example of flow velocity profile

The design engineers had judged the single orifice plate to not cause any vibration problem to the overall pipe system, so this had not been requested for measurement verifications. Full focus was instead on verification of water pump vibrations in the basement. All planning in the preparation phase was focused to do testing on water pumps. The reason was that these pumps have had well-known vibration issues over the years so there was a big concern if the modified pipe system could have influenced the pump vibrations. Due to that the pumps was not in continuously running mode operation the vibration testing needed to be planned carefully during an outage.

When measuring the pump vibrations everything looks normal in the pump room and the vibrations on the pump vibration is acceptable. However it’s notified that the piping two floors up where the orifice plate is installed gives subjective strong vibration on piping and should be verified by test. The sound from the pipe system is perceived as gravel through the pipe and sounds like cavitation. Before reconstruction of the piping no cavitation had been identified.

By this time the vibration engineers just had prepared suitable equipment for measuring expected low level pump vibration as planned. When they put on the standard ICP accelerometers on the pipes the accelerometers were too sensitive (100 mV/g) for picking up the correct level of cavitation vibration.

The recorded cavitation time signal contains impacts from the imploding’s of the cavitation bubbles in the pipe. The high acceleration levels of impact will saturate the sensors amplifier when the sensor has a too high sensitivity. A very common time signal behavior on how an overloaded spike for the sensor will look like after integration to velocity is shown in Figure 29.

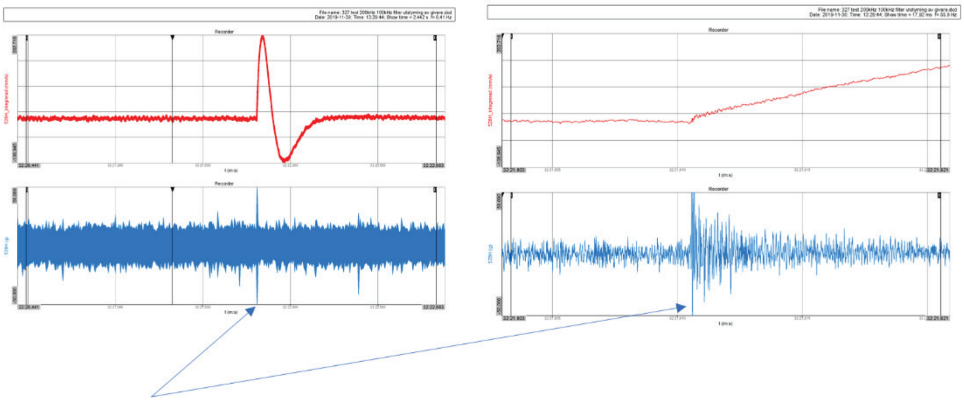


Figure 29: Time signal with a high level spike of 50 g acceleration . Acceleration [g] in blue curve and the integrated velocity [mm/s rms] curve in red. Curves to right are zoomed view of curves to the left.

The integrated vibration velocity level at the spike goes to the extreme with a peak level of approximately 200 mm/s rms. The spike is after integration converted to a low frequency velocity pulse which occurs on the same frequency as the selected frequency resolution, Δf. In this case frequency resolution was set to Δf=0.41 Hz. This is a very common error that low frequency peak vibration tone coincides with used frequency resolution and can easy fool an unexperienced user that this is the dominant tone of the problem. Especially when a more coarse frequency resolution is used it may be misleading. Here it was then detected a spectrum tone at f=0.41 Hz with a vibration velocity of 200 mm/s rms which was not classified as a real vibration. The corresponding vibration spectrum will therefore have the classical ski-slope decaying disturbance form from the peak tone at f=0.41 Hz. A similar behavior which can be visualized in Figure 22.

After having measured an exaggerated low frequency tone of the pipe system there started an investigation on which sensor could do the job best. By this time the running condition after the pipe reconstruction had caused a small diameter piping started to leak at a weld, see Figure 30.

Figure 30: Small diameter piping which started to leak due to cavitation vibration

The pipe system was located high up from floor level. In order to reach the pipes the test engineer needed to stand on a scaffold which made it difficult to find a fixed point for a displacement sensor which otherwise is preferable for low frequency vibration below f=10 Hz. Additionally velocity sensors are not reliable below f=10 Hz, so it was decided to continue with accelerometers when there are both low and high frequency tones in the excitation from cavitation. However, the accelerometers needed to be protected from the high frequency cavitation tone to not interfere with the sensors mounting eigenfrequency. This needs to be done both with digital software low pass filter and mechanical low pass filter. Experiences of the site have shown that it is not enough to just use a digital software low pass filter, it also needs to be accompanied with a mechanical filter in order to suppress the high frequency signal sufficient.

Also it's needed to use a high pass filter to remove the low frequency drift of the signal to avoid problem with integration. Recall from section 3.1.5 that sensors (piezo element based) always leak charge between the positive and minus plates which should be classified as low frequency pink noise scaled to 1/f. As a result a low frequency drift on the measured time signal will be registered and should be treated as noise i.e. removed by a high pass filter. If not the low frequency 1/f noise on the accelerometer signal will be amplified upon integration to to be scaled as $1/f^2$ on the velocity signal.

Both the selection of settings for the low pass and high pass filters was tested out in the site's laboratory before actual measurements on the pipes was performed again in order to optimize filters.

When the correct settings were found the problem was deduced to a f=80 Hz problem (eigenfrequency of the small diameter pipe) i.e. a high cycle fatigue problem which proved that the accelerometer was the best sensor for detecting the problem. The vibration problem was solved by replacing the single hole, single stage orifice with a multi hole, see Figure 31, multi stage orifice plates (3 plates) for a smoother pressure distribution.

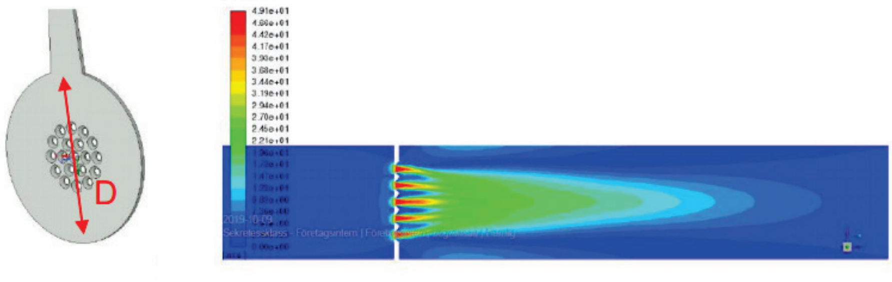


Figure 31: Example of smoother pressure distribution from a multi hole orifice plate

4 Vibration measurement validation

4.1 VIBRATION MEASUREMENT PITFALLS ON A NEW COMPONENT

When a component is new there is no experienced to lay back on. Nothing to compare to and no experiences what to expect.

The first step in the vibration testing of any new system is often a determination of its natural frequencies either through a speed ramping test during operation, impact test or a shaker test during off conditions.

All systems have some degree of nonlinearity present in them. Nonlinearities could be either geometric (i.e., nonlinear restoring force), material (i.e., nonlinear stress-strain relationship), or due to damping (Coulomb friction, etc.), inertia (centripetal and Coriolis acceleration), and discontinuities (impact, backlash, etc.) in the system. The presence of nonlinearity results in a shift in the system response away from the expected linear behavior.

Typically, the deviation from linear behavior increases with an increase in the amplitude of system displacement.

However, due to the nonlinearities one needs to be very careful while deciding upon the sweep direction, sweep rate, and input acceleration level since this affects the results on the measured response curves. If not under control this can easily be a measurement pitfall.

A result on how the nonlinearity affects the FRF function during an modal testing is shown in Figure 32. The degree of bending of the frequency-response curve, FRF, is directly proportional to the strength of the nonlinearity, α. The nonlinearities may be soft ie. $\alpha < 0$ which detunes the bending of the FRF to the left and stiff i.e. $\alpha > 0$ which detunes the bending of the FRF to the right.

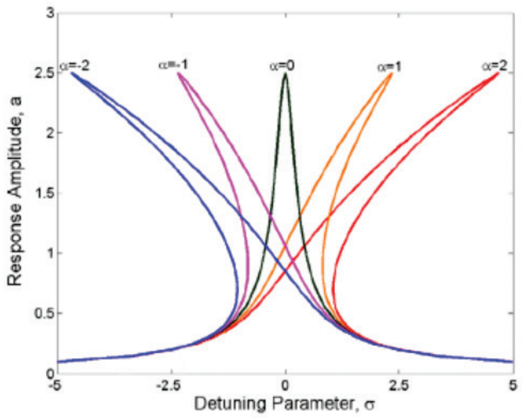


Figure 32: Effect of nonlinearity on the frequency-response curves of the Duffing oscillator (Nayfeh, 1979). The linear behavior corresponds to the case when α = 0

Depending on the sweep direction the measured maximum response amplitude would be different. In other words, different sweep directions lead to different measured values of the natural frequency.

By first doing a simple impact test to get an overview of the status to where the machine/pipe resonances are located. It may then be beneficial to continue with a shaker test to get control of the nonlinearities and how this influence the machine/structure. A complimentary shaker test that you can stop the excitation on a resonance frequency and then move the transducer around on the machine/structure from bearing top and down to the feet of the machine and measure the mode shape at that frequency. By adjusting the shaker frequency and amplitude level slightly there can be better insight if the new component has a strong soft ($\alpha < 0$) or hard ($\alpha > 0$) nonlinearity behavior, or can be treated as a linear component ($\alpha = 0$).

An example of measurement pitfall which was found in the preparation phase of an impact test was a measurement which took place on very large concrete foundation which was mass loaded with three big reciprocating compressors. Concrete is a complex material for dynamic investigations. A concrete foundation is always reinforced with steel rods to have sufficient durability when the concrete cracks, which to some extent always happens especially if it has a high dynamic loading due to heavy reciprocating compressors. Local phenomena will always occurs with local eigenfrequency modes as a result with a lot of nonlinearities for cracked concrete. In this first phase there was a pre-study to investigate where the main resonances of the foundation were occurring. The test was made with an impact cylinder of 32 kg, see Figure 33.

Figure 33: Impact testing with vertical excitation with a 32 kg impact cylinder with force sensor exciting a reciprocating compressor foundation plate.

As explained above impact test is not ideal for an accurate test for an unknown component with expected nonlinearities. However still good enough for a pre-study.

The response accelerometers were planned to be measured with either 10000 mV/g, 5000 mV/g and 1000 mV/g ICP accelerometers. The accelerometer was mounted with a magnet on a cubic steel fixture as seen in Figure 34.

Figure 34: Cubic steel fixture, 10 x 10 x 10 cm, with magnetic mounted accelerometer.

Before deciding on which approach to best perform the impact testing, rowing or fixed impact and which sensors to use. All 5 sensors was mounted by magnet on the cubic steel fixture and positioned on the foundation floor on site. A vertical driving point measurement was performed in two different positions around the cubic steel fixture. The response FRF- functions from the 5 accelerometers in vertical direction excited by two different positions close to the fixture are shown in Figure 35.

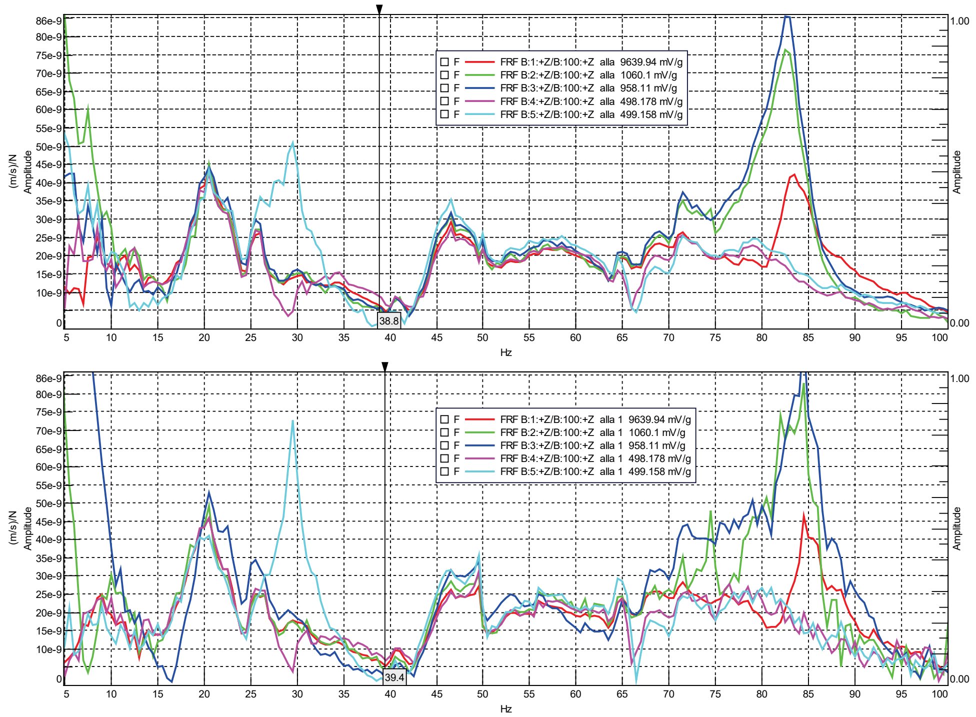


Figure 35: Mobility response curves from two different impacts with same response point equipped with 5 different accelerometer with different sensitivities 10 000mV/g 5000 mV/g 1000 mV/g.

4.2 VIBRATION MEASUREMENT PITFALLS ON AN EXISTING COMPONENT

In following example there are two auxiliary feed water pumps which has been installed and operated during several years. Both pump systems are installed in the same room with same foundation design. One of the pump sets has approved vibration levels in full frequency range on all components and the other pump system generates a vibration problem on motor component at f=100 Hz. A common cause of excitation at 2 x rpm (100 Hz) can either come from the wrong alignment or electrical excitation from the motor (2-pole synchronous motor).

A temporary countermeasure of an extra weight package installed on top of the motor component reduces the vibration to approved levels which allows that both pump sets to be in use during several year. In the meantime vibration investigations are taken place with component suppliers and maintenance engineers to solve the problem. First results from vibration tests indicates that the vibration problem is caused by a "soft foot" on the none drive end side of the motor, see Figure 36 i.e. can be fixed with an improved alignment.

Figure 36: None drive end side of motor-pump set which stands on steel skid which is filled with concrete.

Repetitively and very frequent alignments checks were performed on the motor-pump sets without any major improvement of the vibration level at f=100 Hz. The problem remains.

A complementary bump test (without force sensor) is performed which indicates a f=100Hz peak in lateral direction, i.e. a resonance. The bump test is later verified with an impact test (with force sensor) which also shows a lateral motor peak at f=100 Hz but with a low coherence, ϒ= 0.5, at f=100 Hz on motor component itself and a dip in the coherence at f=100 Hz on the foundation, see Figure 37. Still the amplitude form of the mobility curve for both motor driving point and transfer mobility between motor and foundation have a resonance appearance at f=100 Hz in lateral direction.

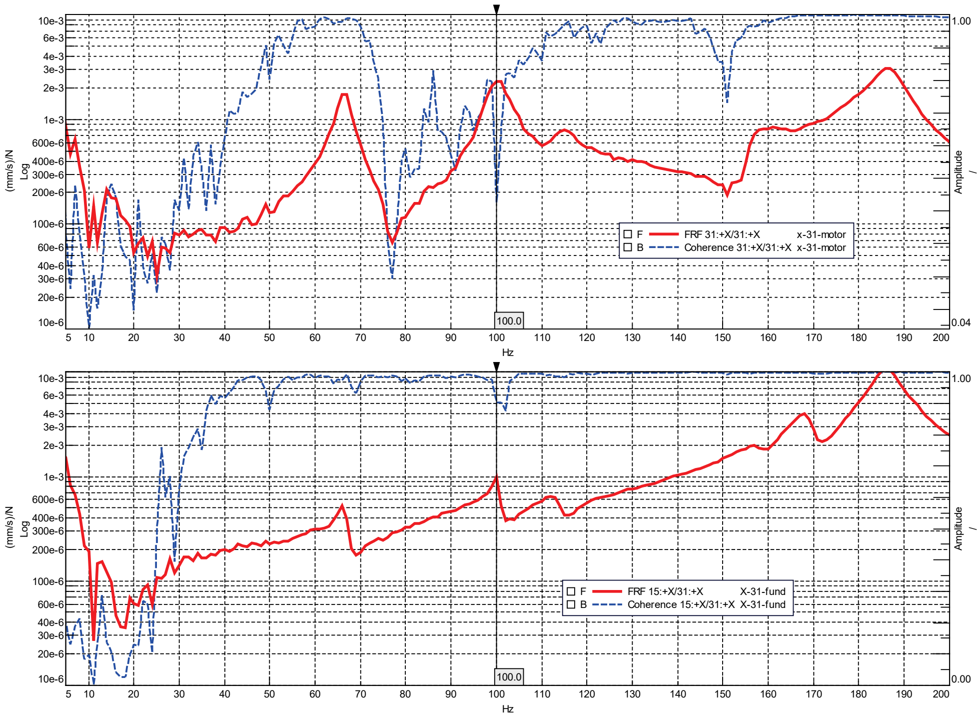


Figure 37: Result from impact test with excitation in lateral direction. Upper curve driving point mobility of motor. Lower curve transfer mobility to foundation.

On the other hand the driving point in vertical direction of the motor shows a dominant vertical mode at f=100 Hz with good coherence, $\Upsilon > 0.95$, which also the vertical transfer point mobility between motor and foundation does, see Figure 38.

However, the operational test showed a dominant lateral motor mode and not a vertical mode at f=100 Hz. The test result from the modal testing is difficult to understand when the operational test and the modal test result do not show corresponding result.

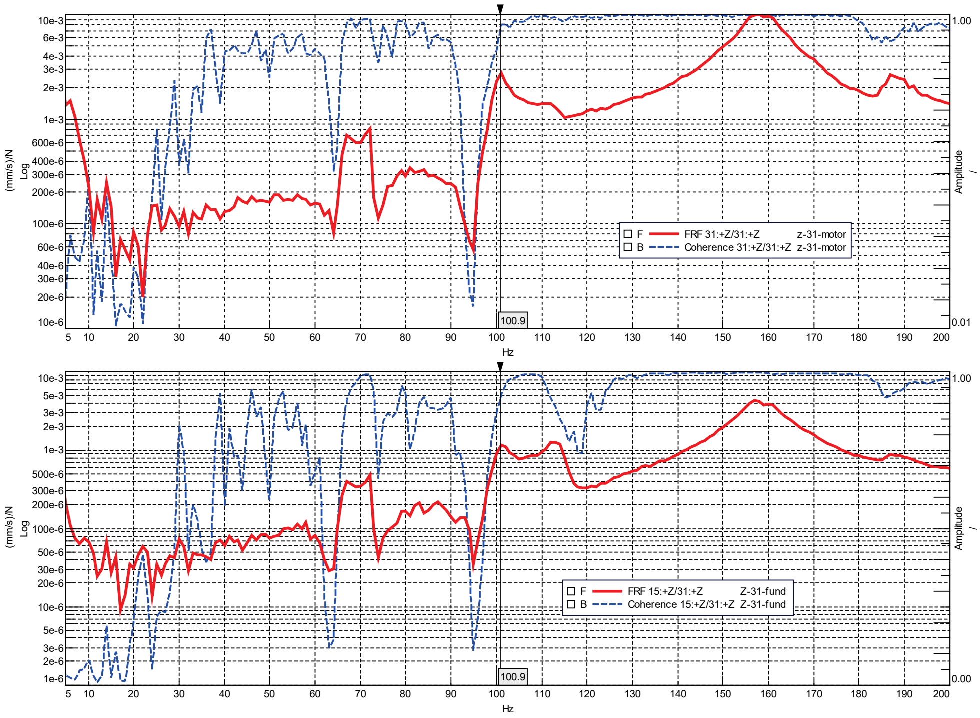


Figure 38: Result from impact test with excitation in vertical direction. Upper curve driving point mobility of motor. Lower curve transfer mobility to foundation.

Thus, so far the investigation had not succeed to verify that the motor component had a lateral resonance or if it were a pure soft-foot problem of the installation which could be corrected with alignments. No proof was available that the motor component had a lateral structural resonances at f=100 Hz. Recall that the twin component was free of resonance at f=100 Hz. There was then suspected that the foundations between the two motor-pump systems were dynamically unequal since the steel skid is molded in concrete there the adhesion may vary between the steel and concrete.

The modal impact measurements give the result on the "shell" of the components and not what actually happens on the inside at the rotor string. Also, experimental modal analysis determines resonances when the machine is at rest, but it is not certain that the impulse excitation will excite all system machine resonances. When exciting the motor the vibrations will by natural reason have difficulties to propagate through the coupling to the pump side and vice versa due to gaps in the coupling between motor and pump during idle conditions.

When measuring during operation, ODS, which usually produces a strong excitation, any missed resonances from modal measurement can sometimes emerge. Always good as a complement to a verification of modal testing

In order to design a new steel skid which is self-supporting i.e. without concrete filling, to the motor-pump system with the vibration problem at f=100 Hz it is of main concern to know the system resonances of present design. The system bending resonances can be tuned by appropriate foundation (steel skid + concrete foundation) if the eigenfrequencies for the system are secured.

The measurement pitfall in this example was that it was too difficult to determine the eigenfrequencies by pure testing and it took very long time before it was decided to investigate the problem with help of rotodynamic simulations as a support to the testing. There was missing a rotodynamic calculations of the full motor-pump set with its present foundation.

The rotor dynamics calculation gives the resonances inside the shell when the component is rotating i.e. in operation. Leaves an imprint on what is happening from the "source" i.e. the rotating parts that create the vibrations. The rotodynamic model was created as a joint session between test and simulation engineers. To create the rotodynamic model both supplier data of bearings, geometry, coupling stiffnesses etc. are required but also test data for verification along with the dynamic stiffness of the foundations. When the model was defined the result showed a dominant lateral rotodynamic mode at f=99.3 Hz, see Figure 39. However the lateral mode shape at f=99.3 Hz had much more dominating motion at pump side compare to motor side. This aligned with the testing and explained why the lateral driving point was measured with such a low coherence as ϒ=0.5.

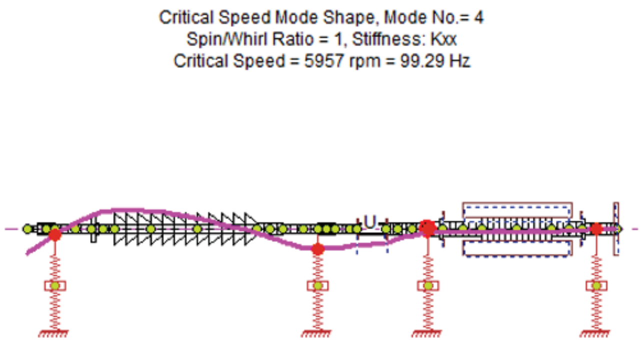


Figure 39: Rotordynamic model of "pump – coupling - motor" with supporting stiffnesses of the foundation.

When the system resonances became known the foundation was redesigned to move the lateral f=100 Hz eigenfrequency to a safer higher frequency range. The new designed foundation was valid for same pump pipe boundary conditions as when problem was investigated. Now a new mistake showed up. The pumps connected pipes, suction pipe and pressure pipe, had during the project been designed with complementary strong stiff pipe reinforcements, see Figure 40.

Figure 40: Strong stiff reinforcements on pressure and suction pipes of the pump.

As a result the lower lateral pump eigenfrequencies in the frequency range f=60-80 Hz increased to be located in the f=80-100 Hz region instead which transferred the originally motor problem during operation to a pump problem during operation instead.

4.3 VIBRATION MEASUREMENT PITFALLS WHEN USING STANDARDS

The vibration values given as limits for rotating machinery like, ISO 10816: *Mechanical Vibration – Evaluation of machine vibration of non-rotating parts,* are only valid for a running machine. A standby rotating component may be affected by running machines installed nearby that may cause damage especially at antifriction bearings of the standby rotating machine, see example in Figure 41 and Figure 42. Unfortunately there are no limits specified in standards for a machine in standby mode. Therefore when validate vibration through standards this is not taken care of and can be seen as a vibration measurement pitfall when preparing the test point setup. All focus is on the rotating component in operation and the standby rotating machine next to it is easily forgotten.

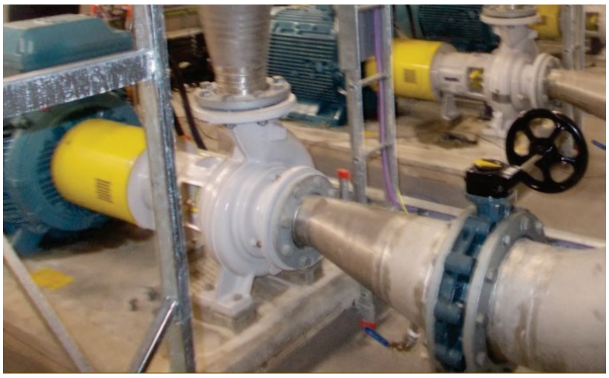


Figure 41: Pump in operation and pump in stand-by mode picking up vibrations mainly through rigid piping connection between the two pump system

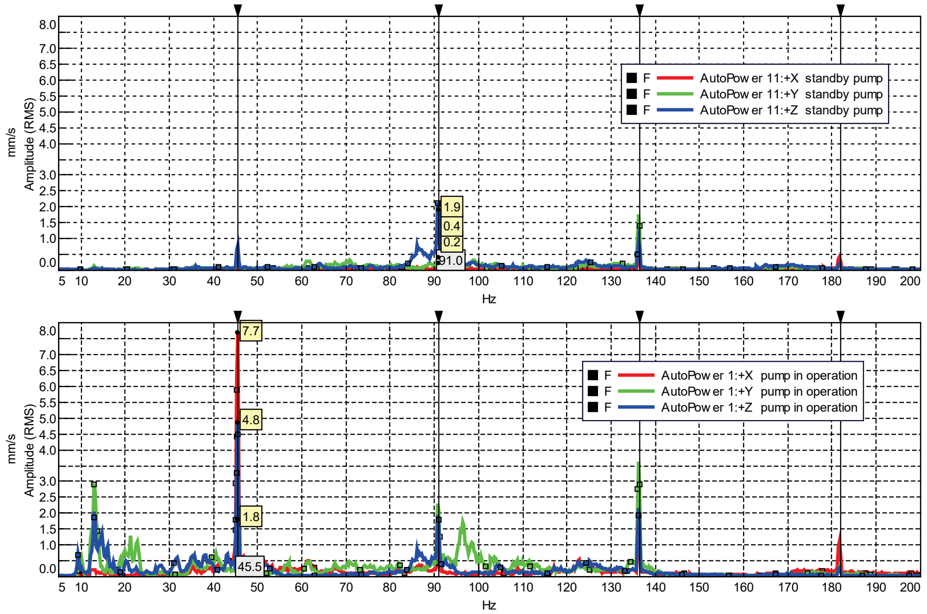


Figure 42: Vibration levels at bearing positions on a standby pump (upper window) and at pump bearing in operation (lower window)

As can be seen from Figure 42 the vibration on the standby machine indicates 1.9 mm/s at f=91 Hz which is of same order of magnitude as the pump in operation 7.7 mm/s rms at the running speed at f=45.5 Hz i.e. it is not a neglectable vibration. Especially when there are ball bearings in the pump where the vibrating balls cause wear on the bearing holder and the bearing is not rotating. As a result the bearing will degenerate too fast by just not be in operation. In this case the pump systems had good stiff foundation which blocked the vibrations in-between the two different pump system. The vibration transfer path was the discharge pipe side that had a common stiff pipe branch which allows vibration to pass through the two systems. As a result the standby pump picked up the vibration very easily from the pump in operation.

A common pitfall when it comes to validation through standard is the selection position of sensor mounting which not always give the actual desired expected vibration level. Especially in warranty measurements if the measurement locations are not exactly according to standard recommendation, it leads to unnecessary "what if" discussions if a vibration level is over agreed warranty value.

Vibration measurements with accelerometers are normally made on exposed parts of the structure or component that are accessible. It may be difficult to access bearing position, due to insulation, protective plates, heat sinks, pipes, cables, etc. See example in Figure 43.

Figure 43: Example of fan with unexposed bearing positions

Not always that vibration sensor can be attached in a stable way to the desired position due to surface area of bearing housing is uneven (due to casting of the housing), or that there are no suitable surfaces to attach sensors to.

Certain machine faults are more easily detected in the axial direction. Axial vibration criteria specified in standards are at present only given for thrust bearings where axial vibration correlates with axial pulsation which could cause damage to the axial load-carrying surfaces. However, it was emphasized from the interviews with the NPP sites that it´s important to measure axially on the driver and driven machine, pumps and fans, compressors when the machine has a specific type of coupling and foundation. Assuming that just machine imbalances can cause vibration in radial direction i.e. vertical and lateral, will might lead you to miss that the cause of bearing degeneration is a too weak machine foundation/machine setup. For instance, a too soft foundation and coupling in the machine may introduce unexpected resonances in all three direction. Natural frequencies with the running speed or other excitation frequencies should be avoided, also in the axial direction.

Special care should be taken when measuring in the axial direction for different positions, position 12-3-6-9 o'clock, which can give a different value dependent on which clock sensor position is chosen, see Figure 44.

Figure 44: Example of motor component with axial sensor positioned at 12 o´clock.

When there is a mixture of different vibration sensor types like for example sensors measuring the relative shaft displacement and ordinary accelerometers, it may be difficult to find consistency between the vibrations at the different positions, see an example of the positioning of a triaxial accelerometer and a relative displacement sensor on a generator component in Figure 45.

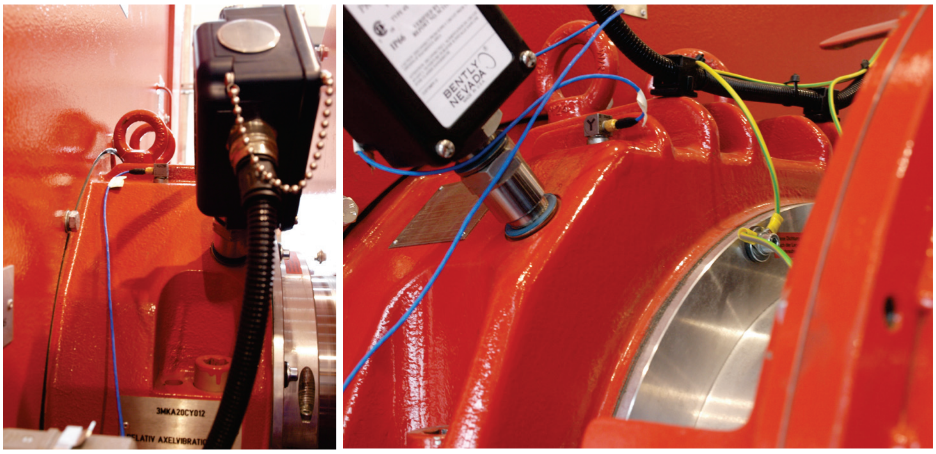


Figure 45: Generator equipped with a triax ICP-accelerometer and a relative displacement sensor from Bently Nevada.

4.4 VIBRATION MEASUREMENT PITFALLS DURING SUPPLIER/MANUFACTURER VALIDATION

The following examples concerns a FAT (Factory Acceptance Test) for two new designed machines called MG-sets.

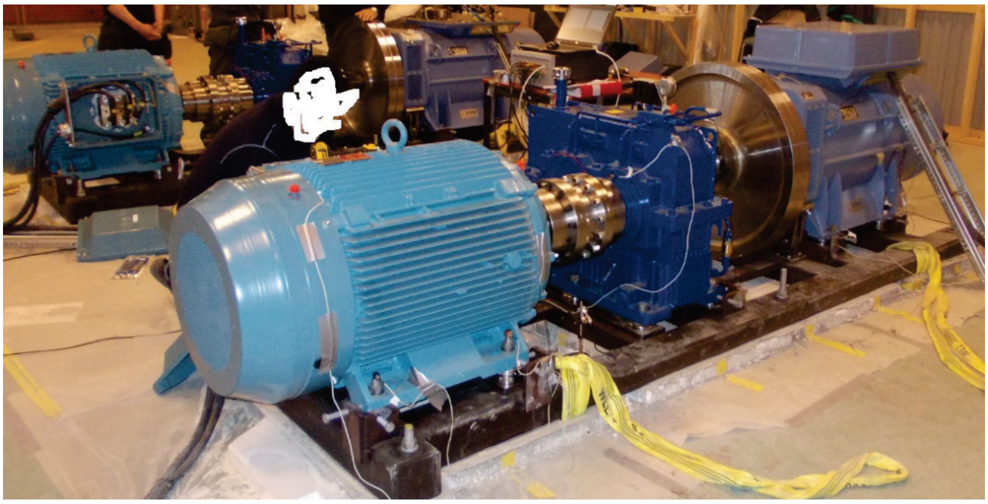


Figure 46: Two Motor-Generator sets at FAT (Factory Acceptance Test)

MG-set is a machine designed as an assembly of four main parts namely an Electric motor, a Gearbox, a Flywheel and a Generator, see Figure 46. This machine will be used to generate electric current at a frequency of 60Hz. Therefore, all assembled parts are designed or selected for this purpose. The electrical motor rotates with 1500 rpm and the generator rotates with 1800 rpm in order to convert the 50 Hz voltage to 60 Hz via the mechanical gearbox.

Due to the combination of heavy components and the extra inertia in form of a flywheel, rotating dynamic unbalance forces may be strong, especially if not appropriate mounted on the steel frame. The installation was carefully checked for shaft runouts, alignment and soft-feet in order to keep the unbalance forces as low as possible before the FAT vibration verification was carried out. The tolerances were set by the limits according to the PSK8301 Shaft alignments standard. All components were directed to meet at least 0.05 mm parallelism and 0.05 mm/100 mm in angle alignments. Additionally, it was specified that all machine feet, shafts and shaft holes should be clean of dirt and dust before installation.

It was decided that these machines should not use ordinary shims to correct for soft feet. The suppliers main field was to design electrical machines and had limited experience with vibration measurements. At this time a new product was available on the market, the SKF Vibracon chock, see Figure 47, which is a self-leveling, height adjustable and re-usable chock. This eliminates soft feet from the machine line through the life cycle of the equipment, which was an attractive solution, especially soft feet with angle errors.

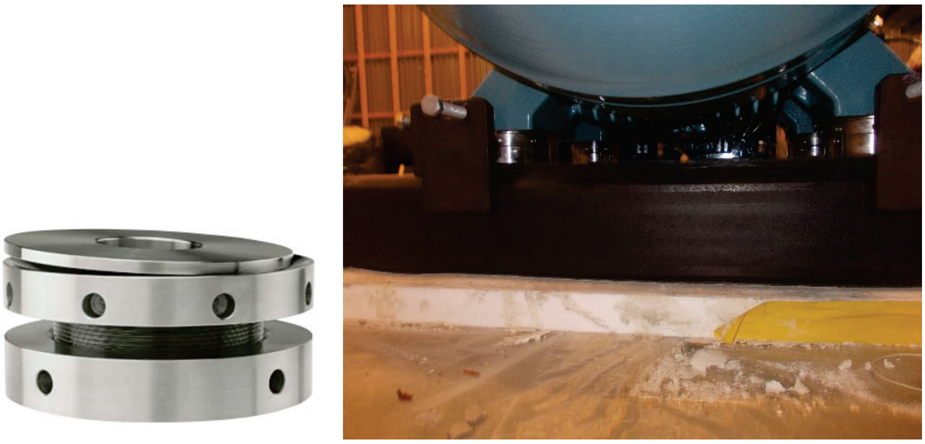


Figure 47: SKF Vibracon foot used on all MG-sets machinery feet. Note that this chock is self-adjusting for angle error.

When doing the vibration runup tests on May 21 of a single operational MG-set the motor and gearbox components showed higher vibration levels (still below limit) in the horizontal X- and Y-directions, see Figure 48, at f=75 Hz.

Figure 48: Vibration response in x (=lateral direction), y (=axial direction) and z (=vertical direction) of gearbox component during two different tests performed on May 21 and May 22.

Energiforsk

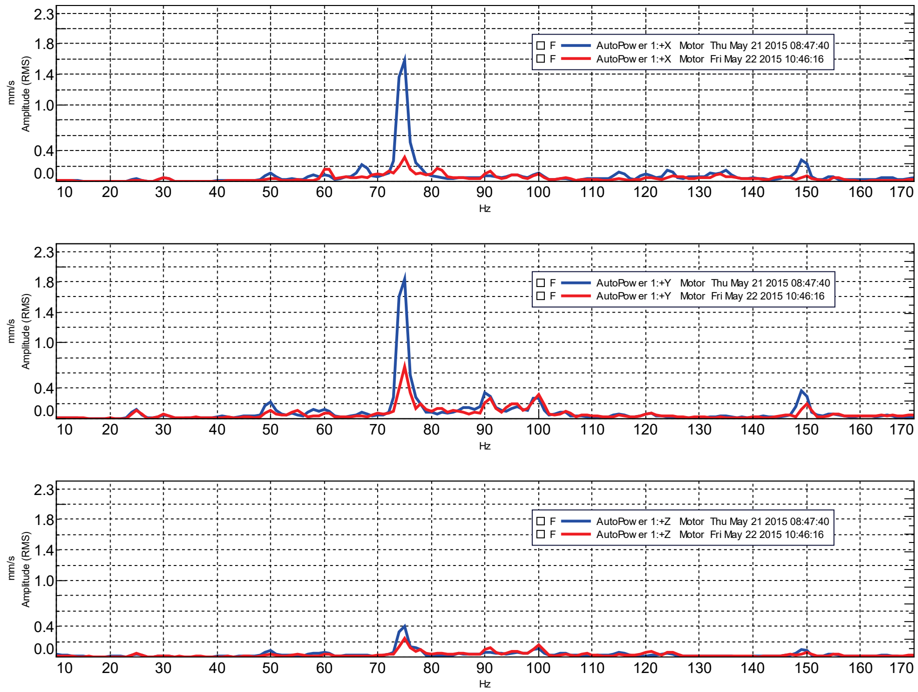


Figure 49: Vibration response in x (=lateral direction), y (=axial direction) and z (=vertical direction) of motor component during two different tests performed on May 21 and May 22.

The day after, on May 22, vibration runup tests continued on the same MG-set with the same set of accelerometers positioned in the same positions using same cables and testing equipment. Same test conditions were applied as the day before and a new runup was taken but now with a completely new result, see comparison in Figure 48 and Figure 49. No changes had been made on either of the two MG-sets. The machines had just been in off conditions during the night. The new result showed that the vibration at f=75 Hz had almost disappeared which was very surprising. However, the vibration of the gearbox component in axial direction, y-direction, had got an enhanced component at f=100 Hz instead of at f=75 Hz, see Figure 48.

The first thought was that this must be a measurement error. Checking of alignment protocol from supplier confirmed that everything was OK. Switching the cables and sensor between generator and gearbox component gave the same results. Complementary measurements with handheld logger showed the same result as in the test performed May 22. It was verified that there was a resonance in the assembled gearbox at f=75 Hz but why was the source of excitation so small on May 22 compared to May 21?

A discussion started with the supplier if they had observed anything strange during the mounting process of all components and if they had followed the instructions on how to mount the SKF Vibracon chocks between the machinery feet and the steel frame. The supplier mentioned that they had noticed grease in the cup holder of the chock. Maybe the low friction in the cup holder due to the grease might cause a non-stabilizing effect in the horizontal direction when loaded by high dynamic forces at startup. A call to the SKF experts verified that this was a reasonable explanation to the problem. The grease had a purpose if the machine had been heavier in order to easier find the self-adjusting angle position of the chock, but that was not relevant here.

After the grease had been removed from the Vibracon Cups, the next SAT-test, Site Acceptance Test, succeeded to obtain repetitive consistent results in-between runups.

5 Test method vibration measurement pitfalls

5.1 VIBRATION MEASUREMENT PITFALLS WITH ACCELEROMETERS AND DISTURBANCE OF HIGH FREQUENCY VIBRATION

The diagrams below, see Figure 50, shows a turbine roll-up where an accelerometer has been overloaded by high-frequency vibrations caused by throttled steam flow in the speed range of 300-1100 rpm. When the steam is wet i.e. saturated, its dynamic response on the structure in proximity will excite high frequency tones i.e. above f=10 kHz.

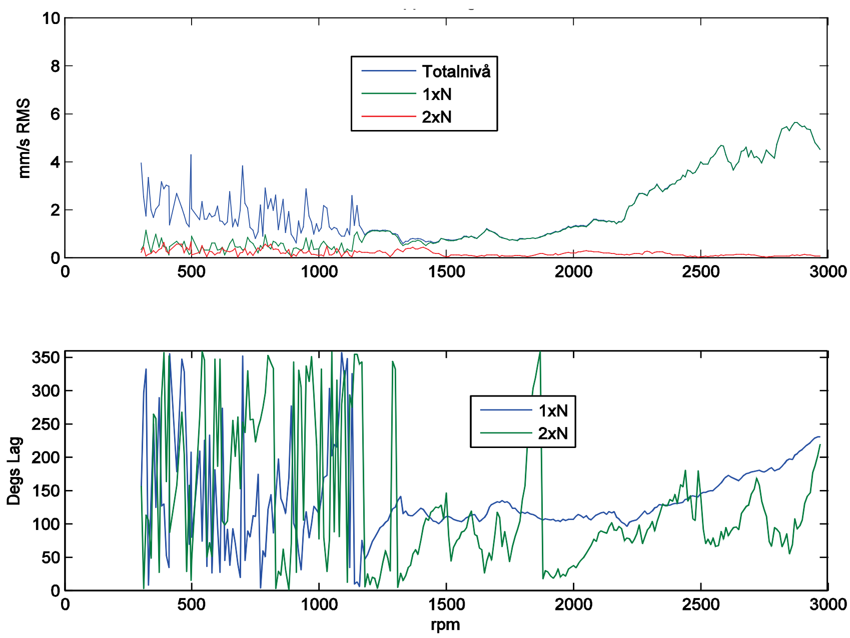


Figure 50: Turbin roll-up with accelerometer showing amplitude and phase of vibration velocity.

As can be seen from the upper diagram in Figure 50 there is a much higher total level compared to first order at ´1 x rpm´ and second order at ´2 x rpm´, up to approximately 1100 rpm. As a result the high energy in the total level is not dominated by the natural unbalance rotating natural forces. Instead there is more likely that the accelerometer resonance has been excited, see Figure 51, and overloaded the sensor dynamic range. Additionally, note the random phase pattern up to approximately 1100 rpm in the lower diagram of Figure 50. Above 1100 rpm amplitude and phase stabilizes when the steam flow conditions changes to not contain high frequency tones which interferes with accelerometer resonance.

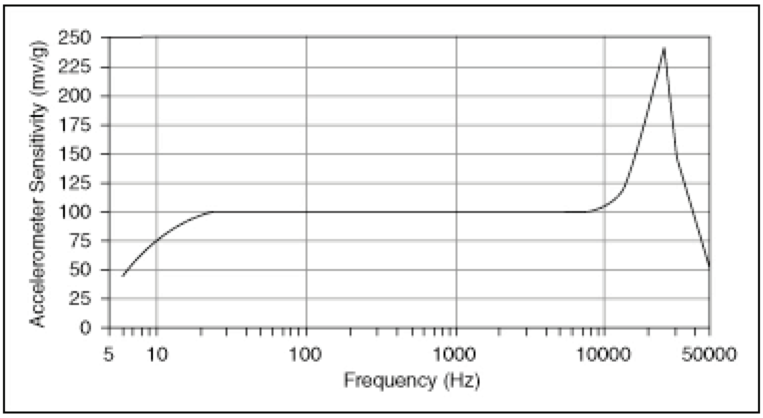


Figure 51: Example of accelerometer sensor response with flat frequency response up to f=10 kHz. Above f=10 kHz the sensor resonance is showing up which if excited will amplify the sensor and cause an overload on the sensors dynamic range.

The diagram below, see Figure 52, shows a roll-up where a velocity sensor has been used at the same measuring point as in Figure 50. As compared to accelerometers, velocity sensors have lower sensitivity to high frequency vibrations, making them less susceptible to amplifier overloads. The spectrum is not affected by high-frequency vibrations such as an accelerometer in the low speed range up to approximately 1100 rpm. Here the total level is controlled by the natural unbalance forces due to the ´1 x rpm´ vibration is in the same magnitude as total level in full speed range 600-3000 rpm.

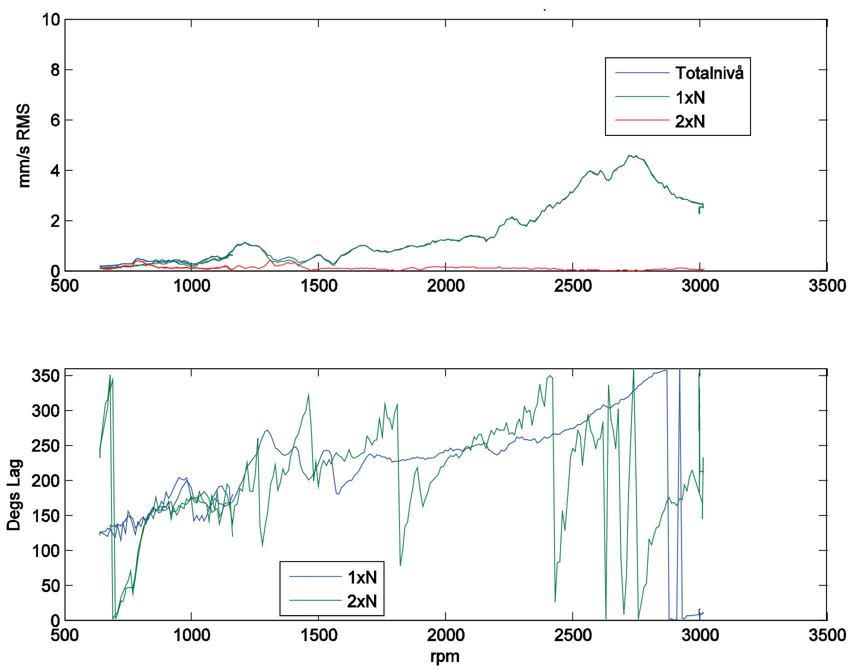


Figure 52: Turbine roll-up with velocity sensor showing amplitude and phase of vibration velocity

Depending on the frequency range of interest adding a mechanical low pass filter in-between the sensor and the structure to be tested might be a useful countermeasure for an accelerometer measurement, as described in Figure 50. There are commercial products available. An example is seen in Figure 53.

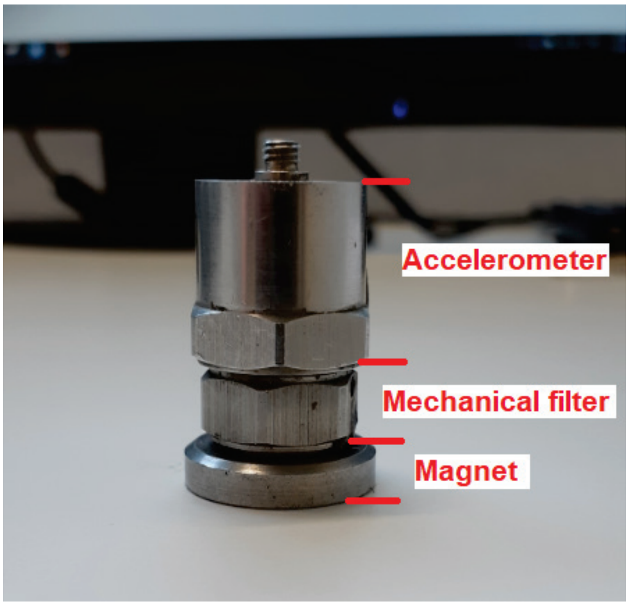


Figure 53: Mechanical low pass filter for accelerometer from B&K https://www.bksv.com/media/doc/bp0297.pdf

The effect of the mechanical filter on the frequency response of an accelerometer is shown in Figure 54. Transverse and main axis resonances, which are typically 30 dB in amplitude, are substituted by a highly damped resonance response of only 3 to 4 dB amplitude. The accelerometer's own axial resonance is suppressed by 25 to 30 dB and shifted up in frequency due to decoupling of the mass above the filter.

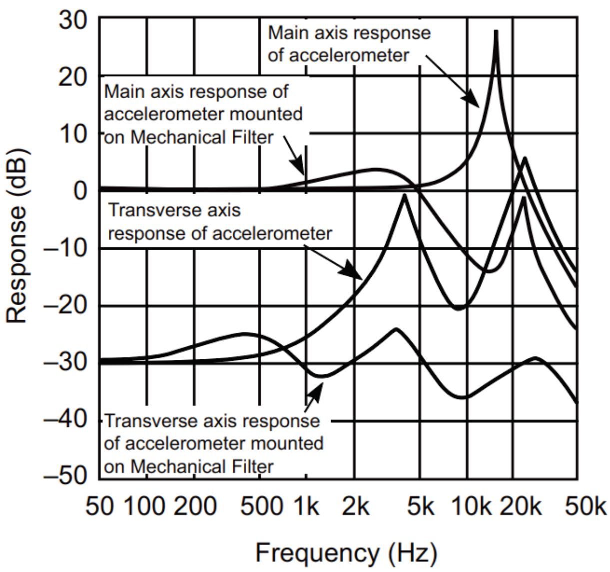


Figure 54: Example of the effect of a mechanic low pass filter from B&K. Typical main axis and transverse axis frequency response of Piezoelectric Charge Accelerometer Type 4370.

If a particular accelerometer, when combined with the mechanical filter, does not cover a high enough frequency range, an accelerometer with a lower mass should be used. Conversely, to reduce the cut-off frequency at the high-frequency end, additional mass loads can be added. Special attention should be taken to always test a new designed low pass filter, preferable on a shaker table, before bringing it out for real measurements in order to ensure correct measurements and to avoid secondary measurement pitfalls.

As an alternative to velocity sensors and accelerometers with mechanical low pass filters to mitigate the high frequency disturbances on the sensor, a non-contact sensor method may be used. An example below shows a Laser Doppler Vibrometer, LDV see Figure 55, measuring on an accelerometer without mechanical filter mounted on a motor to a centrifugal pump.

Figure 55: Laser Doppler Velocity, LDV, and accelerometer comparison on an electrical motor to a pump.

As can be seen from upper curve of Figure 56 the LDV measures the low frequency range below f=10 Hz in a consistent way in contrast to the accelerometer which shows the ´ski-slope´ problem in the low frequency range due to transients from the pump see 3.1.6. However in the frequency range f=10-1000 Hz the accelerometer and LDV response curves shows both consistent results.

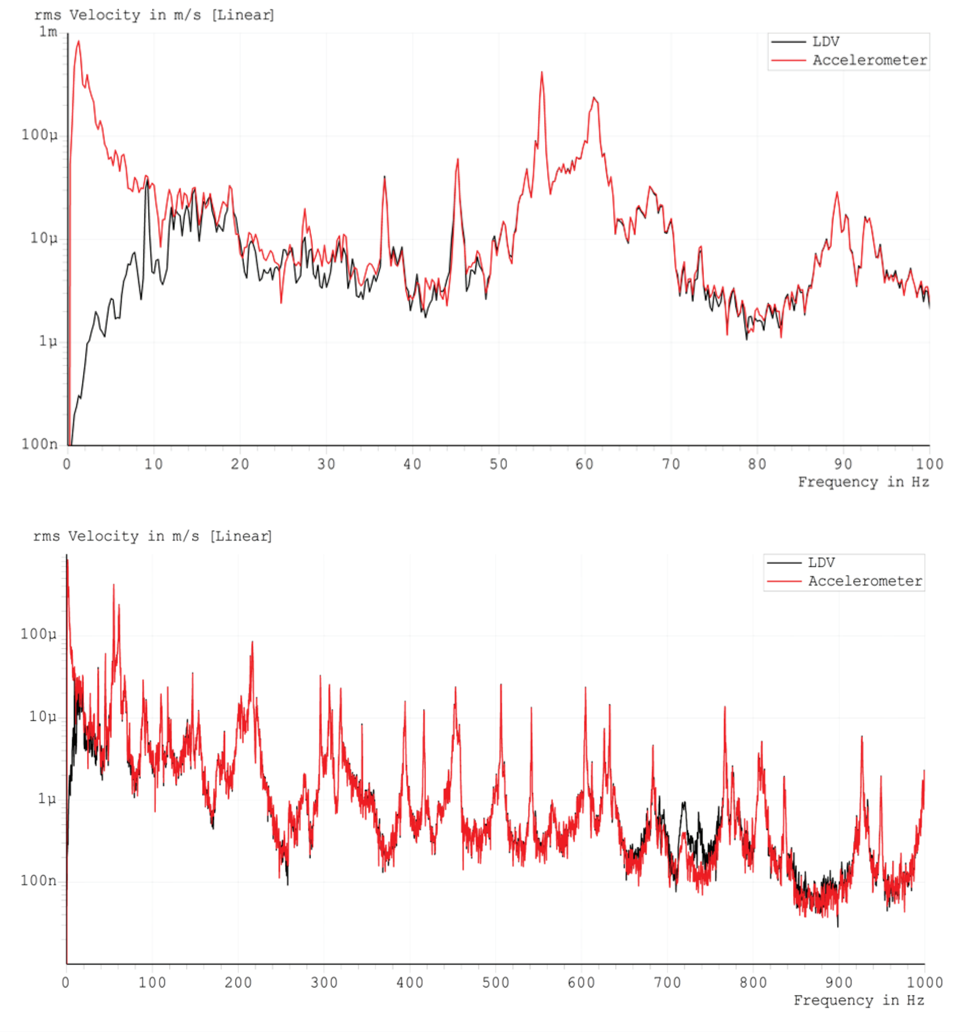


Figure 56: Response spectrum FFT of the LDV and Accelerometer signal measuring in the same point.

Upper curve - frequency range f=0-100 Hz

Lower curve – frequency range f=0-1000 Hz

5.2 VIBRATION MEASUREMENT PITFALLS IN AN ELECTRO-MAGETIC ENVIROMENT

Isolation from electromagnetic fields is especially important with respect to the analog input signals that we want to measure. So many of these signals exist at relatively low levels, and external electrical potentials can influence the signal greatly, resulting in wrong readings. Imagine the output of a thermocouple, which is just a few thousands of a volt, and how easily it could be overwhelmed with electrical interference.

Interfering potentials can be both AC and DC in nature. For example, when a sensor is placed directly on an article under test, (e.g. a power supply) which has a potential above ground (i.e., greater than 0 Volts), this can impose a DC offset on the signal. Electrical interference or noise can also take the form of AC signals created by other electrical components in the signal path or in the environment around the test.

Common mode voltages, CMV, are unwanted signals that get into the measurement chain, usually from the cable connecting a sensor to the measuring system.

The most basic approach to eliminating common-mode signals is to use a differential amplifier. This amplifier has two inputs: a positive one and a negative one. The amplifier measures only the difference between the two inputs.

Electrical noise riding along on the sensor cable should be present on both lines - the signal positive line and the ground (or signal negative) line. The differential amplifier will reject the interfering signals common to both lines, and only the measurement signal will be passed through, as long as the CMV is small enough to be cancelled out. See example in Figure 57.

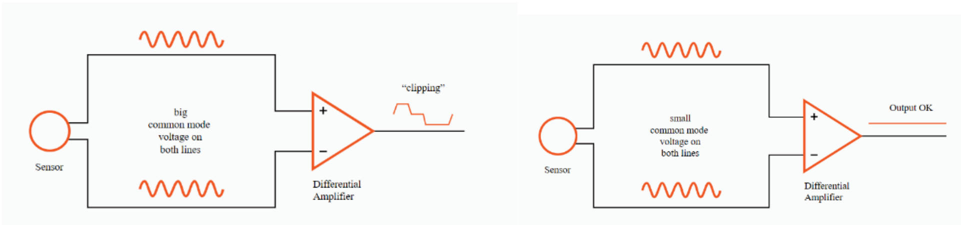


Figure 57: Left picture - A differential amplifier distorts or "clips" when its common-voltage mode input range is exceeded.

Right picture - A differential amplifier successfully eliminates common-mode voltages within its CMV input range.

Often vibration monitoring systems will not have the bias checking on the monitoring system itself and need to be check with for instance a voltage checker. By checking the bias voltage it may give hints if there is wiring short circuited, problem with power supplier, cables problems, loose connectors etc.

Typical pitfalls which can be detected by voltage checking which are very easy to correct when known, but difficult to detect because you often think they depend on something more complicated may be:

- Sensor powering, ON/OFF
- Wrong sensor powering when using an external power supply
- Looseness in the connectors

By knowing the expected CMV level a troubleshooting with a voltage checker is possible. Figure 58 shows an example of a measurement chain check-up where the accelerometer is supposed to have a healthy system bias of 12 VDC. Any deviation to the predicted 12 VDC is an indication of error.

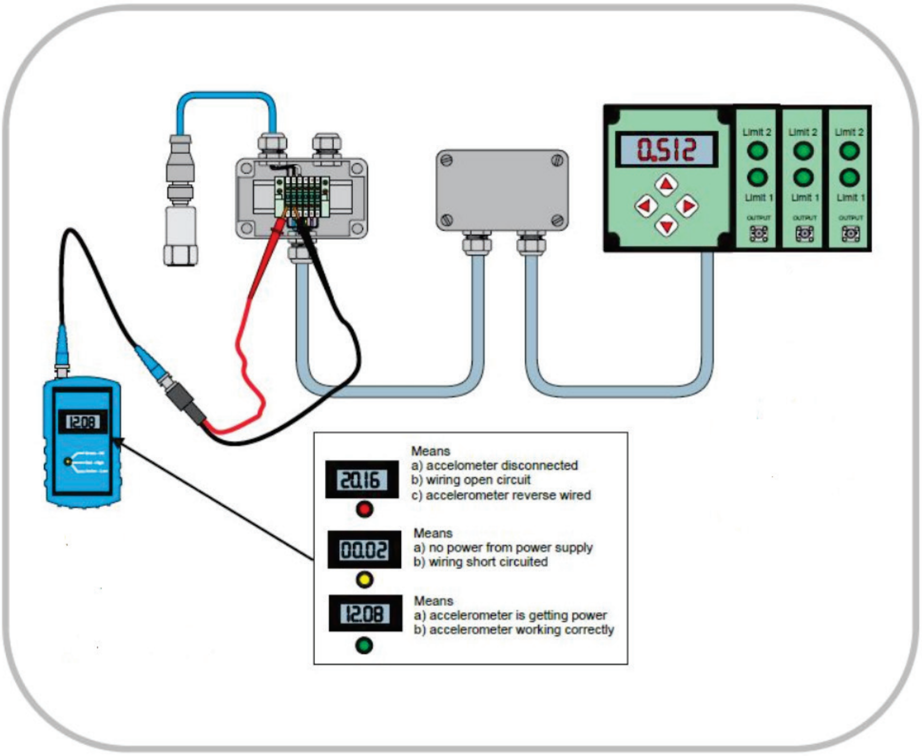


Figure 58: Example of permanently installed accelerometers, powered by a vibration monitoring system, being measured with a voltage checker.

Another common vibration measurement pitfall in electro-magnetic environments is the ground loop introduced in the measurement chain. Basically, ground loops cause problems by adding or subtracting current or voltage to or from a process signal. As a result, the receiving device can't tell the difference between the wanted and the unwanted signals. So it can't accurately reflect process conditions.

In Figure 59 there is a measurement of a dynamic pressure which picks up 50 Hz disturbance, i.e ground loop. As a result the spectrum will almost drown in the 50 Hz component with its harmonic components due to the strong modulation with the 50 Hz to other tones. The modulation reveals from the time history in the lower window in Figure 59 the corresponding time trace with a dominate 50 Hz wave on top of the other spectral components. It's therefore important to get rid of the 50 Hz disturbance so that the correct amplitude and frequency of other tones can be revealed from the measurement.

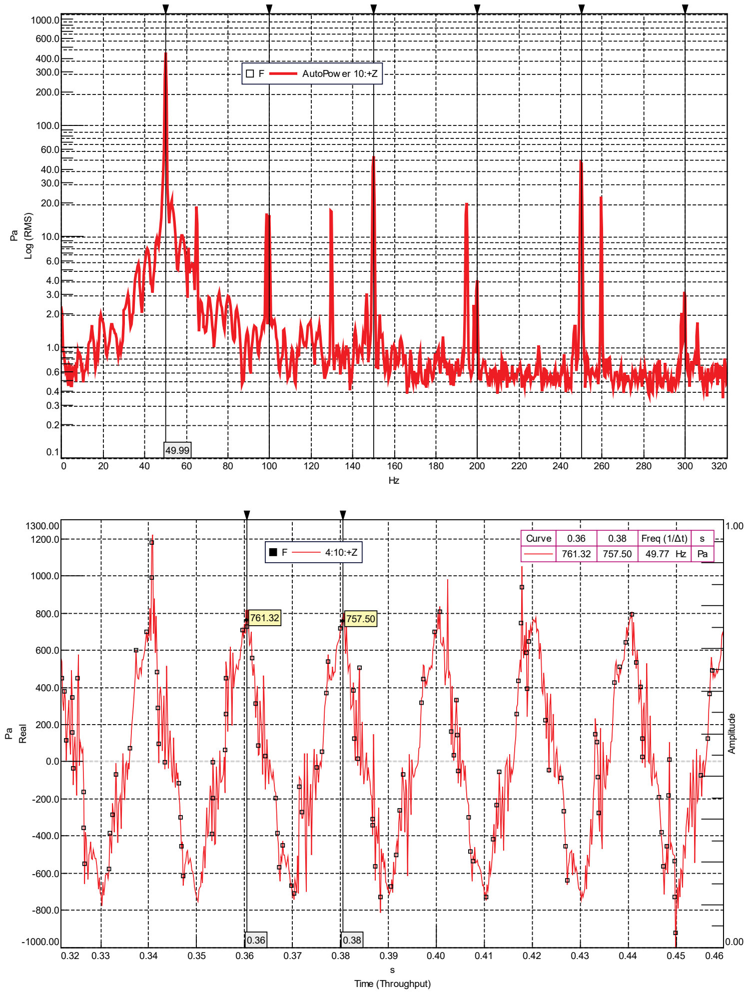


Figure 59: Example of dynamic pressure signal with 50 Hz grounding problem. Upper window – Spectrum of the dynamic pressure. Lower window – Time trace of the dynamic pressure.

For an unexperienced user by just evaluating the spectrum for a 50 Hz problem it looks like the testing has found a possible 50 Hz resonance by examining the spectrum shape at f=50 Hz, see upper window in Figure 59. It is therefore important to measure with a sufficiently high frequency resolution so the electrical network frequency can be distinguished from nearby frequency tones.

Ground loops can come from the instrument itself, via its own power supply. Keeping in mind that the measurement system is plugged into the power outlet, which has a ground reference. It is critical, therefore to decouple this reference from the signal handling components of the instrument to ensure that ground loops cannot be created within the instrument.

Examples of common measurement pitfalls due to grounding loops can be:

- A damaged sensor cable.
- A loose or dirty cable connector.
- A cable extension connector to touch metal structures.

In the left picture of Figure 60, the measurement amplifier is connected to the ground (GND 1) on one side. An asymmetrical shielded cable is used to connect the sensor, whose metallic housing is placed on a conductive surface at GND 2. Due to the length of the cable, there is a difference in potential between GND1 and GND 2. This potential difference acts like a voltage source, coupled to the electromagnetic noise from the environment. If the sensor could be decoupled from GND2, it might solve the problem. But sometimes this is not possible.

The best solution is to use a differential amplifier within the signal conditioner which is isolated as described in the right picture of Figure 60.

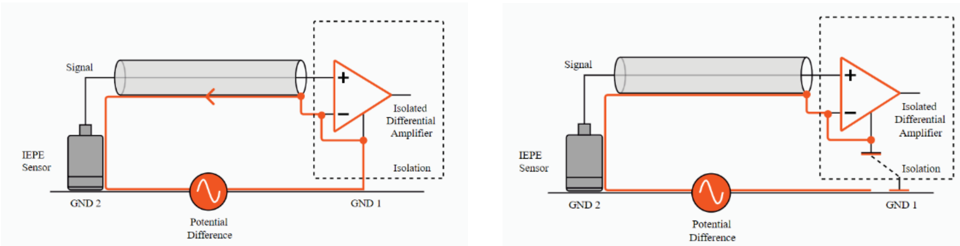


Figure 60: Left picture - A ground loop caused by ground potential differences. Right picture - Eliminating differential ground potential problems via isolation.

5.3 VIBRATION MEASUREMENT PITFALLS FOR MULTICHANNEL TESTING

5.3.1 Occasional vibration measurements

When intermittent monitoring is made, it is not usually that repeatability measurements are made. The machine could be running under different loads each time a measurement is taken, or it could be running at different speeds. Both these conditions will cause different values for the vibration levels being measured. For periodic conditioning it's critical to keep an eye on the running conditions when doing the analysis of the test data. Maybe the test engineer needs to redo the test in order to find an adequate comparison to former tests. However, often when measurements are taken during wrong running conditions they can reveal other information of the system, which may bring inputs to the machine/structure health- or problem investigation phase.

Often a wellknown periodic condition control system that has been used for several years become so established and reliable that the users keep on using it without thinking of all details when it comes to the replacement of spare parts. Below is an example of such a pitfall where no one thought about what was in the "black box".

For periodic condition control, a measuring equipment bag and a triax sensor were used for vibration measurements on pumps engines, etc. On machines with hard-to-reach measuring surfaces, fixed sensors connected to a measuring box are mounted.

When changing sensors on a machine, the sensors were replaced by sensors with the double sensitivity compared to the previous one. As a result, vibration levels rose to double because there was the wrong sensitivity setting in the measuring bag for the machine in question.

Maintenance work had been carried out on the machines and in connection with this, the sensors were replaced. The cause of the increased vibration levels was not at first entirely obvious as a number of measures had been carried out.

Other common measurement pitfalls which can be avoided but are easy to forget due to a tight time table etc. are:

- Did not make sure correct mounting of the transducer, so it was loose. Maybe the environment is tough, radiation, so it is difficult to verify the mounting.
- Did not use same type of sensor with similar sensitivity and properties in case there is a need to compare with another object.

When taking complementary fixed points where the sensor delivered on the machine, the measurement position shows either higher or lower level comparing to hand-held measurement. This can be very tedious and complicated work to find out the reason for. Often this is not a measurement pitfall since the two sensors is not exactly measuring in the same point and is most likely not the same sensor types or has the same signal analysis applied to it so there are often natural explanations.

5.3.2 Continuous conditioning monitoring

With a continuous monitoring system a machine is being monitored 24/7 (24 hours 7 days a week). Often it is limited to record at a fixed number of measurements per day each year for trend comparison. However, different speeds / loads can be accounted for depending on setup parameters of the system in use.

Continuous monitoring can be done in areas difficult to access or in areas exposed to radiation. In those areas it is difficult to verify the measurement point with hand-held measurement, so once set up and confirmed the monitoring system are assumed to be reliable until next outage.

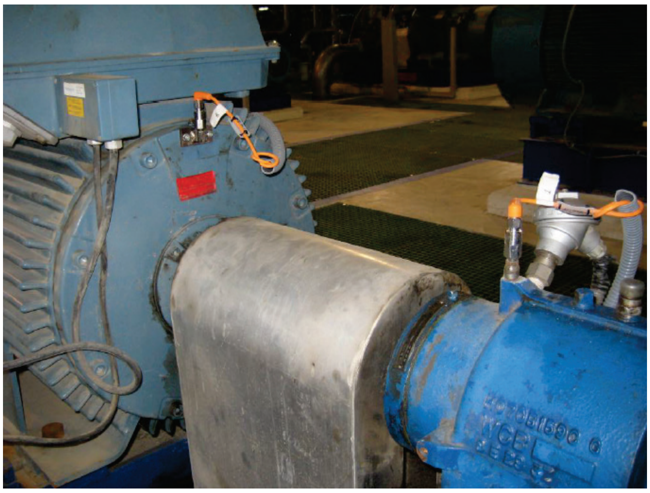


Figure 61: Motor pump setup equipped fixed single axis accelerometers to a conditioning system.

To be cost efficient often uniaxial sensors are applied instead of simultaneous triax sensor, see Figure 61. If there exist a problem the unwanted energy in the system will most likely spread in other directions as well and this will not be logged which makes the trouble shooting process more complicated.

During a temporary power outage and a restart of a pump facility where bearing vibration to pump and motor component and floor vibrations were hooked up to the same vibration monitoring system. After a power outage at the site the floor sensor started to record lower values than expected as can be seen in Figure 62. The vibration kept a mean 0.50 mm/s rms level before outage and a mean 0.35 mm/s rms level after the outage. There was no direct explanation to why the floor vibrations had been changed. The motor and pump vibration, which are the main excitation sources to the floor vibration, remained at the same vibration levels and were not affected by the power outage. An electrician verified that nothing had happened with either the cables, connectors or connection to the PCL panel.

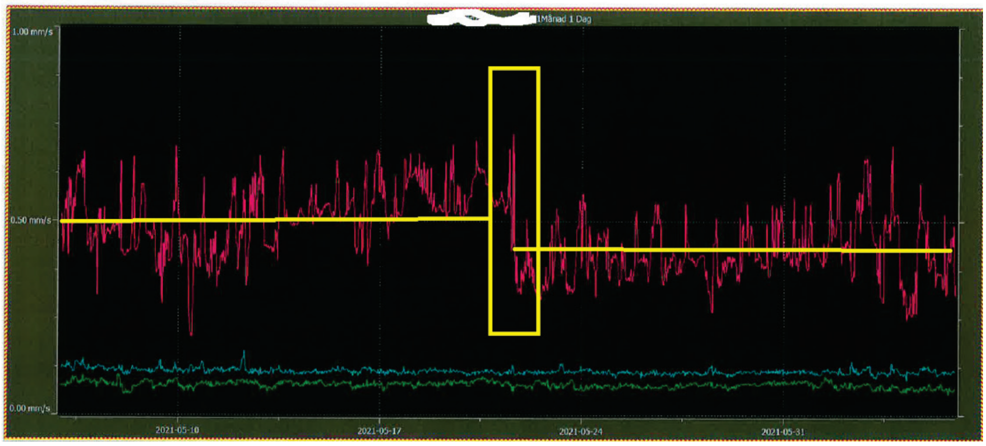


Figure 62: Floor overall level vibrations in x y (horizontal direction, blue and green curve) and z (vertical direction red curve) during a month period. Power outage changes the vertical mean vibration level from stable 0.50 mm/s rms to 0.35 mm/s rms at marked time event.

It is an important measurement pitfall that sensors may degenerate due to sensitive electronics when it comes to electric failures like temporary electrical outages, short cuts etc. Best practice is to calibrate the sensors after an electrical failure at the site to know if it is affected in some way. However sometimes this is not an easy thing to do since the sensor is not always reachable and hidden under covers. Also there are often too many sensors to go through.

Common continuous conditioning monitoring measurement pitfalls refers to:

- Cables and connectors, see Section 6.3.
- Electrical disturbances, see Section 5.2. Depending on changes in the sensors environment over time with impact of dust, humidity, oil leakage, radiation etc. may disturb the electronics. As a result the sensor performance will be degenerated.

5.4 VIBRATION MEASUREMENT PITFALLS FOR MODAL AND OPERATIONAL STRUCTURAL TESTING

A modal structure testing (impact or shaker) of a structure is always a test which should follow by an operational test, operational deflection shape test (ODS). The modal testing alone does not give the answer to how the boundary conditions (heat, flow, loading, speed etc.) during operation influence the structure modes.

Preferable the same measurement positions should be used in the operational test as in the modal test. It is easy to understand the reason why by comparing the dynamic response from a modal test on one machine with same measurement points but where the analysis of the sum-FRF mobility curves is based on different number of measurement points, see Figure 63. The mobility curve between the two analysis sets are different, mainly with respect to amplitude but also to frequency. Note the discrepancy around dominating tone at f=360 Hz.

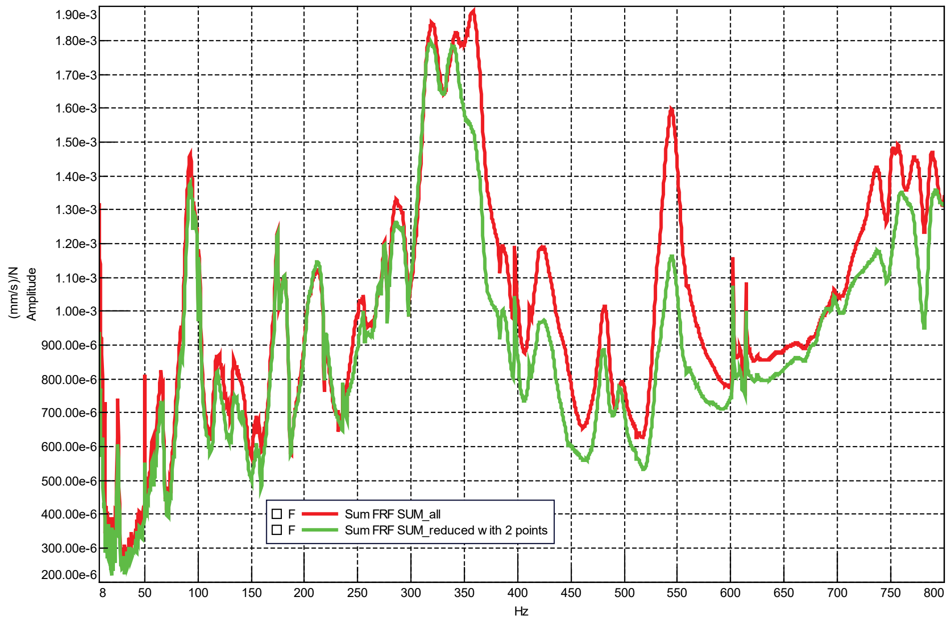


Figure 63: Mobility Sum FRF curves with different number of points in the set.

- "Sum_all" includes 30 channels (10 sensors x 3 direction=30 channels) .

-"Sum_reduced with 2 points" includes 24 channels (8 sensors x 3 direction=24 channels)

As a result there can easily be measurement pitfalls by not judging two consistent sets of operational and modal data. Wrong assumptions on how the boundary conditions and load conditions influence the modal analysis of the structure.

Maybe not all points can be measured due to protection covers during operation test but as many points as possible from the modal test should be considered for making correct assumptions between the modal and operational test. Both modal and operational frequencies and mode shapes should be judged for comparison.

It is especially critical for a modal test to be followed by an operational verification test if there is a lot of rotating inertia involved at high speed. The reason is that the machine in operation with rotating inertia will have resonances which shift with speed i.e. forward and backward whirl resonances.

These resonances are not fixed and cannot be verified when the speed of the rotating machine is zero. At the nuclear power plants this is often relevant for steam turbine generator constructions. For this component the boundary conditions are almost never the same at stand still as during operation which makes it extra difficult.

If the purpose of the modal test is a verification measurements to update a simulation model a measurement pitfall can be to forget to take driving point measurements, i.e. response sensor measuring in same direction as the excitation when response accelerometer and excitation are in close proximity. The driving points are used in the simulation model to scale and normalize the modes in the simulation model.

Major pitfalls for modal testing is related to the input force if it is not sufficient to excite the structure or if the excitation is blocked from propagation in the structure to transfer the energy across the component. The blocking can be due to small clearances or gaps which are often occurring at coupling elements, for instance a disc pack coupling. The energy across the coupling can just flow when it is in operation. This means that the excitation force at a modal test under off condition only can pass from one side to another side via the foundation, instead of the natural way through the coupling of the machine setup. As a result both driver side and driven side of the machinery needs to have separate modal tests performed.

Another example of a blocked energy propagation path which makes it very difficult to maintain a sufficient excitation, is a stacked metal plate structure showed in Figure 64, an oil cooler.

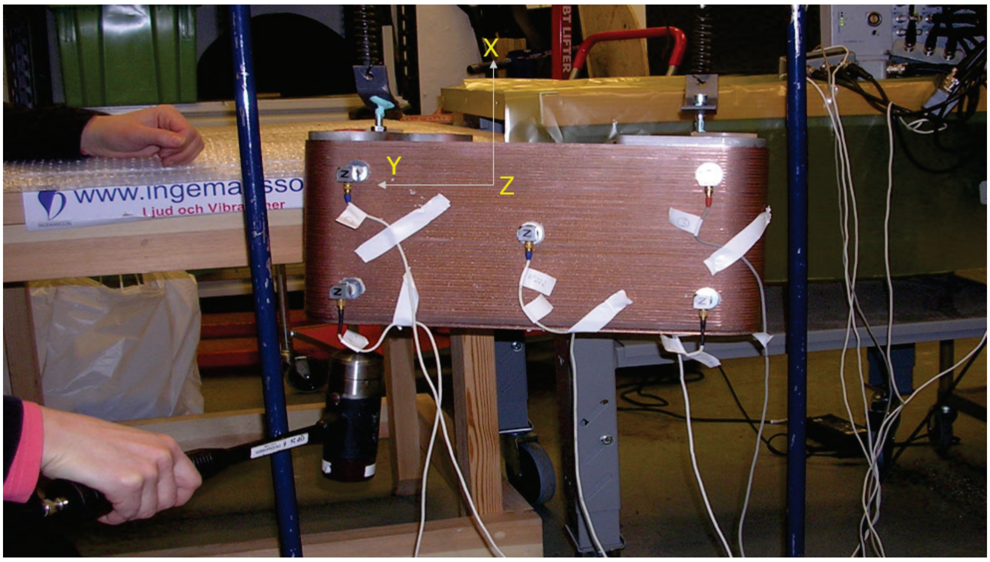


Figure 64: Example Oil cooler to a truck. Structure impact tested without oil and freely suspended. Hammer excitation in vertical x-direction and horizontal y- and z-direction.

This oil cooler has natural small clearances due to the stacking of the metal plates which makes it extra difficult to excite in horizontal Y-direction compared to other directions as can be seen in Figure 65.

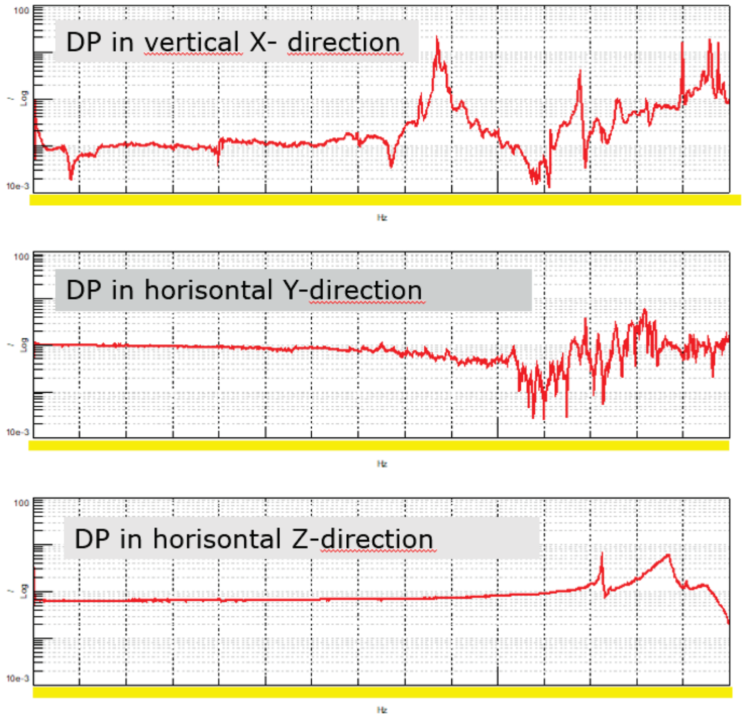


Figure 65: Driving point spectrum, DP, in x y and z-direction. Note, the noisy result of the Driving Point in Y-direction.

More common measurement pitfalls for ODS and Modal measurement are:

- Setup of wrong sensor direction which results in none physical mode shapes
- Selection of wrong driving point which cannot distribute energy to all modes. The mode of concern will not be excited.
- For impact testing - loose connector to impact hammer so no high level trigger can be found.
- Too much focus on the main component under investigation and measurements on connecting piping and foundation to system under investigation are forgotten.
- Wrong selected accelerometers. Modal tests often requires higher accelerometer sensitivity compared to ODS in order to maintain a good signal to noise ratio.

6 Hardware related vibration measurement pitfalls

6.1 SENSORS

Excessive shock is the largest damage risk for accelerometers due to the piezo crystal polarization which changes when exposed to shocks and in worst case get cracked.

Do keep in mind that a cracked crystal usually doesn't result in rattling in the accelerometer and can have unexpected effects on the vibration signature, raising some frequency levels and lowering others, which may result in a measurement pitfall since it's not obvious that the accelerometer measures wrong. Also, the handheld calibrator often only calibrates at a single frequency and will not warn the user if levels are not OK at other frequencies. It's therefore good to have a reference accelerometer that you rely on when taking periodic measurements. Additionally, regular verification of the sensors at a wider frequency range in a calibration lab could help reducing the risk of errors. Accelerometers used with portable data collectors should be calibrated annually because they do get knocked around in everyday use. Permanently installed accelerometers not operated near their rated temperature limit have it pretty easy. Calibration on a 3 - 5 year cycle is recommended to ensure the quality of the results.

Calibration pitfalls of accelerometers can happens especially when changing calibration routines, calibration staff and calibration equipment. The following example occurred at a vibration group which had accelerometer types with sensitivities ranging from 5 mV/g to 500 mV/g. They required to have these accelerometers calibrated annually. Each year the accelerometers drifted slightly as a group over time. They would all go up a percent or two for a specific time, and all down a percent or two for another time. Were all the accelerometers drifting as a group? No...the reported sensitivity changed each time the calibration lab changed their reference accelerometer!

The piezo crystal ages over time and some of the molecules become depolarized. This happens in an logarithmically decreasing manner. When the crystal is polarized (by passing a high DC current through it while it's at elevated temperature) there is a fall-off over time. From day 1 to day 10, there is a fall-off in sensitivity of around 1%. From day 10 to day 100 there is another fall-off of 1%, and again from day 100 to day 1,000, day 1000 to day 10,000 and so on.

The other common factor that can shorten the life of an accelerometer is operation near or above its rated temperature. When the crystal is heated above its Curie point, it loses polarization and you get no output. Operating at elevated temperatures accelerates the natural aging of the crystal, causing the accelerometer to lose sensitivity over time.

Quality accelerometers have a hermetic seal, which should hold up over the life span of the sensor. Hermetically-sealed accelerometers actually fuse a glass bead between each connector pin and the case to maintain an air-tight (and electrically insulated) seal to the case. A lower-quality accelerometer may use plastic or epoxy for this purpose which will break down over time, allowing moisture to enter the accelerometer which the high-impedance charge mode circuit between the crystal and integral amplifier just cannot handle.

When selecting accelerometer which will be used for long-term measurement it's important to consider which design, top- or side-exit accelerometer, see Figure 66, best fits the mounting structure to achieve a good cable route which minimize the wear on the connector to the sensor. By visual inspection a faulty cable may be easier to identify than a faulty connector.

Figure 66: Top exit design accelerometer to the left and side exit accelerometer to the right.

6.2 AMPLIFIERS AND EXTERNAL MECHANICAL FILTERS

Slew rate decides the capability of an amplifier to change its output rapidly, hence it decides the highest frequency of operation for a given amplifier. The slew rate of the amplifier can limit the performance of a measurement circuit and it can distort the output waveform if it's limit is exceeded, see Figure 67. This might result in high frequency roll-off and rounding of square waves.

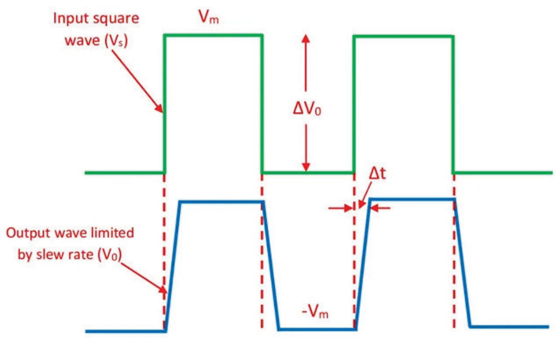


Figure 67: Input and Slew Limited Output Voltage Waveform.

The slew rate, S, effects the limited bandwidth, f, according to the relation

$$f = \frac{S}{2\pi V} \qquad \text{Equation 2}$$

where V is the peak voltage.

The slew rate should be as high as possible to ensure the maximum undistorted output voltage swing if higher frequencies should be measured. A typically general-purpose device may have a slew rate of 10 V/μs. This means that when a large step input signal is applied to the input, the electronic device can provide an output of 10 volts in 1 microsecond. To ensure a minimum disturbance of the high frequency signal, a low pass filter inside the amplifier is applied. Depending on how the filter/filters are setup they also affect the phase of the measurement system, as well as the amplitude.

Below is an example of a measurement pitfall when measuring the voltage and current generated from a turbine-generator set, where the phase shift from each sensor chain (sensor, cables, amplifiers, transformers etc.) were not checked carefully before making the measurements. Initially, a wrong assumption was made concerning how much reactive power that was distributed to the electrical net. However, it was soon ascertained to be a measurement error, since the phase lag between voltage and current was unrealistically high, with a measured phase shift of 36 ° between current and voltage, i.e., too much reactive power generated instead of active power. Expected was < 1° to ensure a good balance between reactive and active electric power. The measured faulty phase lag result for both current and voltage for all three phases are shown in Figure 68. The measured peak current value, 2.4 A, and voltage value, 4.3 V, corresponded to expected values (2.4A and 4.4 V, respectively).

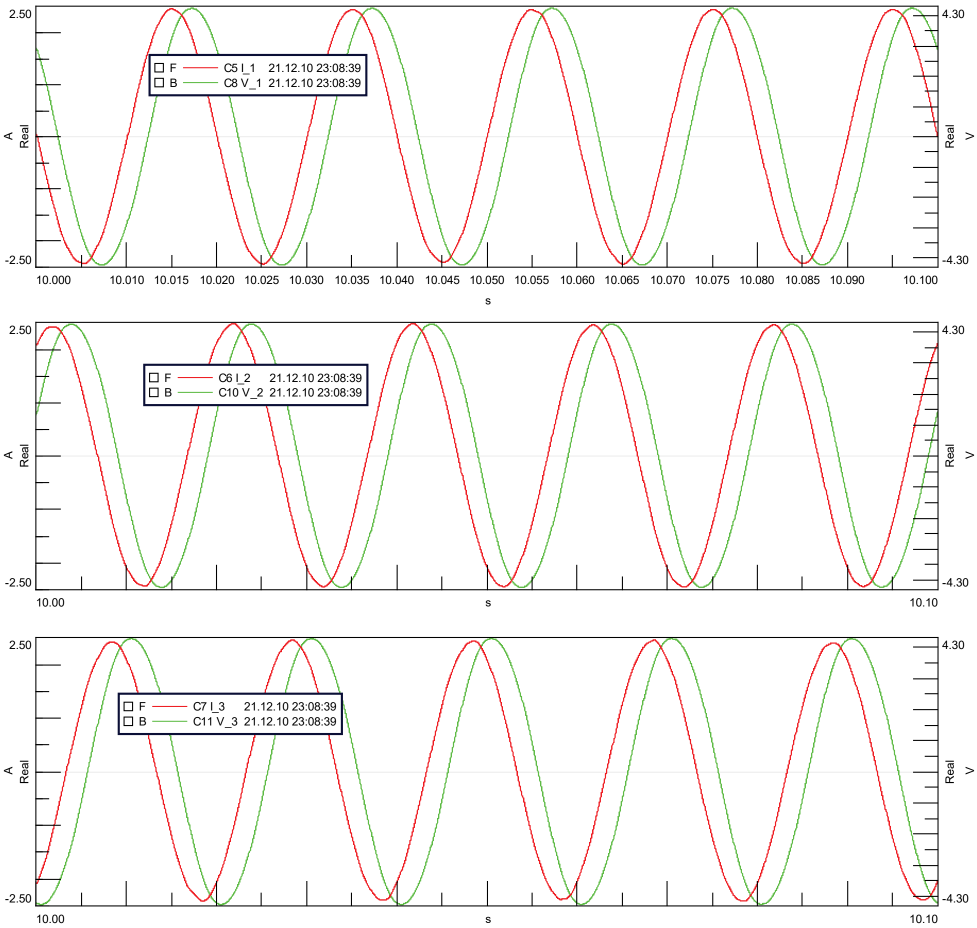


Figure 68: ***Examples of collected raw data of U (red curve) and I (green curve) at full power about 450 MW for all three AC currents.*** **Current I** ***is 36° before voltage V (φ= -36°). Y-axis to the left in Ampere and Y-axis to the right in Voltage.***

The three phase AC was measured with AmpFlex current sensors, see Figure 69, which have a varying phase and amplitude specification supplied by the supplier.

Figure 69: ***Mounted AmpFLEX sensors for measuring three phase currents I1,I2 and I3 on terminal. Observe the current direction arrow on the sensor.***

However, the varying phase and amplitude deviations were only verified on the product data sheet at a few number of specified currents, where the one closest to the measured levels was 10 A (measured 2.4 A). After a complementary verification of the current sensor, the phase shift ended up to be 24˚ @ 2.4 A instead of the specified 20˚ @ 10 A at f=50 Hz.

Between the generator voltage measurement transformer on the terminal and the measurement system, an isolation amplifier was used, see Figure 70, to register the voltage from the three phases.

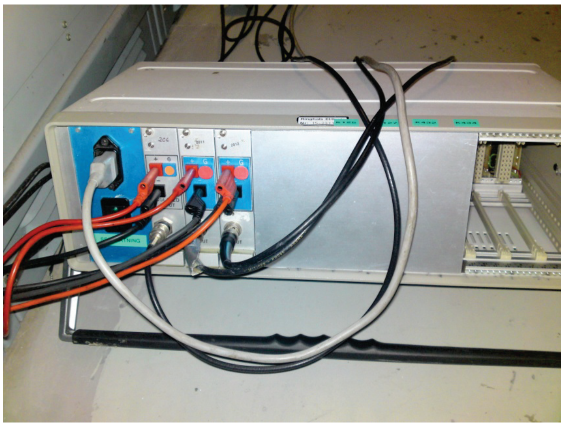


Figure 70: Analog isolation amplifier used to transform voltage 110.0 V on terminal to 5.47 V range suitable for measurement system.

The insulation amplifiers were used to transform the voltage down to levels ≤ 10 V adapted to the measurement system. The amplifiers have filters to reduce the slew rate effect of the high frequency signal, which affects the limited bandwidth depending on which voltage ratio that is selected. At first, no one thought about that also the isolator amplifier add a phase shift. Upon phase verification it was verified that each input module of the isolator amplifier add a phase shift of approximately 17° @ 50 Hz during the prevailing circumstances.

As a result all subcomponents in the measurement chain contributed with a phase shift between current and voltage which needed to be considered in the analysis. To summarize, it's very important to check up all contributions to the phase shift of the measurement chain in order to maintain reliable measurement result.

6.3 CABLES/CONNECTORS

Unfortunately, many cables fail long before they should, and, it is not necessarily the fault of the cable. One of the biggest factors affecting cable life-span is determined by the installation procedure, not the cable itself.

Accelerometers and cables are often used in severe, contaminated environments, under vibration and shock conditions. All of these conditions stress the accelerometer/cable connection and ultimately contribute to decreased service life and cable failure.

If the accelerometer is to be operated in a contaminated environment with moisture, dust, dirt, etc. the cable connection should be sealed with silicone sealant and/or heat shrink tubing. This is extremely important for high impedance charge mode sensors as any contamination in the cable connection will lower the insulation resistance, degrading the low frequency response and may cause drift.

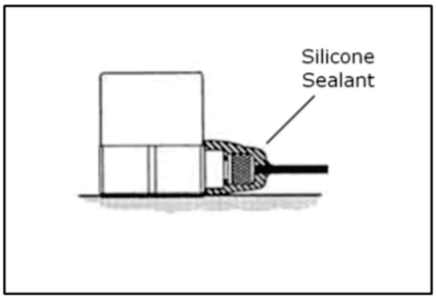


Figure 71: Connector to sensor environmental protected with silicone sealant.

Operation over long cables, above 30 m, may affect the frequency response of IEPE accelerometers, and introduce low frequency noise and high frequency distortion when the available current is insufficient is to drive the cable capacitance. Generally, this signal distortion is not a problem with low frequency testing within a range up to 1,000 Hz. However, for highfrequency vibration, shock or transient testing using cables longer than 500 ft. (approx. 150 m) , the possibility of signal distortion exists. If insufficient current is supplied, the "slew rate" is limited see 6.2, resulting in some high frequency roll-off and rounding of square waves and transients.

The cable driving nomograph, see Figure 72, provides a simple, graphical method for obtaining the expected maximum frequency capability of the measurement system when using long cables.

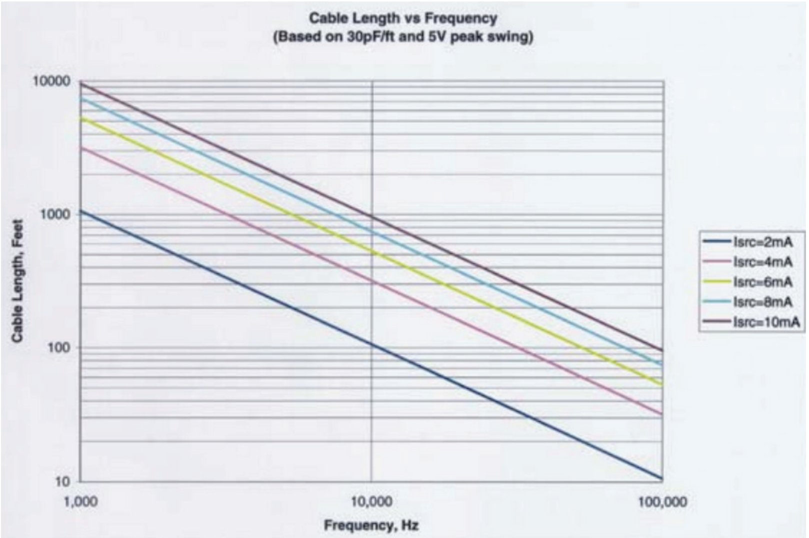


Figure 72: Example of cable driving nomograph on 30pF/feet cable and a 5V voltage amplitude.

The maximum peak signal voltage amplitude, cable capacitance and supplied constant current must be known or presumed. However, there may be pitfalls to take into consideration when reading the cable nomograph. The cable nomograph does not indicate whether the frequency amplitude response at a point is flat, rising or falling. For precautionary reasons, it is good general practice to increase the constant current (if possible) to the sensor (within its maximum limit) so that the frequency determined from the nomograph is approximately 1.5 to 2 times greater than the maximum frequency of interest. Also, any current not consumed in, the cable goes directly to power the sensor’s internal electronics which will create heat. This may cause the sensor to exceed its maximum temperature specification. For this reason, do not supply excessive current over short cable runs or when testing at elevated temperatures. This will both degenerate the sensor and cause a low-frequency problem.

It is also good practice when operating through long input cables to use a short adapter cable at the sensor to connect into a long extension cable, see Figure 73. Thus, any cable/connector failure involves only the replacement of the short adapter cable, rather than changing the long extension cable.

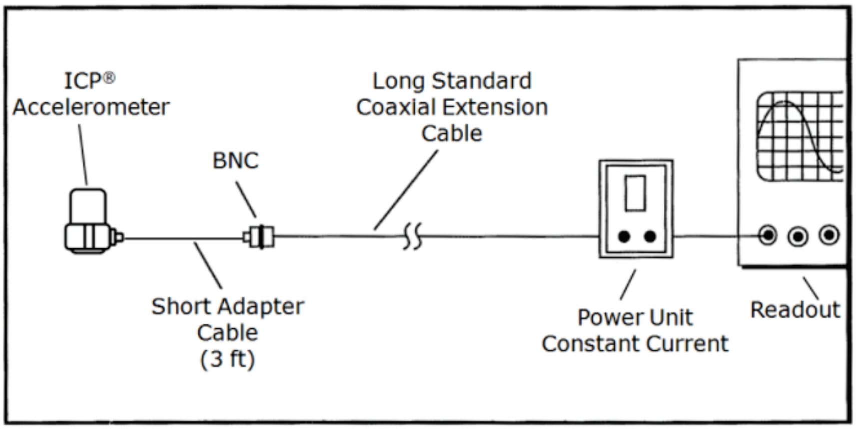


Figure 73: Example with short adapter cable closest to the sensor, then connect into a long extension cable.

When running cables near electric motors, always approach the cable perpendicular to the motor rotor axis. The cables should always run directly away from the monitoring point and be maintained at the maximum distance from the motor case to avoid influence from the stator winding magnetic field. A principle sketch to minimize magnetic interference is shown in Figure 74.

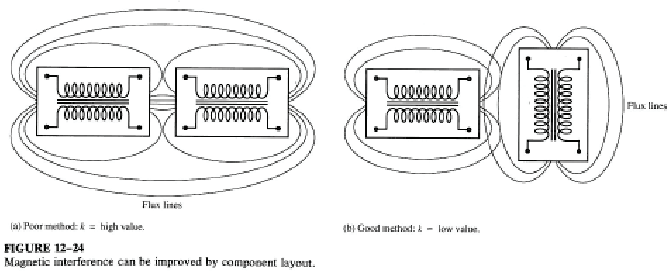


Figure 74: ***Examples of minimizing magnetic interference between cables and electrical devices. A. illustrate worse placement B. illustrates better placement.***

6.4 ACQUISITION SYSTEMS

Shock and vibration testing goes beyond basic data acquisition. The test is only effective when you are able to understand what the data means for your application. And it takes some creative skill to gather and analyze your shock and vibration data properly.

The sensor selection will often dictate the type of acquisition system that will work based upon the sensor's output. Does the sensor have a digital output? Is it 0 to 30 volts, or is it ±5 volts? Low sensitivity sensors may require amplification of their output. The shock and vibration measurement system setup can be significantly simplified if the measurement system can provide the excitation voltage to your sensor and power it, so that clunky power supplies can be avoided.

A universal data acquisition system should offer a universal signal conditioning, low power consumption, convenient storage possibilities and an easy-to-use software

There are plenty of parameters to consider for an acquisition system in order to avoid measurement pitfalls. When bringing in a new system solution to the site a comparison to an old reliable system needs to be made carefully. If the evaluation parameters do not fulfill the site demand, the users will run into measurement pitfalls. Consistency with older reliable systems needs to be confirmed before a new system is accepted. The following points should be checked to avoid having pitfalls with a new system:

- Experience level of the system operators – Worst measurement pitfall of all. If not a correct setup can be prepared due to a too complicated logger/trouble shooting system/CM system, no one can interpret the result from the system.
- Temperature (minimum, maximum and temperature change) influences the hardware. How is the electronic in the system surviving the working environment. Built in electronics may be sensitive, for example electrical filters like analog anti-aliasing filters with resistors and capacitors that change properties with temperature. More complex electronics, such as higher order filters for steeper roll-off, requires more electronical components and thus can be extra sensitive to temperature changes.
- How the system measures vibration and impacts. Compare both vibration amplitude mm/s rms and µm peak, as well as the phase angle so that they agree with the expectations, and if they do not then you can explain why. Also check that there is no change of polarity compared with the old reliable system.
- Exposure to ESD, EMI, and RFI. Is the hardware working properly in strong electrical and magnetic fields.
- LAN interface between measurement PC/laptop/tablet and fronted. It can happen that Firewalls must be turned off and/or IP address needs to be fixed instead of dynamic to maintain a stable connection to the frontend. Often better to go for a USB interface where no interference is to the sites network.
- System sensitivity to water and humidity.
- System sensitivity to corrosive chemicals / salt spray
- System sensitivity to radiation
- Dirt, sand and dust. How is input modules sealed to the fronted housing?
- Battery – Maybe you think that you don't need it but think in case you run into a grounding problem then it's nice to switch to battery power supply. Also make sure that the integrated battery works in a wide temperature range. This means that an integrated charging circuit helps to prevent electronics from overheating or battery from crystallization. For instance the circuit stops charging the battery below a minimum temperature or above a maximum temperature.
- Cooling fan for electronics - it makes unwanted noise for acoustical measurements. Users are seldom aware of that a too long turn off of the fan can overheat the electronics on the cards.
- Data sharing – is the system open for data sharing which allows for easy analysis using other systems.

- Ex. 1 : Impact testing performed with system 1-> Modal analysis performed with system 2. -> Finally data should made accessible for simulation FE- software.
- Ex. 2: For Conditioning Monitor Systems check if the time signal can be exported. Transient shocks needs to be recorded in time domain. Wrong assumptions can be made if the time signal is not available and checked. Often this is needed in a system trouble shooting.

After finding a replacement to the old acquisition system the user often will be introduced to unpredictable problems which can easily be a measurement pitfall if not adequately evaluated. A/D conversion may have raised from 12 bits to 24 bits or higher. Higher available sampling frequency and higher number of spectral lines etc. Transients which was not registered before on the old system are suddenly revealed due to increased performance. This can be both good and bad. Good if the transients are caused by real physics, but bad if the transients depend on measurement noise. The system will measure everything and it is up to the user to determine if the vibration or shock is real and true. The quantization error, see Figure 75, will be less when having higher performance compared to a system/logger with lower ADC bits conversion and sampling frequency. The system is better prepared to register transients and shocks.

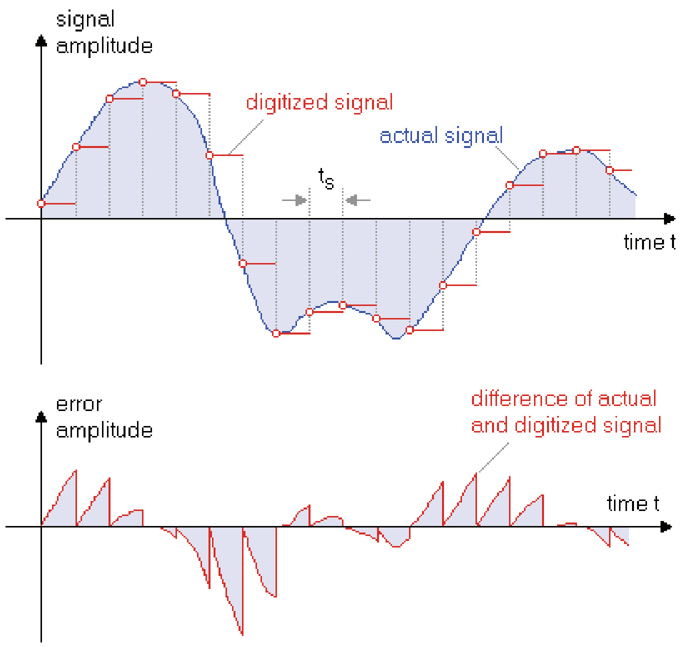


Figure 75: Example of actual and digitized signal. Upper window – amplitude comparison. Lower window – quantization error amplitude between actual and digitized signal. Note the greater quantization error for signal with steep slope.

As an example, a Vibration Control System, for instance Random Control or Stepped Sine Control, where a control loop continuously updates the reference signal to a shaker to achieve close loops for performing endurance testing had unexpected problems after having the old acquisition system replaced with a new high-performance system. All old setups did not work anymore due to much more sensitive equipment to pick up transients from the measurement chain. However the problem could be solved by adapting the settings. However, this may be difficult for an unexperienced user to find a solution for.

7 Human factor related vibration measurement pitfalls

As measurement engineer there are a lot of pitfalls that you may fall into. For example where you place your cabling, connecting the correct cable to the correct channel, choosing the measurement positions or directions and much more.

There are many stages involved and it is a learning process to become an experienced measurement engineer. Sometimes you need to learn the hard way, especially for unique machines or unusual measurement challenges. It is important that a junior engineer is involved in learning, and one of the best ways is to work together with an experienced engineer who can show and tell how they perform measurements and what pitfalls they have encountered etc.

To reduce the risk of errors, careful marking of each cable is important to allow for simple follow up of an installation. Make sure that you have a good connection base and how it is tested. Additionally, it is not at all certain that you can access the positions that you really want to measure.

To avoid pitfalls remember that NOTHING is obvious, and check every step. Also remember that no machine is dynamically identical even if it is a one-to-one replacement.

As a test engineer you often collaborate with the simulation engineers when planning measurements. However, it is quite often that the measurement points selected based on the computer model cannot be found or accessed at the actual measurement site. You have to convince both the junior/unexperienced engineer as well as the simulation engineers about how to choose positions and how to adapt when in the field. It is important to review in advance and to carefully document on site and test as much as possible before the actual measurement.

7.1 PREPARATION PHASE

The preparation phase might be seen as a fairly unimportant stage when performing a routine measurement that has been performed many times before. However, even though it is a routine/repeated measurement it is easy to make mistakes when rushing the preparation phase. For example, the so called routine measurement might turn out to have other circumstances than expected, other operating conditions, or new unexpected problems might be discovered. . Rushing through the preparation phase is something both experienced and unexperienced staff might do but it is important to take care, check the instrumentation, the cables etc and to think through the measurement beforehand. For example, what positions and directions to measure, what type of measurement that is needed, does the site look like it does in the drawings, what is the purpose of the measurement etc. Further questions to consider is e.g. what measurements have been done before and what was the conditions and settings for these? Are the new measurement to be compared with old results? And so on.

Pitfalls when not taking care in the preparation phase are typically to not have the correct instrumentation, not enough or correct cables, the positions that was planned for measurements were not accessible or not possible to measure, or that the number of points or the modal shape resolution is not high enough. When not checking instrumentation beforehand (preparing the measurement setup, connecting all sensors and cables etc.) it might be discovered that some sensor or a cable is not working properly. If not extra spare equipment is brought to the site it may affect the measurement to a large extent.

Planning measurement positions and operating conditions etc. is extremely important. For modal impact measurements or ODS measurements it is preferable to prepare a geometry model of the structure before taking the measurements to have the possibility to quickly verify the measurement quality in the initial testing phase. For example by animating the modal shapes to verify point resolution, measurement settings or that the Euler angles are correct in the model vs the measurement.

Another example of a pitfall may be that measurements are planned at a site where you may not have access to information about the layout and what is actually possible to setup. For example, the cables cannot be laid out properly etc. This can usually be solved on site. However it can be stressful and many other personnel waiting etc. There are often problems with many other engineering areas working at the same site at the same time. Then equipment can break by mistake and it is important to plan for that situation and what can happen. For examples if cables are touching against hot pipes by mistake and can melt etc.

When skipping the different preparation steps for each measurement there are many mistakes that can be made and they are usually due to the 'human factor' and lack of time and many mistakes can be avoided by careful but effective planning.

7.2 WORKING TOGETHER – DIFFERENT TEAMS/DISCIPLINES

Working in teams are most of the time beneficial when it comes to vibration measurements and investigations. However working together in different teams and disciplines might at the same time contribute to the amount of pitfalls one might encounter.

A team that is used to work together can be like a well-oiled machine were everyone knows what to do and what to expect from each other. The roles are clear and communication is often easy and sometimes without words. However, for a new team there are many pitfalls that can be encountered due to lack of communication, lack of understanding of what is needed, what is communicated or expected and so on.

For example, when working cross-disciplinary with measurement specialists and simulation specialists, the simulation specialist might be the one ordering a measurement and the vibration specialist the one performing it and delivering the results. If it is not clear what the data should be used for, what format should be delivered, what measurement points or modal shapes that are to be measured/verified etc., the project might be very demanding and the cooperation or the results not satisfactory.

Another pitfall related to cooperation is when doing the documentation of measurement positions and directions. If not clearly decided/communicated before or during the measurement, this might cause unnecessary confusion when analyzing the results.

When working together in a very noisy environment it is often difficult to talk to each other. Misunderstandings and stress increase the number of mistakes. This can be related to positions, directions, wrong cable to the wrong accelerometer, forgetting to connect the ground and getting grounding issues etc.

Despite this, it is mostly preferred to work in teams. When communication and planning works and is done properly the team is much stronger and more pitfalls are avoided together than one single vibration expert usually can. For example, over the responsibility for the measurements and for the documentation can be splitted between the measurement officers. Inspecting the site prior to the measurement and involving the simulation expert can sort out many misunderstandings and possible mistakes before and after the measurement.

Teamwork is on a whole more successful.

7.3 BOOKKEEPING: DOCUMENTATION AND REPORTING

When measuring vibrations one of the most common pitfalls is to avoid or minimizing good bookkeeping due to lack of time or due to that it might be a repeated measurement which have been performed many times before.

Proper documentation and reporting of each measurement is one of the most important tasks when doing a measurement. It should be possible for engineers not directly involved in the measurement to follow the tests and interpreting the data and know what was done and why etc.

Most of the documentation mistakes are because of inexperience and/or carelessness, due to for example lack of time or a very tight measurement schedule/slot. This mostly appears in the report phase involving the documentation of the data and how to store the data.

One example identified in the interviews was when one NPP had changed sensors several times and different personnel performed measurements at different times. The directions of the sensors were different each time. Afterwards it was very difficult to sort out and to compare the different measurements with each other because of the sometimes insufficient documentation. Some of these mistakes regarding bookkeeping can be mitigated by performing most measurements together with a colleague.

Another pitfall is to not document a measurement sufficient and when a follow up is made, for example a year later, most details are forgotten and it is difficult to know what was done and how to repeat the measurement or how to use the results.

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Appendix A: Questionnaire

Questionnaire

Vibration Measurment Pitfalls - Project KKU52450

ÅSA COLLET AND JESSICA FROMELL, EFTERKLANG™

2021-02-16

Sammanfattning

Frågorna i detta dokument är främst relaterad till att belysa vilka fel som är vanligt förekommande vid dynamiska mätningar av vibrationer. Genom att belysa vanliga fallgropar kan dessa undviks. På så sätt blir mätningarna mer tillförlitliga och noggranna.

Mottagare av detta dokument är medlemmar i refrensgruppen i projektet

KKU52450.

Summary

The questions in this document will be used to collect information on common pitfalls for dynamic vibration measurement. By knowing the mistakes, pitfalls can be avoided to not endanger the reliability and accuracy of the measurements

The receivers of this document are the members of the reference group in the project KK50450.

List of content

1 Measure response vibrations on a machine/pipe/foundation etc.

Factors that shall be considered when measuring vibrations on machines are according to new upcoming standard ISO 20816-3,2: Mechanical vibration — Measurement and evaluation of machine vibration — Part 3: Coupled industrial machines :

- temperature variations;
- magnetic fields, including magnetisation of the shaft;
- sound fields;
- power source variations;
- transducer cable length (some designs of shaft vibration probe require matched cable lengths);
- transducer cable faults;
- transducer orientation

However, there are also other common standards VDI3842 for pipes, SSG3030 rotating equipment etc which describes measuring procedures.

a) Describe with specific examples if your site has been helped by following vibration standards in general to avoid measurement pitfalls. Which standards are you then following and for what components (pipe, machine etc)?

b) By following standards have you experienced additional factors (for instance radiation, airborne and structure born noise, earth faults, cable impedance etc) than those listed in conventional standards that you need to take into account? Please specify all additional factors you found important to avoid any measurement pitfalls.

c) Have you developed any guidelines of your own for some kind of measurement based on the sites experiences? Please specify and declare if you have site specific guidelines for following measurements:

   a. Eigenfrequencies and eigenmodes.
   b. Operational vibrations, continuous/regular mobile or campaign.
   c. ODS, Operational Deflection Shapes

d) What specific factors have you noticed are expecially important to check/validate in order to securing measurement data quality and relevance for the problem or task at hand?

e) What kind of pitfalls have you experiences wrt measurement of vibration response? What have the results/consequences been of the different pitfalls.

f) What might the pitfalls be when following a specific standard? Please give examples.

2 Measure reference signal (s) from force input

When performing modal analysis testing one or more source outputs is required to sufficiently exite the structure in the correct frequency range. Also the state and boundary conditions of the structure to be measured shall be the same as during operation. The temperature may be an issue.

a) For impact measurement there are different sizes of hammers. Which modal impact hammer (s) are your site using. Specify model and weight of hammer.

b) Do you have any rule of thumb for how much load the impact hammer you use can excite?

c) Have you notice any problem with the connector and cables when using the impact hammer? If yes how did you observe the error and how did you fix it?

d) Have you had any problem with insufficient excitation force to the structure w.r.t. magnitude or frequency. How did you find out that the excitation was the problem and how did you solve it?

e) Have you had any problems with finding the correct trigger settings and window settings? If yes how did you observe that this was the problem?

f) Do you have experience with different force sensors of charge mode type and ICP type. Known problems that you have identified wrt polarity, disturbances, cables, connectors etc.

g) Fixed hammer/Rowing hammer excitation techniques. When do you find them useful?

h) Lessons learned from shaker tests

i) What kind of problems or pitfalls are in your experience most common wrt force reference signals and impact testing? Please define at least three examples that has been identified.

j) What is in your experience the most important factors to consider to avoid measurement pitfalls and to ensure good measurement and data quality?

3 Preparation of measurements

A good planning of the testing is considered as very important and it can be very time consuming and costly if some factors are missed in the preparation phase. Many times a vibration specialist gets a request for a vibration test but needs to interpret what actually needs to be performed. Additionally there are circumstances for the place of concern which may influence the measurement and finally interpretation of the result.

a) A problem can be the state of the system that the component shall be measured under. How do you cope with full power/reduced power measurements? Any known miss-plannings and how did you solve it (calculation/remeasure etc)?

b) How do you prepare for unexpected temperature, humidity, radiation or other environmental factors? Have you experience of failures of environmental factors that you better could have planned for?

c) People and work in the same area may induce vibrations that disturb the measurements, especially for modal testing. Have you any experience in this field and what do you do in order to avoid these pitfalls?

d) Protection of the measurement chain as people may step on cables. How do you prepare for having a good measurement chain. Any lessons learned which can be useful when you prepare a new test campagne?

e) What kind of pitfalls have you experiences wrt preparation of measurements? What have the results/consequences been of the different pitfalls.

4 Validation of measurement chain - Transducers

Questions below concerns following:

- The right transducer for the right measurement range
- Settings/configuration
- Fixation and eigenfrequencies of the fixation
- Difference between transducer installation and operational situation.

a) Which brands and type of vibrations sensors are your site using?
b) When you perform a vibration measurement how do you select sensors? Do you select different sensors for a modal test compare to an operational test etc.?
c) Have you any experience of a faulty vibration sensor. How did you detect it as damaged or/and malfunctioning? What did you do to fix it?
    a. What are the typical signs you look for wrt faulty vibration sensor or measurement chain?
    b. What is your routine for troubleshooting or what are your usual steps in finding the issue?
d) Lessons learned from faulty settings/configuration. Please specify at least 5 cases for both operational tests and modal impact setups.
e) Have you any experience of a malfunctioning fixation which was verified by calculation but did not work under real conditions. What was the problem and how did you detect the problem?
f) How do you verify by testing that a fixation is OK?
g) What types of transducer installations do you use and what might the typical issues be with them that might impact the measurement and data quality?
h) What kind of pitfalls have you experiences wrt transducers? What have the results/consequences been of the different pitfalls.

5 Validation of measurement chain – Signal

Questions below concerns following:

- Raw signal versus transformed signal
- Type of signal
- Signal transformations between raw signal and software application
- Different kinds of filters

1) In what format do you collect your data/signals?
2) Do you apply any filters, mechanical or digital, on your signals?
    a. What kind of filters and in what applications/situations?
    b. Do you also store raw data with your filtered data?
3) What, in your experience, are the most critical parameters needed to be taken into account in order to ensure correct signal for different purposes?
4) What signal transformations are applied and what are, in your experience, the most common pitfalls and what is important to take into account when validating signal and data quality?
5) What kind of pitfalls have you experiences wrt validation of measurement chain? What have the results/consequences been of the different pitfalls.

6 Validation of measurement chain – Connections and cables between transducers

Cable and connections are important in the measurement chain. Often a site are using the same cables and connectors for several years if they still "look" good. Additionally, cables are used in different environments (radiation, temperature gradients, electrical disturbances etc) during their life span.

a) What kind of different cables and connectors do you use?

b) What is, in your experience the pros and cons between the different cable and connector types?

c) What parameters is important to consider/take into account, when choosing cable and connector for each different measurement application?

   a. Please specify examples for different applications and measurement environments that are applicable to your site.

d) Typical issues and pitfalls regarding cables and connectors

   a. Please specify at least five examples

   b. Please specify how you usually mitigate these issues described above.

e) Do you have any routine or best practice regarding life-span of cables and connectors and how to document, follow up and check? Please specify.

f) What kind of pitfalls have you experiences wrt validation of measurement chain? What have the results/consequences been of the different pitfalls.

7 Validation of measurement chain – Frontend and intermediate boxes

a) What kind of frontends and intermediate boxes do you use?

b) How do you validate measurement and data quality wrt to these?

c) What are the typical issues/pitfalls/mistakes you have noticed/experienced ?

d) How do you avoid/mitigate these issues?

e) Do you have a routine to follow up and check reliability etc of frontends etc?

f) What kind of pitfalls have you experiences wrt validation of measurement chain? What have the results/consequences been of the different pitfalls.

8 Validation of measurement chain – Applied software and firmware

a) Which/what software are you using?

b) Do you check your software after upgrade? Are there any routines for this?

c) How do you communicate and validate within your organisation that everyone is using correct software version ?

d) Do you take into account 'backward compatibility' of software and data formats ?

e) What are the typical issues/pitfalls regarding software and firmware and how do you mitigate or solve these?

f) How do you secure that software used is correct for the current vibration measurement at hand ?

g) How do you secure knowledge transfer of software or firmware 'bugs' that might affect your measurement or data quality?

9 Validation of measurement chain – Book keeping

Questions below concerns following:

- Comes from the right transducer
- Has a known direction (X, Y and Z) or (H,V and A) or (P, T and A) or (rad, tan and Ax)
-
- Has a known positive and negative direction

a) What are your typical routines for book keeping?

b) What are 'best practice' and possible pitfalls?

c) Pictures or no pictures?

d) How do you store notes and measurement information relevant for report and or data storage for e.g. future use/analysis

e) What kind of pitfalls have you experiences wrt book keeping? What have the results/consequences been of the different pitfalls.

10 Selection of measurement points

Questions below concerns following:

1. Parts to be measured
    - Location of response transducer
    - Location of reference points (modal)
    - Direction of the measurement

a) How do you usually select measurement points/positions?

b) How do you select an adequate co-ordinate system for your structure?

c) What is best practise in your organisation regarding measurement point selection and co-ordinate system?

d) What is, in your experience the most common mistakes/pitfalls made?

e) What is uncommon mistakes/pitfalls that still might be considered important to avoid?

f) How do you avoid these pitfalls?

g) How do you validate that the points selected are relevant/correct for the current measurement?

h) What kind of pitfalls have you experiences wrt selection of measurement points? What have the results/consequences been of the different pitfalls.

11 Validation of result

Questions below concerns following:

- Location of transducer
- Direction of the measurement

a) How do you validate the quality of the measurement results and signal data as well as analysis or filtering done?

b) Do you have a routine for validating measurement and analysis results?

c) If yes, please describe

d) If no, please describe why not and if this could be applicable for your organisation

e) How do you verify that the orientation of the sensors directions are adequate in your selected co-ordinate system

f) What kind of pitfalls have you experiences wrt validation of results? What have the results/consequences been of the different pitfalls.

VIBRATION MEASUREMENT PITFALLS

Vibration measurements is an important part of the nuclear power plant condition monitoring. Knowing that the measured results are correct is vital. If you are an experienced user you are often aware of all the common pitfalls and know how to avoid them, but for an inexperienced user it is valuable to get information on how to avoid common pitfalls. In this project experienced vibration experts have been interviewed and common pitfalls are documented. It is important to share experience on pitfalls, it is often very difficult and time consuming to detect, investigate, analyze and to solve the mistakes in measurements.

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