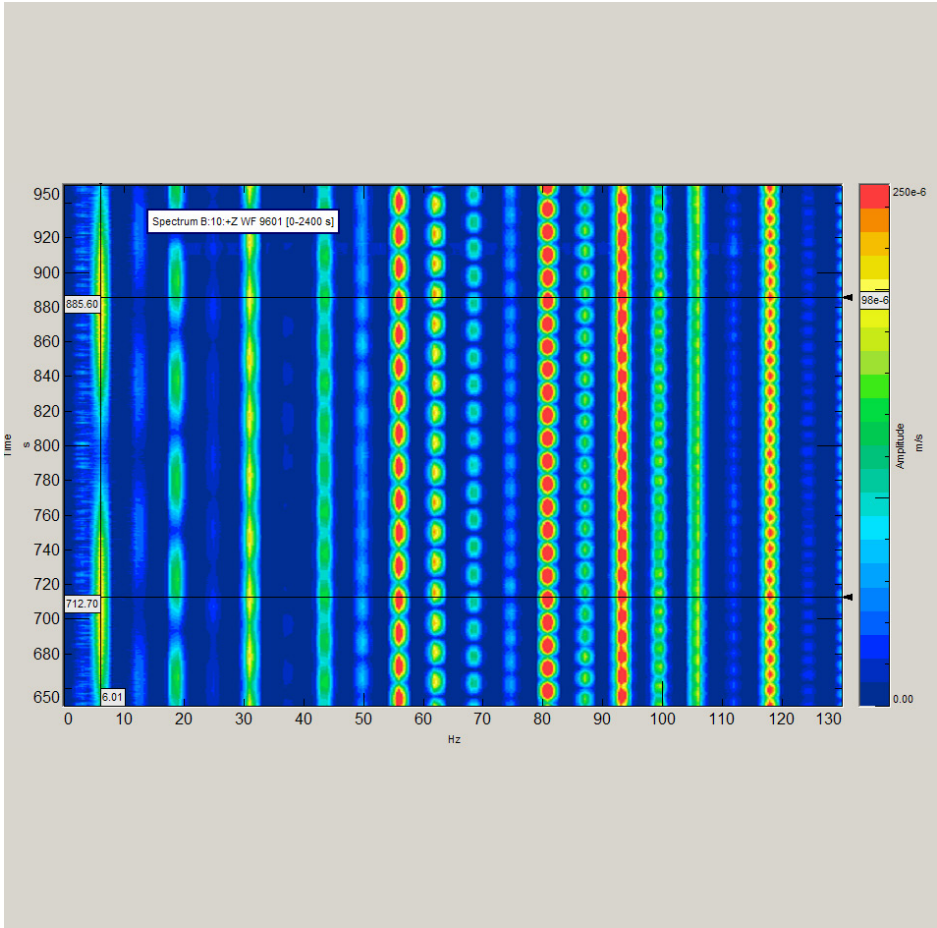
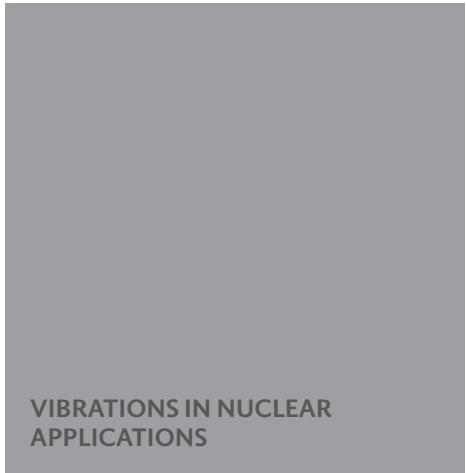


PIPE VIBRATIONS

REPORT 2017:351



Pipe Vibrations

Measurements

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Foreword

Vibration problems in nuclear power plants can originate from different sources. Pipe vibrations can be induced for example by flow along surfaces or around discontinuities, acoustic resonance or by some mechanical excitation. There are also fluid structure interaction phenomena where vibrations of structures influence the vibrations of adjacent structures by vibration induced pressure waves through the medium.

The objective of this project was to assemble knowledge and experience in the area of piping vibration measurements and study in some depth what are the best practices to perform the measurements. This information can be used when planning the measurement systems to validate piping vibrations acceptability when changing components, flows, pressures and/or temperatures in the plants.

This project was performed by ÅF, a Swedish engineering and consulting company, with senior consultants Åsa Collet and Magnus Källman as project leaders. The project is part of the Energiforsk R&D program Vibrations in nuclear applications, financed by Vattenfall, Sydkraft Nuclear, TVO, Fortum, Skellefteå Kraft and Karlstads Energi.

Monika Adsten, Energiforsk

Reported here are the results and conclusions from a project in a research program run by Energiforsk. The author / authors are responsible for the content and publication which does not mean that Energiforsk has taken a position.

Sammanfattning

Syftet med projektet "Mätning av rörvibrationer" är att samla kunskap och erfarenhet av hur man på bästa sätt skall mäta in rörvibrationer inom kärnkraftindustrin. Vibrationerna som samlas in finnas på rören, rörstöden eller ventilerna. Genom att veta hur man mäter kan ett möjligt rörvibrationsproblem avhjälpas effektivare och val av rätt åtgärd lättare verifieras.

Rörvibrationer på ett kärnkraftverk är ofta mycket komplexa eftersom rören innehåller ånga, vatten och ofta är trycksatta. Generellt har rörvibrationer i kärnkraften genom åren orsakat långa driftuppehåll och det finns därför ett uttalat behov av att återanvända kunskaper och erfarenheter inom området för att förhoppningsvis undvika längre driftuppehåll.

I detta projekt har erfarenheter från fyra nordiska kärnkraft (TVO, OKG, FKA, RAB) tillsammans med ÅFs konsulterfarenheter inom process- och kärnkraftsområdet använts för att sammanställa denna rapport.

Erfarenheter från de fyra kärnkraftverken har erhållits genom intervjuer med vibrations- och underhållsspecialister vid kraftverken. Som grund för intervjuerna har ett frågeformulär använts där frågorna har grupperats i sektionerna:

- Förberedelser inför mätning
- Kunskapsöverföring
- Vibrationskrav och dokumentation
- Utföra mätningar
- Mätutrustning
- Mätinställningar
- Laborativa modellskaleprover

I denna rapport presenteras en vägledning till hur rörvibrationer skall mätas och administreras på bästa sätt men även hur de processparametrar som påverkar vibrationer kan mätas in för att bättre fånga helhetsbilden. Rapporten belyser val av mätutrustning, mätinställningar, mätstandard, fallgropar vid mätning och hur resultat från mätningen kan analyseras och presenteras. Olika givarmonteringar som speciellt passar rörvibrationer finns exemplifierade i rapporten.

Följande slutsatser kan dras:

- Varje rörvibrationsproblem är unikt och det kräver god förståelse av vilka aktiva processhändelser, angränsande maskiner, rörupphängningar/stöd som kan påverka vibrationer.
- Val av mätutrustning styrs framförallt av vilken bandbredd/frekvensområde som behöver registreras för att fånga det aktuella vibrationsproblemet.
- Val av mätpunkter styrs framförallt av erfarenhet och tillgängligheten men det är att sträva efter att välja mätpunkterna från en beräkning där rörresonanser och spänningsgradienter kan klassificeras för maximala påfrestningar på rören.

Summary

The objective of the project "Pipe Vibrations – Measurements" is to assemble knowledge and experience in the area of piping vibration measurements at the Nordic nuclear power plants. The vibrations of the pipes concern the pipe structure, pipe support and valves. By setting up a guideline for pipe measurements based on experience the problem can be resolved in the most efficient way and selection of appropriate countermeasure could also be verified according to best practice.

Pipe vibration problems at a nuclear power plant are often complex since the pipes often contain water or steam under pressure. In General, the related vibration problems cause long periods of shutdown and therefore, there is a pronounced need to reuse knowledge and experience in the field of hopefully avoid long periods of shutdowns.

In this project has experience from four Nordic nuclear power plants (TVO, OKG, FKA, RAB) together with ÅFs consulting experience in process and the nuclear field been used to write this report. Experiences from the four nuclear plants were obtained by performing interviews with vibration and maintenance specialists at each power plant. A questionnaire was used as the basis for the interviews in which the questions have been grouped into following sections.

- Preparation for measurements
- Knowledge transfer
- Vibration requirements and documentation
- Taking measurements
- Measurement equipment and settings
- In-situ and Laboratory measurements

This report presents a best practice to how pipe vibration should be measured and managed but also how the process parameters that influence the vibrations can be measured in order to better capture the big picture. The report highlights the choice of measurement methods, measurement settings, measurement standard and pitfalls in measuring as well as how results from the measurement will be analyzed and presented. Various sensor mounts as especially suitable for piping vibrations are exemplified in the report.

The following conclusions can be drawn:

- Each pipe vibration problem is unique and requires a deep understanding of active process events, adjacent machines, pipe supports that may affect the vibrations.
- Selection of measuring equipment is controlled primarily by frequency bandwidth / range which capture the vibration problem.
- Choice of measurement points are selected mainly by experience and accessibility of the measurement location and areas. However, it's preferable to choose the measuring points from a calculation where pipe resonances pattern and stress levels can reveal hot spots for measuring positions.

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List of abbreviations

AET	Acceleration Endurance Test
BOV	Bias Output Voltage
BNC	Bayonet Neill Concelman
BWR	Boiling Water Reactor
CFD	Computational fluid dynamics
EDS	Energy Density Spectrum
EMA	Experimental Modal Analysis
EMI	Electromagnetic Interference
ESV	Emergency Shutoff Valve
F	Forsmark
FDS	Fatigue Damage Spectrum
FE	Finite Element
FEM	Finite Element Method
FEMA	Finite Element Modal Analysis
FKA	Forsmarks Kraftgrupp AB
ICP	Integrated circuit Piezoelectric
LO	Loviisa
LVDT	Linear Variable Differential Transformer
MRS	Maximum Response Function
O	Oskarshamn
OA-level	Overall-level
ODS	Operational Deflection Shapes
OKG	Oskarshamns Kraftgrupp AB
OL	Olkiluoto
PSD	Power Spectral Density
PWR	Pressurized Water Reactor
R	Ringhals
RMS	Root-Mean-Square
RAB	Ringhals kraftgrupp AB

RFI	Radio Frequency Interference
RPV	Reactor Pressure Vessel
SBC	Small Bore Connections
SBF	Small Bore Failure
SEA	Statistical Energy Analysis
TVO	Teollisuuden Voima Oyj
VVER	Vodo-Vodyanoi Energetichesky Reaktor; Water-Water Power Reactor

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1 Introduction

1.1 OBJECTIVE

The objective of this project is to assemble knowledge and experience in the area of piping vibration measurements and study in some depth what are the best practices to perform the measurements.

The nuclear power plants participating in the project were:

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

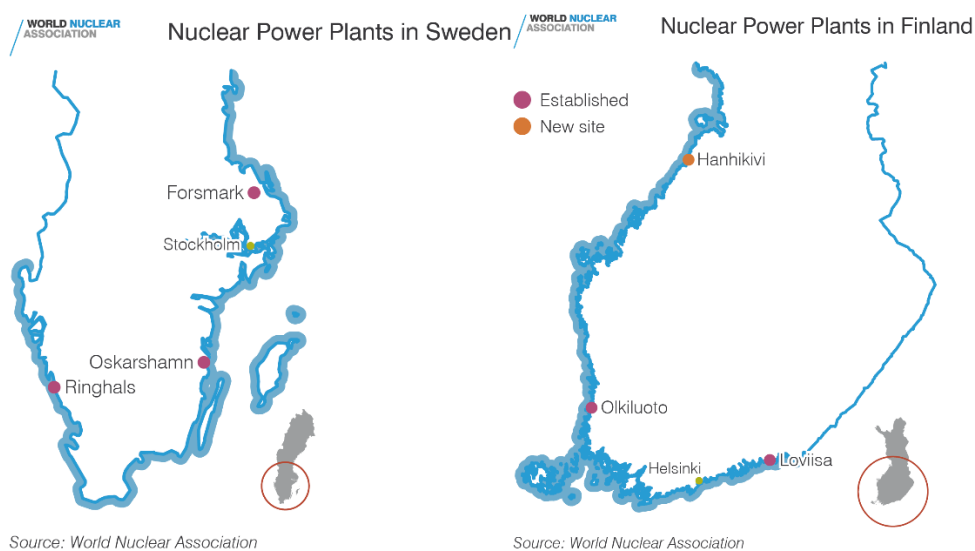


Figure 1 Nuclear power plants in Sweden and in Finland

Reactor	Operator	Type	MWe net	First power	Expected shutdown
O1	OKG	BWR	473	1972	2017
O2	OKG	BWR	638	1974	Closed in 2015
O3	OKG	BWR	1400	1985	2035 or 2045
R1	Vattenfall	BWR	878	1976	2020
R2	Vattenfall	PWR	807	1975	2019
R3	Vattenfall	PWR	1062	1981	2041
R4	Vattenfall	PWR	938	1983	2043
F1	Vattenfall	BWR	984	1980	2040
F2	Vattenfall	BWR	1120	1981	2041
F3	Vattenfall	BWR	1187	1985	2045
L1	Fortum	VVER	488	1977	2027
L2	Fortum	VVER	488	1980	2030
OL1	TVO	BWR	885	1978	2038
OL2	TVO	BWR	880	1980	2040

Table 1 Sweden's and Finland's operating nuclear power reactors

In the project, there are a joined reference group and a steering group. The group members are:

- Lena Skoglund and Stefan Melby (RAB)
- Petri Lemettinen and Paul Smeekes (TVO)
- Kent Andersson , Tobias Törnström and Carl Möller (OKG)
- Magnus Adolfsson and Ylva Vidhög (FKA)
- Heiki Haapaniemi and Jari Tenhunen (Fortum)

Figure 2 shows some of the members of the group.



Figure 2 Some of the members of the vibration group. From left side Lena Skoglund (RAB), Petri Lemettinen (TVO), Kent Andersson (OKG), Ylva Vidhög, (FKA) Jari Tenhunen (Fortum).

It has been shown that there exist many similarities between the vibration problems at the different sites (1). One of the key findings in reference (1) was that very large benefits have been obtained by the cooperation between the sites.

In general piping vibration problems have been well documented for nuclear power plants. Conventional power plants experience many of the same problems, but documentation of their problems is sparse.

In this report a selection of documented problems in the NPPs involved in this study are presented and some typical examples are discussed.

1.2 SCOPE OF THE WORK

1. Assemble information for the best practices on the pipe vibration measurements.
2. Assemble list of available measurement equipment (own \ available via consultants) for the pipe vibration measurements at the four participating nuclear power plants (NPP) (FKA, OKG, RAB, and TVO).
3. Group the information and make a technical report with a description of the best practices. Include example cases for the best practices. Include also typical pitfalls related to the measurements.

1.3 CONDUCTING THE WORK

ÅF in house experience from evaluation of pipe vibration problems together with reports and information from the NPPs were used. Four different interviews were

held with nuclear power plants. A prepared questionnaire, Appendix A: Questionnaire, was delivered to the contact person before the visit for preparation.

- RAB physical meeting 2016-05-03 with Fredrik Yngvesson, Björn Severinsson, Stefan Melby and Lena Skoglund.
- OKG physical meeting 2016-06-09 with Tobias Törnström and Kent Andersson.
- TVO virtual meeting 2016-06-13 with Petri Lemettinen and Jaakko Rostedt
- FKA physical meeting 2016-09-12 with Ylva Vidhög.

As a result of the meetings with the four power plants there were a good experience exchange of the pipe vibration routines at the sites. All four power plants have a lot in common but also have a lot of discrepancy. The result is described in the following Chapter 2.1.

In conjunction with the meeting, sites were encouraged to share pictures of site specific sensor mountings to the project.

2 Pipe vibration measurement capabilities

2.1 PIPE MEASUREMENT CAPABILITIES FROM THE FOUR NPP SITES

There are a lot of conformities but also a lot of discrepancies when it comes to measurement capabilities at the four power plants. Due to cost reductions at nuclear power plants the investments in new instruments and sensors have been very limited over a long period of time. As a result measurement equipment and sensors which was purchased from the start are still utilized. Each nuclear power plant has developed their own way of performing pipe measurements which are influenced by three main factors:

- Type of reactor BWR (Boiling Water Reactor), and/or PWR (Pressure Water Reactor).
- Sensor types, acquisition system and data logger capabilities.
- Number of dedicated personnel working with vibration measurements.
- Know-how experiences between similar blocks ex. RAB block R3 and R4 are sister reactors.

2.1.1 Results from interview with RAB

RAB has one BWR R1 and three PWR R2, R3 and R4. There is a dedicated measurement group which work with all four blocks R1-R4 simultaneously. Many experiences can be reused between different blocks, especially between the sister reactors R3 and R4.

RABs measurement group uses a lot of different sensor types such as pressure, strain, flow velocity etc. for trouble shooting of pipe problems, not just dedicated vibration sensors. The policy for selecting pipe vibration sensors are mainly based on frequency bandwidth.

Mechanical LVDT transducers, Figure 3, are considered for steam pipes measurements for bandwidth below 30 Hz. The disadvantage is the short sensor distance ~ 10 cm.



Figure 3 Axial and lateral mechanical LVDT sensors mounted on steam pipe. Source "delivered from RAB".

In the frequency range of $f=10-1600$ Hz mechanical velocity sensors are often used if the pipe vibration energy expects to be strong enough to cause overload to a regular piezoelectric accelerometer, ex. steam release. Mechanical velocity sensor without electronic linearization is often reliable from 10 Hz to 2000 Hz. A disadvantage with mechanical velocity sensors in general compared to accelerometers are that the velocity sensors are heavy and might give mass load to pipe system. Mechanical velocity sensors may also be too slow to respond fast enough depending on vibration nature from a repetitive transient vibration.

For general verification and trouble shooting in frequency bandwidth $f=10-1600$ Hz accelerometers are often used. In Figure 4 there is an example of accelerometer mountings with U-clamp in three perpendicular mountings on a hot pipe without isolation.



Figure 4 Accelerometers in three perpendicular directions mounted on a U-clamp on a pipe without isolation. Source "delivered from RAB".

As for on-line monitoring RAB is using fixed vibration monitoring with cameras and acoustic emission sensors to listen to incipient pipe cracks for their BWR block R1. For the PWR system online monitoring is performed with LVDT sensors on the steam pipes for block R3

In addition, the pipes next to the turbines/generators are checked for vibration once a year. Complementary measurements will be necessary if vibration levels differs more than 5 mm/s rms per year.

There are also control program for pipe hangers that is performed on regular basis. This is based on risk assessments and takes into account for instance the welding qualities.

2.1.2 Results from interview with OKG

OKG has three BWR's O1, OL2 and O3. Due to governmental and owner decision to just keep O3, it's difficult to build a sustainable engineering vibration group. Today the vibration group is limited to two people with help of external consultancy companies. It is then very important to complement with daily vibration monitoring by operating staff that also has subjective impression of the machinery and pipe systems.

The former Barsebäcks plants B1 and B2 are sister plants to O2. When all plants were power producing they could use expertise between plants.

On-line monitoring systems are available on all three plants which are BWR:s. However, O3 is the only active one. On-line sensors are installed by prioritization on steam-lines and in the auxiliary around turbine and generator. Cables and wiring are expensive which restrict the number of on-line measured channels. Temperature is an important design factor in choice of cable and transducer. It is therefore important to check cable assembly that all cables are secured from heat and correctly fasten.

Visual inspections of pipe hangers are performed during outage.

For pipe vibration measurements mainly accelerometers mounted with magnetic foot are used for all pipe investigations regardless of bandwidth. It is preferable to measure pipe vibrations in three direction simultaneously and in the frequency range of $f = 2\text{--}1000$ Hz. However, if the pipe vibration energy expects to be very strong, ex. steam release, where a regular piezoelectric accelerometer would get overloaded, mechanical velocity sensors are used. OKG does not use velocity sensors with digital linearization. Complementary process information to vibration measurements are taken from fixed installed pressure-, temperature sensor etc. registered by the on-line monitoring system.

2.1.3 Results from interview with TVO

TVO has two BWR's OL1 and OL2. These plants are almost identical and could then use expertise between the plants. There are small differences especially noted on the turbine piping area.

Finland does not conform to the same KFM (Konstruktionsföreskrifter för Mekaniska Anordningar) in the TBM (Tekniska Bestämmelser för Mekaniska Anordningar) as Sweden. KFM reflects "design/service/test loadings" and "design/service/test limits" for a mechanical device i.e. pipes. As a result, it is difficult to exchange knowledge in pipe design/modification output between Sweden and Finland.

Five year ago, there were more resources to plan and execute vibration measurements projects. Typically, the high cost of wiring installation or lack of input channels limits the possibility to install on-line measurements.

Today a team of roughly ten persons works in a team with vibrations in different roles i.e. structural FE, test engineering, maintenance and mechanical staff. Among them, the plant operators perform daily walk around at the units.

For pipe vibration measurements, mainly accelerometers are used for all pipe investigations regardless of bandwidth. It's preferable to measure pipe vibrations in three direction simultaneously and in frequency range of $f = 2\text{--}10\,000$ Hz in the first run. When knowing more about the vibration problem bandwidth can be decreased. If there is a pipe vibration problem below 10 Hz an appropriate accelerometer with large frequency bandwidth is selected (from 1 Hz up to 10 000 Hz) in first place.

Piping vibrations are constantly on-line monitored with alarm limits only for the generator cooling water pipes.

Accelerometer type of transducers with cabling to control room measurement cabinet are installed for main steam (inside containment) and turbine steam lines on both OL1 and OL2. These measurements are not constantly on-line monitored due to lack of input channels.

Visual inspections of pipe hangers are performed during outages.

For multichannel trouble shooting of pipe vibration problems TVO has a close cooperation with external testing company for performing modal analysis and operation deflection shapes (ODS).

2.1.4 Results from interview with FKA

FKA has three BWR's F1, F2 and F3. All blocks are different but unit F1 and F2 are the same from design. However, F2 runs 120 % but F1 109 % reactor power. Unit F3 and OKG's O3 was also the same from design but O3 has made modifications to run 129 % and unit F3 runs 109% reactor power after some modifications.

FKA vibration analysis group was before working in the technical department for structural integrity, flow, materials, inspection and vibration.

With the new organization since end of 2015, the vibration analysis is in the mechanical maintenance department, Turbine group together with condition based monitoring of machines. In addition, the technicians who perform the regular vibration measurements of components are organized in the mechanical maintenance groups for each unit.

In the last year, the cooperation between RAB and FKA has intensified.

For pipe vibration measurements, mainly linearized mechanical velocity sensors are used. The resonant frequencies of mechanical velocity sensors are often at 10 Hz. For special low frequency transducer, 4 Hz are common but those transducers are made for one direction, horizontal or vertical. Through electronic linearization of the respective frequency range, it is possible to measure vibrations that lie well below these resonant frequencies with high accuracy. FKA uses small velocity transducer with linearization down to 1-2 Hz. The high frequency border depends of how the transducers are mounted. For bolt mounting, FKA can use the frequency range 2-2000 Hz.

At FKA they have over time developed a network of very long cables, 300-400 m, from sensors mounted on a hot radiation pipe like in Figure 7 brought into the safe zone into the control room. Due to the long cables with velocity transducers, it is important to use linearization amplifiers with balanced inputs with high CMRR (common mode rejection ratio) to reduce noise and 50 Hz disturbances. In addition, it is important to use shielded twisted balanced 2-wire cables to reduce noise pick up as described in Section 8.2. In the radiation zone special "Raychem" cable or any other radiation-hardened cable are used.

For measurement with shorter cables or local measurements often, accelerometers are used. Sensitivity depending on type of vibrations.

FKA's standard sensor mounting for hot environment is shown in Figure 5 and Figure 6. Note that the drawing in Figure 5 should be turned so the transducer bracket is horizontal or vertical not in 45 degrees as the figure shows.

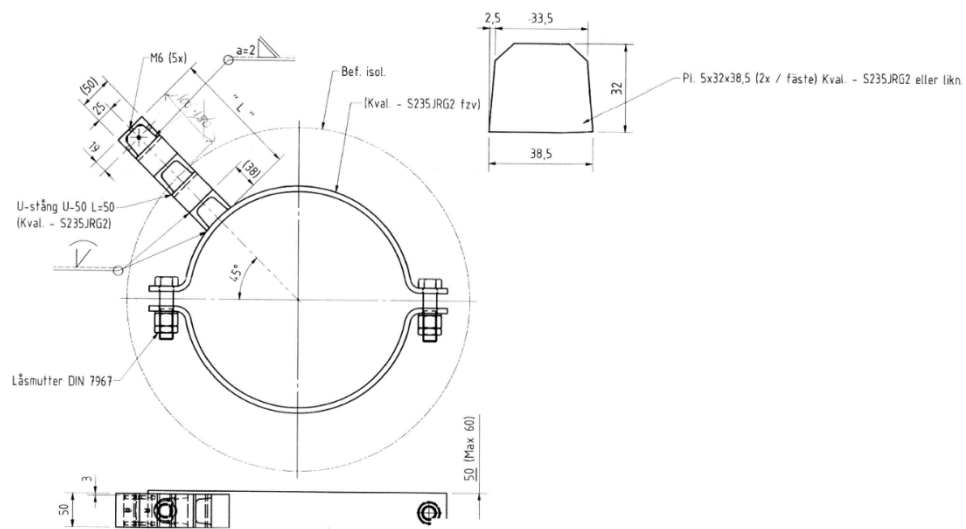


Figure 5 Drawing of typical pipe sensor mountings. Source “delivered from FKA”.

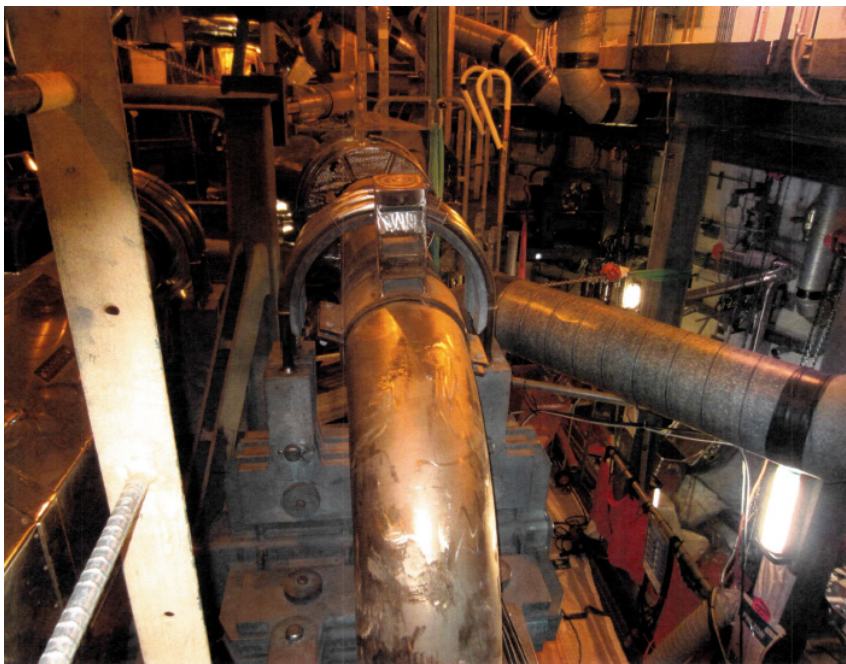


Figure 6 Preparation of pipe sensor mounting on hot pipe with radiation with sensor mount according to Figure 5. Source “delivered from FKA”.

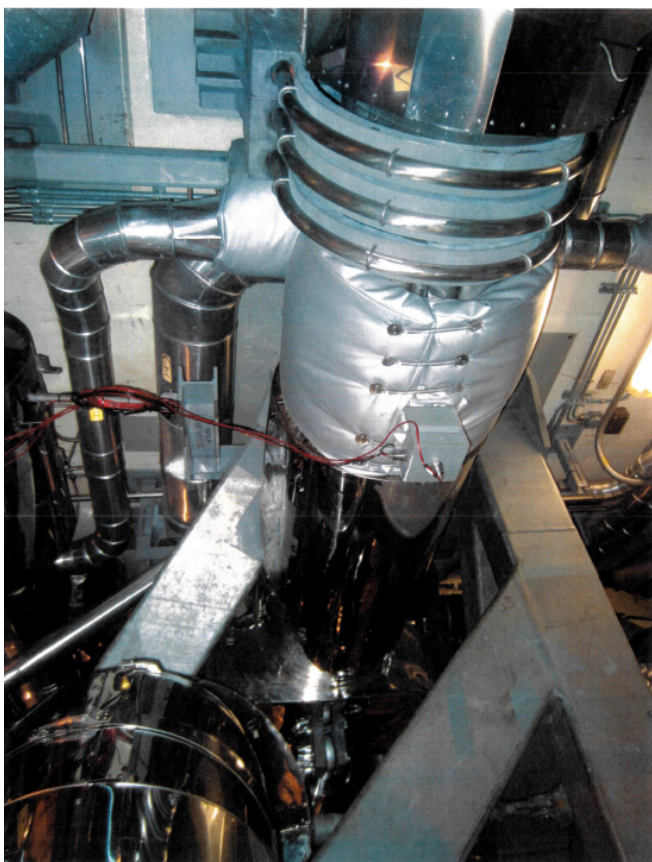


Figure 7 Sensors in radial and vertical direction mounted outside isolation. Source "delivered from FKA".

When changing valves to new, a resonance test, see 2.3.1, is performed before and after the change. When changing pipes vibration, measurements are done before, after the change, and during/after power upgrade.

2.2 PIPE VIBRATION MEASUREMENTS DURING OPERATION

For the purposes of piping measurements during operation, vibration typically divided into three types: steady-state random, steady-state periodic and dynamic transient vibrations. Each type has its own potential causes and effects that necessitate individualized treatment for measurements. For a more comprehensible understanding of a pipe system performance during different load cases it can be feasible to do a multichannel Operational Deflection Shapes, ODS.

However, there are some general guidelines, which can be used for all three-signal types mentioned above.

- Mount sensor as close as possible to the maximum amplification of the pipe vibrations
- Make sure the sensor is firmly attached.
- Make sure the sensor is oriented correctly.
- Mount the same sensor in the same location between measurements.

- Mount the sensor on something substantial.
A sensor must never be mounted on a very flexible part of the pipe system as the spectrum will be distorted by the flapping of the flexible part. The sensor must never be used on structures that are very light as the weight of for instance an accelerometer and magnetic mounting will distort the vibration behavior of the structure. In general, the combined weight of the accelerometer and magnetic mounting should be less than 10% of the weight of the vibrating structure.
- Take care of the sensor and connecting cables.
The accelerometer cable should never be twisted acutely, but must be anchored in a manner that prevents it from being damaged. Twisted or freely swinging cables can distort the measured spectrum

2.2.1 Stead-State random vibration

Steady-state random vibration can be defined as a repetitive vibration that occurs for a relatively long time period. The measurement time should then be long enough to capture the variation of the vibration in terms of frequency and amplitude.

The preferable measured spectrum type for steady-state random is Power Spectral Density, PSD, spectrum. It applies for signals existing over all time, or over a time period large enough (especially in relation to the duration of a measurement) which complies with a random vibration.

For the assessment of the piping vibrations in steady-state random vibration, the measurement of the vibration in a frequency range of $f=2$ to 2000 Hz can provide a rough orientation. If the frequency maximum value, F_{max} , required is very large the resolution of the spectrum will be low, and information pertaining to low vibration frequencies may be lost. It may be necessary to take some low F_{max} measurements in addition to the high F_{max} measurement.

It's a good practice to use overlapping data, which means of reusing a percentage of a previously measured waveform to calculate a new spectrum. The higher the 'Overlap percentage', the less newly acquired data is needed to generate a spectrum, and thus the faster the spectrum can be displayed. 50% overlap is ideal for most cases.

The parameter 'Average type' determines how spectra are averaged. 'Linear' averaging is recommended for most cases. 'Exponential' averaging is usually used only if vibration behavior varies significantly over time. 'Peak hold' does not really involve averaging but causes the worst-case (largest) amplitude for each spectral line to be displayed. The larger the number of spectra used for averaging, the more noise spikes are smoothed out and the more accurately true spectral peaks are represented. However, the larger the number of averages, the more data needs to be collected, and therefore the longer it takes to obtain the 'average spectrum'. A 'Number of averages' of 10 are sufficient for most cases.

The collected data is usually not directly used to generate a spectrum, but is often modified beforehand to cater for certain limitations of the FFT process (the process that transforms the data into a spectrum). Data is usually modified by

multiplication with a correction window. This prevents spectral lines from 'smearing' or 'leaking' into one another. 'Window type' is the parameter that determines the kind of window that is used. The 'Hanning' window is normally used for steady-state random vibration. If the 'rectangular' window is used, the data will effectively not be modified.

2.2.2 Steady-State periodic vibration

Almost the same parameters as for steady-state random as described in 2.2.1 can be applied to steady-state periodic. However, there are discrepancies with respect to:

- Frequency bandwidth
For the assessment of the piping vibrations in steady-state periodic vibration, the measurement of the vibration in a frequency range should often be higher than in the steady state random case. A frequency bandwidth of $f=2$ to 2000 Hz can provide a rough orientation. It may be necessary to take some low F_{max} measurements in addition to the high F_{max} measurement to capture the problem.
- Window type
Due to the periodic type, i.e. tonal nature of the vibration a Flattop window is most appropriate.

The preferable measured spectrum type for steady-state periodic is an ordinary RMS spectrum due to the sinusoidal nature.

2.2.3 Dynamic transient vibration

Dynamic transient vibrations occur for relatively short time periods and is usually generated by much larger forces compared to steady-state. It is then important to use less sensitive sensor compared to the steady-state case.

The measurement should be performed in time domain or preferable in a synchronous time-frequency domain. It is preferable to capture the time signal with a high sampling frequency. A best practice can be to use the maximum sampling frequency allowed by the measurement system in order to acquire the very short duration of the phenomenon.

The preferable measured spectrum type for transient vibration, which has the energy of the signal, concentrated around a finite time interval is the Energy Spectral Density, ESD, spectrum.

2.2.4 Operational Deflection Shapes, ODS

This measurement is carried out on an operating system at different load conditions for each subsystem. This gives information of how flow and flow speed, density, damping etc. influence critical system parameters. Critical positions with possible risk of high vibrations are pointed out.

The aim of operational deflection shape measurement is to determine the *forced* dynamic deflection at the operating frequency. The simplest and most accurate

technique is to mount an accelerometer at some point as a reference; and then to attach a roving accelerometer at other points and, if necessary, in different directions. The measurement points should be chosen sufficiently closely spaced to obtain good spatial resolution. At all points, the magnitude and phase differences between the roving and reference accelerometers are measured during steady state operation. The instrumentation used can be two individual single-channel systems or a dual-channel FFT analyzer. The measurements are then plotted to obtain an impression of how the individual parts of the structure move, both absolutely and in relation to each other.

2.3 IN-SITU MEASUREMENTS DURING MAINTENANCE OUTAGES.

Vibration testing during outage can be performed to quantify system parameters such as modal frequencies, damping, and mode shapes. Experimental parameters obtained by means of testing can then be used to improve and verify analytical models.

2.3.1 Experimental modal testing – Impact testing

Impact testing refers to impulse excitation with a modal impact hammer. The purpose of an impact is to obtain information about the system's dynamic properties for subsequent analysis.

To estimate how many modes are present within a certain frequency band, one can have a look at the different FRFs, but it is more convenient to summarise the information from all of them. The summation of FRFs helps to detect the resonance peaks because it will show all excited modes and will suppress the noise level.

The measurements are performed with an impact hammer or sledge with a force transducer mounted on the top. We often use an impact hammer to excite a structure in order to measure its dynamic properties. This device is similar to an ordinary hammer and instrumented with a force transducer to measure the dynamic force transferred to the test object. The impact can be made harder (shorter) or softer (longer) by selecting different hardness for the hammer tips as explain by Figure 8. The length and energy of the impulse is also influenced by the mass of the hammer, and a heavy hammer produces a longer impulse.

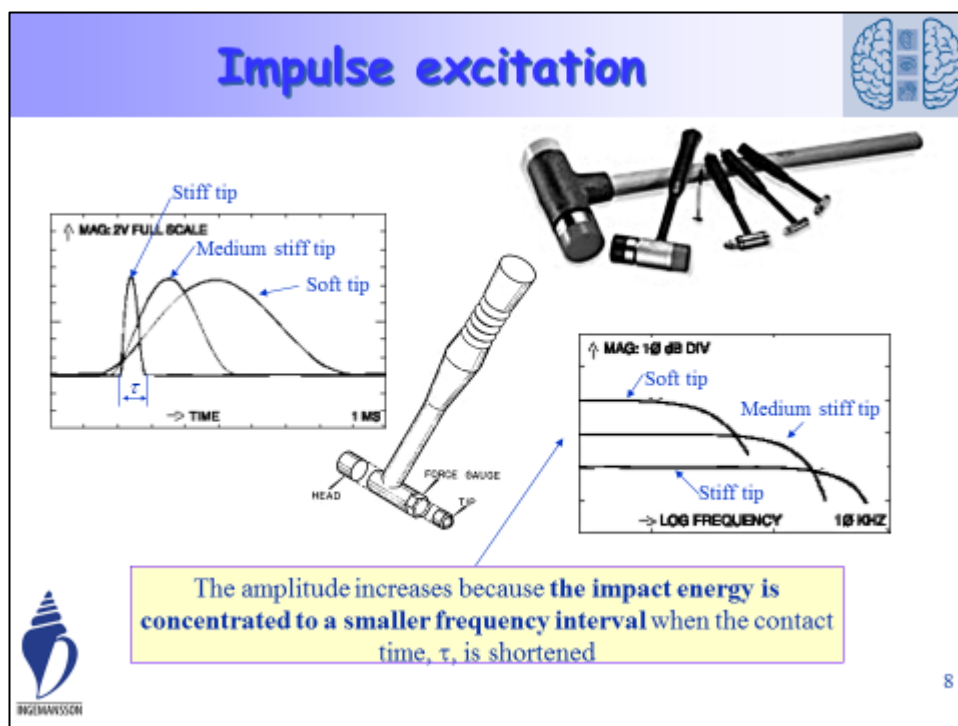


Figure 8 Different impulse hammer tips. Source "ÅF internal material".

The length of the impact will directly determine the frequency range of effective force excitation. In most cases one tries to avoid to excite with an excessively wide spectrum.

Commercially available, instrumented impact hammers are available in different sizes, from tenth of grams up to tenth of kilograms. Larger impulse exciters need frames and e.g. pendulum arrangements to be operated.

In general, you must choose an exciter that provides a high force-to-weight ratio for pipe applications, this ratio should preferably be greater than 8. To ensure that you choose an exciter that can generate enough force, you must know the masses of your test structures and the accelerations specified for your tests. You can then use Newton's law of dynamics, $\text{force} = \text{mass} * \text{acceleration}$, to calculate how much force the impact hammer will have to generate. When calculating this force, be sure to include the mass of the exciter armature in your calculation. The total mass that the exciter must accelerate is the mass of the armature plus the mass of the test structure.

The response acceleration is measured in a position close to the sledge "hit point" (point mobility) or at selected points in the system (transfer mobility). This prediction how well predicted, expected or calculated excitation force spectrum match the structural eigenmodes and the risk of increased vibrations. Estimations of vibration levels based on the force are carried out.

2.3.2 Mobility measurement of adjacent pipe structure

Mobility is a measure of vibration velocity as function of force excitation of the system.

The best way to avoid vibration problems due to resonance is to avoid high dynamic flexibility (low dynamic stiffness) at the frequencies where the input forces are the greatest. If you would like to anchor a damper countermeasure for the pipe system, you must find out where on the adjacent structure you have a low dynamic stiffness, typically 10 times more stiff than the pipe itself. These stiff places are appropriately where the damping counter measure will be connected to.

The dynamic stiffness is both temperature and frequency dependent and should be determined by measurements.

When defining the stiff places a co-operation with the civil design should be established as a concrete pillar or floor may not be as stiff as one expected.

2.4 LABORATORY MEASUREMENTS

The advantages of the laboratory measurements include (1):

1. Different process conditions and mitigation alternatives can be tested almost without restrictions.
2. No risk of damaging the system, compromising safety or causing production losses.
3. Simplified measurement procedures.
4. Possibilities for better visualization, e.g. by using transparent pipe walls.

Main steam lines, steam dryers and steam isolation valves have been investigated by laboratory measurements. Problems studied have been acoustic resonances, flow induced vibrations, multiphase mixture flow and pipe line vibration (1).

Model measurement is where a physical model is used instead of the real system. In cases where flow excitations of valves, bellows or other local equipment are investigated laboratory models might be helpful in trouble shooting purposes. In pipework both the real mechanical and flow conditions are of major importance and it could be difficult to scale these conditions and parameters correct in a laboratory measurement set up.

Today CFD (Computational Fluid Dynamics) has become a very strong alternative to laboratory measurements even at more complicated structures. It could be mentioned as an example that the entire propulsion system of an underwater vehicle was designed with CFD with great success at year 2005. The afterward model testing in a laboratory showed a perfect congruence.

However, for complicated structures as valves and especially at multiphase flow full-scale tests are still the best way for verification by author's opinion. Even if the CFD simulation model the outcome will not be better than the input flow data.

It is important to note that it is not possible to remove the need for measurements at the site with the laboratory measurements.

2.5 MOCKUP – DAMPING COUNTERMEASURES

Small bore connections are often experiencing high vibrations. Counter measures of SBC might be tested by impact testing at the site or at a mockup. In Figure 9 verification of damping countermeasures on valve in a built mockup with impact testing is presented.

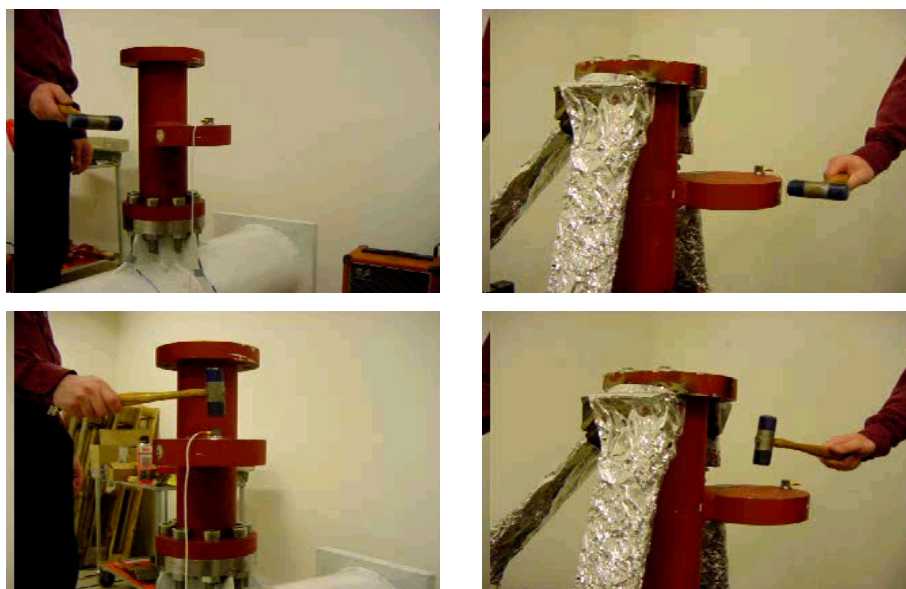


Figure 9 Reduce vibrations with damping. Verification of damping countermeasures on valve in a built mockup with impact testing. Left picture valve without damping countermeasures. Right pictures with attached damping countermeasures. Source "ÅF internal material".

Dynamic difference between the conventional pipe and the damped pipe is then demonstrated by playing the sound of a 3-axial acceleration signal that is amplified through a loudspeaker. The accelerometer is the tiny metal cube near the hammer.

Along with the sound recordings conventional reports of the vibrations effect was reported i.e. a modal analysis to determine the added damping to the pipe system mockup.

3 Standards related to pipe measurements

Standards with focus on piping vibration measurements are limited. But there are some general standards and guidelines covering actions and requirements for the avoidance of piping vibration problem.

Requirements for measurements, how many measurement points and locations are in most cases to be decided by the specific project or the vibration specialist.

Examples of piping vibration standards and guidelines are:

1. ASME OM-SG-2007 Standards and guides for operation and maintenance of nuclear power plants
2. ANSI/ASME Operation & Maintenance Standards/Guides Part-3, 1991, "Preoperational and Initial Startup Testing of Nuclear Power Plant Piping Systems" (OM-3)
3. VDI 3733-1996, Noise at Pipes
4. VDI 3842-2004, Vibrations in Piping Systems
5. Companion Guide to the ASME Boiler and Pressure Vessel Code, Volume 2, Second Edition 802191, ch37, PIPE VIBRATION TESTING AND ANALYSIS, David E. Olson
6. Guidelines for the Avoidance of Vibration Induced Fatigue Failure in Process Pipework, 2nd Edition, January 2008, Published by Energy Institute, London, Royal Charter 2003
7. NORSOK L-002, Edition 3, July 2009
8. DET NORSKE VERITAS, STRUCTURAL ANALYSIS OF PIPING SYSTEMS, RECOMMENDED PRACTICE, DNV-RP-D101, OCTOBER 2008

3.1 EVALUATION AND JUDGING OF PIPE VIBRATION LEVELS

In ANSI/ASME (OM-3) the judgment and evaluation of a pipe system is based on acceptable stress levels. However, as it is much easier to measure vibration levels than stress; therefore, vibration limits are commonly used for validation or defining vibration problems. While generating vibration criteria for every possible situation would be next to impossible, vibration limits based on field experience have been established, chapter 3.2 and 3.3.

Acceptable stress and vibration levels depend on many factors, a few of which are:

- Material (composition, strength, endurance, etc.)
- Geometry (size, quality of manufacturing, stress concentrations such as tee-intersections and cutouts, etc.)
- Number of stress cycles and
- Amount of residual static stress.

When comparing readings it is essential that all readings be taken at the same location and the same plane. Even small differences in location can affect the overall readings. All vibration transducers are single plane devices and only measure in the plane in which they are held or are mounted.

3.2 VIBRATION REQUIREMENTS

In ASME OM-S/G-2007 standard a vibration level of 12,7 mm/s, 0-peak value, screening vibration velocity level is given for pipe vibration. The standard does not include any frequency dependency.

In Guidelines for the Avoidance of Vibration Induced Fatigue Failure in Process Pipework (2), a diagram of acceptable, concern and problem vibrations versus frequency up to 300 Hz. An almost identical diagram is included in VDI 3842-2004, Vibrations in Piping Systems (3).

The diagram gives orientation for vibration velocity for assessing steady-state pipe vibrations. These values are based on experience in the petrochemical industry over a period of more than 25 years. They can be used as a first approximation for assessing vibrations in pipes which have the geometries and support spacing usual in the petrochemical industry but cannot be used for shell vibrations or for extremely short pipe components. The values are on the safe side for pipe vibrations of short duration (3).

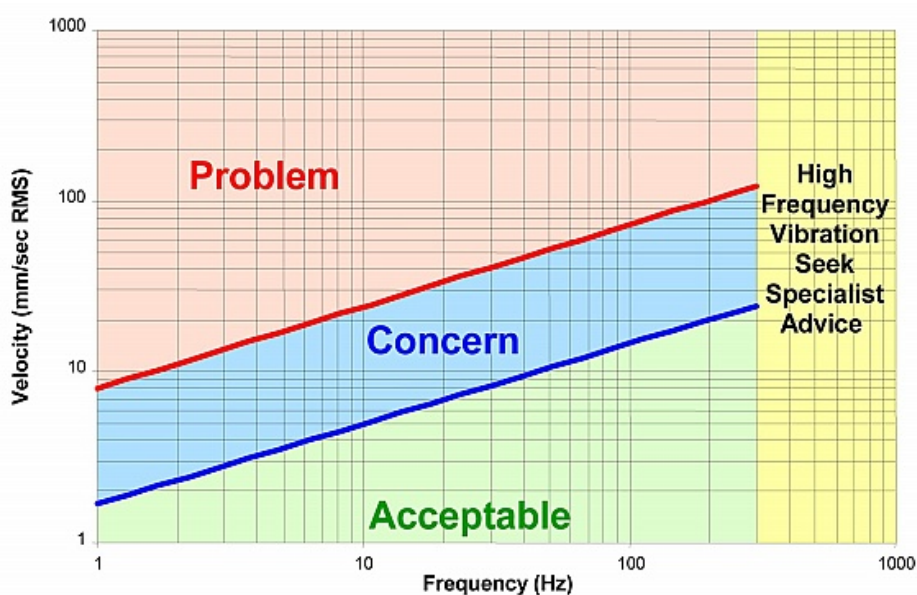


Figure 10 Acceptable, concern and problem vibration levels versus frequency, up to 300 Hz (2). The diagram is based on a large amount of measurements and experience from the petroleum industry. Source "Example figure from non-nuclear industry".

3.3 THE NPP'S LOCAL VIBRATION REQUIREMENTS

Below are the levels used at the different sites (1):

- OKG [1]: 8 mm/s (rms)
- RAB [71]: There are no general requirements. ASME Operational maintenance guide (ASME OMb Code) is used. Approximately 12 mm/s (peak) is a conservative value.

- TVO [83]: Empirical based VDI curve is used. 12 mm/s (peak) for the lowest eigenfrequency
- FKA [56], [70]: For new machines with connecting pipes, normally 8 mm/s (rms), sometimes 10 mm/s (rms). If it is higher, calculations and measurement on more points need to be done. Normally no longer times over 20 mm/s (rms). But it depends on what kind of pipe it is. Also ASME is used – regarding what to be done if higher vibrations are noted.

3.3.1 NPP purchase vibration requirements from connecting pipes from machinery

Generally, requirements are not set on pipes but often on valves and then in terms of maximum acceleration, which has been determined by calculation.

FKA defines their vibration criteria for connecting pipes from machinery in following way:

The overall vibration level in the frequency range 1-1000 Hz shall be measured using vibration velocity in mm/s rms and vibration displacement in microns peak.

If the vibration level is above 8 mm/s rms or above 150 microns peak, steps shall be taken by the Contractor to reduce the vibrations.

4 Selection of the measurement equipment

Transducers are available to monitor nearly every possible parameter relating to piping vibrational response and vibration sources. All instruments handle signal in different ways. Different instruments have their own frequency response and filtering.

The choice of equipment is depending on purpose of the measurements but a handheld four channels acquisition system which both can record time and spectrum is a good choice. The data collectors should if possible have the capability of calculating transfer functions collected from impact/response signals. The pipe system motion pattern can then be described from transfer functions by always knowing the phase relations from the transfer functions. Pipe vibrations should be collected in the X, Y and Z axis for motion pattern purposes together with a forth phase reference channel for ODS measurement or force input for impact measurements.

Unfortunately, many handheld data acquisition systems are limited to two to three channels to determine pipe vibration amplitudes and frequencies.

4.1 DATA COLLECTORS AND ACQUISITION SYSTEMS AT THE NPP'S

A wide variety of different acquisition instruments in terms of handheld loggers and multichannel systems are available at the four NPP's. The available instruments are listed in Table 2.

Instrument	Oskarshamn	Ringhals	Forsmark	TVO
Handheld vibration logger 1-4 channels	PerCon Logger (old)	VibXpert	CSI-2130	CSI-2130
	SKF Microlog	Svantec		
Multichannel acquisition system, > 4 channels	NI-VXI	LMS (external company)	CSI 2600	Beran 766 (old)
			Oros 16 channels	Oros OR-38
			Oros 32 channels	LMS (external company)

Table 2 Handheld data loggers and multichannel acquisition systems available at the four NPP's

A handheld vibration logger is typical used for trend taking, detecting alarms and check out vibration levels and frequencies.

When it comes to multichannel system a majority of the NPP's have selected to use external companies' equipment. An efficient way of using a multichannel system is for trouble shooting of a pipe vibration problem during operation is with Operation Deflection Shapes, ODS, as described in Section 2.2.4. Alternative if the

purpose is to determine the resonances and modes during a maintenance outage a modal analysis should be performed instead, which is described in Section 2.3.1. Both the ODS and Modal Analysis result gives animations of vibration pattern measured on for instance a pipe system. The analysis is often performed with commercial vibration animation software. The used animation software at the four NPP's are listed in Table 3

Vibration animation softwares	Oskarshamn	Ringhals	Forsmark	TVO
ODS, Operational Deflection Shapes	Modal View (external company)	LMS (external company)	ME-Scope	LMS (external company)
Modal Analysis	Modal View (external company)	LMS (external company)	ME-Scope	LMS (external company)

Table 3 Available analysis software at the four NPP's

However, it should not be forgotten that it's possible to perform both modal analysis and ODS measurements with a handheld vibration logger, which can record 4 channels simultaneously. Three channels are used for recording the vibration response at one point in three direction and the forth channel is used as a phase reference in the ODS or as the force input in the modal analysis.

4.2 ACCELEROMETERS

Acceleration, velocity, and displacement can be measured with the use of accelerometers. Velocity and displacement readings are obtained through single and double integration, respectively. The advantage of accelerometers is that they measure absolute acceleration and therefore do not need to be tied back or attached to any plant structure. Accelerometers are, however, subject to noise caused by high accelerations at high frequencies, such as from sudden shocks caused by looseness in the accelerometer bracket; integration of these signals, moreover, can distort the results at low frequencies.

Two useful types of accelerometers for pipe measurements are:

- Piezo resistive and strain gauge based accelerometers
- Piezo electric accelerometers

Piezo resistive accelerometers are typically used for shock pulse measurements. Practical use of such sensors is more cumbersome as it usually involves the use of more cabling than is the case for piezo charge accelerometers.

Piezo charge accelerometers are not used for strong shock loads for the simple reason that when integrating acceleration to displacement, it does not do its job as well as the piezo resistive type does. The reason is that the piezo charge crystal

produces a DC charge offset after a shock spike and this DC offset disrupts the signal processing as the offset accumulates to the displacement signal.

The charge output signal is very weak. From the beginning, the accelerometer used a charge output. This accelerometer type is still in use but mostly for high temperature application, at temperatures higher than 120 C (to 150 C for recent models).

The charge amplifier was later moved into the sensor house by the use of external constant current excitation. The constant current excitation can be 2 mA to 20 mA or 4 mA to 20 mA at 18 Volt DC to 30 Volt DC depending on the specification. A high pass filter removes the DC offset that is provided by the excitation. This circuit goes under many trade names, e.g. ICP (PCB Piezotronics), Deltatron (Brüel & Kjær), Isotron (Endevco), IEPE (Dytran, Kistler, National Instruments, etc).

Be aware of that most industry type accelerometers that are used for condition monitoring with short warm up and is moved between hot/cold conditions would use the 3 Hz or higher setting.

A long and weighty cable of mass m that is vibrated at acceleration a , excites a force on the accelerometer housing. This force infers an erroneous signal. Securing the accelerometer cable to the vibrating object at a location with roughly the same acceleration close to the sensor makes suppression of such loading.

When measuring on hot pipes regular ICP accelerometers will add unwanted temperature drift to the captured accelerometer signal. A good practice of heating protection is then to glue a heat resistant material on the pipe location for sensor position in between. In Figure 12 the selected material is ordinary car brake pads.

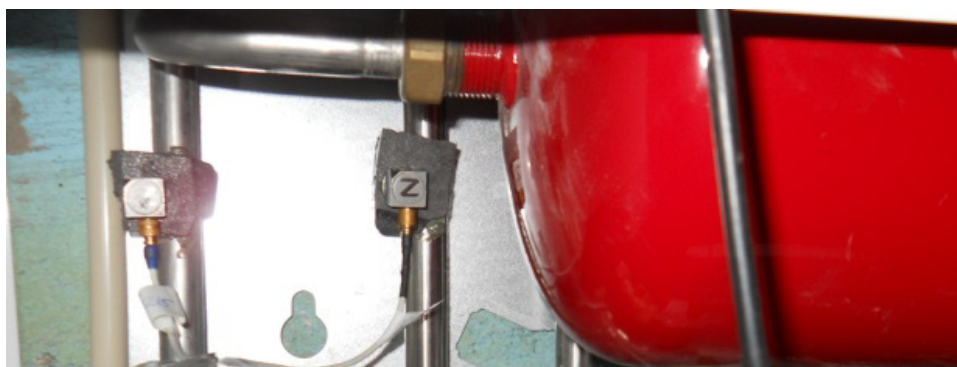


Figure 11 ICP accelerometers magnetic mounted on hot pipe system with brake pads in-between sensor magnet and pipe to limit heat transfer to the sensor. Source "Example figure from non-nuclear industry".

4.3 VIBRATION VELOCITY TRANSDUCERS

These transducers are particularly suitable for applications requiring high sensitivity or for use in high electrical noise environments where integration of an accelerometer signal in the vibration monitor is not preferred due to unwanted signals induced on interconnecting cables.

Two types of Velocity Sensors exist, mechanical and electronic. Mechanical types are the most common and are made up of a spring-mounted coil mounted inside a magnet. Vibration causes the coil to move in relation to the magnet, which produces a voltage output directly proportional to Velocity. Electronic Velocity Sensors are Accelerometers with an electronic integrator built in to the unit. Output of a Velocity Sensor expressed in millimeters/second (mm/sec) being the standard.

The moving coil type of velocity transducer is sometimes preferred for steam pipes measurement applications where steam noise can saturate the output of piezoelectric accelerometers.

Now, hardier piezoelectric velocity sensors (internally integrated accelerometers) are gaining in popularity due to their improved capabilities. A comparison between the mechanical velocity sensor and the modern piezoelectric velocity sensor is shown below in Table 4.

	Mechanical velocity sensor	Piezo electric velocity sensor
Flat Frequency Response		
10 -*1500 Hz	Yes	Yes
2-10 Hz	No, (Yes, if linearized)	Yes
Low off-axis sensitivity	No	Yes
Mounting in any direction	No, (Yes, if linearized)	Yes
EMI resistance	Poor	Excellent
Mechanical durability	Fair	Excellent

Table 4 Comparison electromagnetic velocity sensors versus piezoelectric velocity sensors. *The upper frequency limits depends on the type of transducer mounting, could be up to > 2000 Hz.

Mechanical velocity sensors can by use of electronic linearization maintain a flat frequency response also in low frequency region 2-10 Hz.

4.4 DISPLACEMENT TRANSDUCERS

Displacement transducers, such as a linear-variable differential transformer (LVDT) provide good indications of piping vibrational response. The drawback of displacement transducers is that one end of the transducer must be attached to a building structure; they measure relative displacement between the piping or component and a fixed reference.

4.5 LASER VIBROMETER

The laser displacement type of vibration sensing sensor principle is based on a laser diode that emits a laser signal and a light sensitive cell that detects where the reflected beam impinges. The sensor outputs a DC signal with a superposed AC signal, i.e. position (DC) plus vibration (AC).

For field use, a limitation lies in the fact that the sensor must remain stationary and measure on a flat surface truly to track its vibration. (Imagine replacing the flat surface in with a cylinder and moving it in a plane that is parallel with the sensor.)

Some practical comments on laser vibrometers:

1. A laser does not have problems with warm surfaces and it can be applied from a distance (Commercial equipment available measuring from some mm up to about 150 m).
2. Painted surfaces or better, reflex tape/paint greatly improves the correct reflection angle.
3. Measuring from DC to AC signal.
4. Lasers tend not to like too much slow large motion amplitude as they rely on focusing for the laser beam.
5. A laser can only pickup what is 'visible' to the laser beam.

4.6 STRAIN GAUGES

Strain measurements are very useful for determining the effect of vibrations. There are two types:

1. Foil sensors and the Wheatstone bridge are best used for the static to 50 Hz range and for relatively large strain fluctuation
2. Piezoelectric sensor with built in amplifier above 50 Hz and relatively small strain fluctuations

A piping acceptance criterion is given in terms of stress, so strain measurements produce data directly applicable them. Strain readings can also be used to determine the frequency and approximate magnitudes of pressure fluctuations inside the piping, and strain in system supports can be used to calculate vibrational loads on supports. Care must be taken in the placement, orientation and bridging of the strain gauges to ensure that meaningful data, related to the vibrational strains, is obtained.

As strain gauges sense a change in resistance, we must use flat cables to avoid phase shifting the signal. This leaves the cabling vulnerable to external electromagnetic sources. Unfortunately, external electromagnetic sources may provide a signal that is stronger than the voltage produced by the strain gauge. The balanced constant current circuit and the frequency-modulated excitation avoid this difficulty. Another way to suppress electromagnetic excitation is to improve the gauge output. The Gauge Factor, GF , is defined as $GF = \Delta R/R_G/\epsilon$, where the strain gauge average resistance is R_G . The resistance change is ΔR . A foil type usually has a Gauge Factor of about 2, while a semiconductor type strain sensor has a GF that is two orders of magnitude large. One way of increasing output, therefore is to use a strain gauge with a larger GF, the other way is to supply the gauge with more electric power which can be found from the combination of strain gauge resistance, R_G , and the type of excitation (Constant voltage- or constant current- excitation).

The strain sensor must be attached to the structure where it should sense strain. This usually is made using glue but there are types of strain sensors that can be

flame sprayed or micro spot-welded to the structure. The latter types typically apply for high temperature strain gauge sensing, which is a topic in itself. Therefore, the above mentioned discussion typically applies for strain sensing at temperatures below, $\sim 120^{\circ}\text{C}$.

For example, dynamic bending strains due to vibration can be obtained with the strain gauge orientation in Figure 12 and Figure 13.

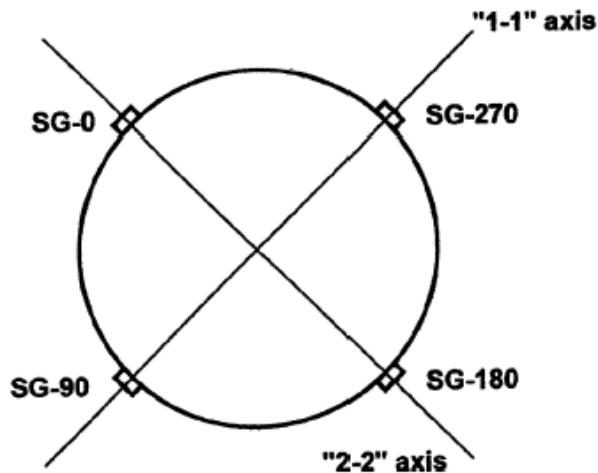


Figure 12 Strain gauge orientation for measuring bending from vibration.

In the plane of the moment, bending results in an axial tension strain and an axial compression strain 180 degree apart. Therefore, bending strains are measured by subtracting the output of two axial gauges orientated 180 degree apart. This has the advantage of subtracting out other axial strains existing at that location, see Figure 13.

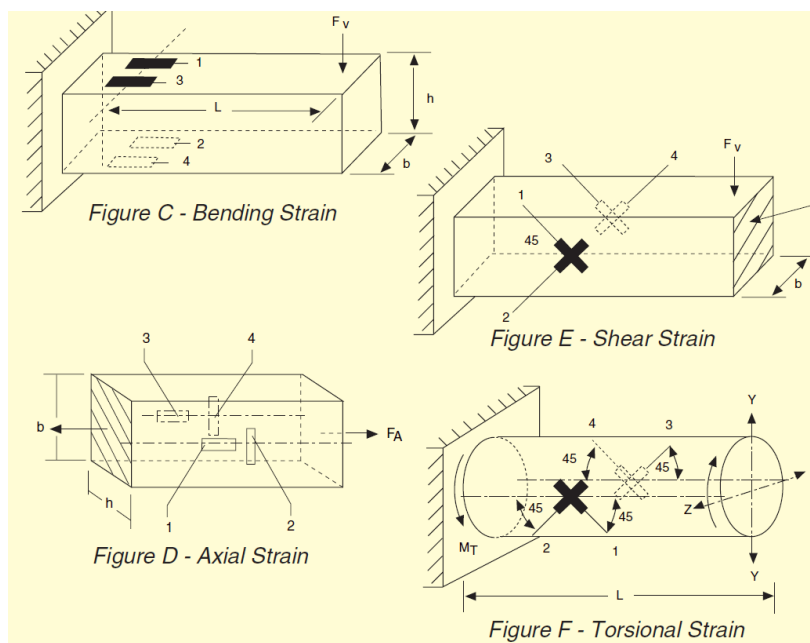


Figure 13 Different strain sensor arrangements for determine bending, axial, shear and torsion strain. Source "<http://www.omega.com/faq/pressure/pdf/positioning.pdf>"

The other type of strain sensing element is the piezoelectric type. As for pressure measurement, it does not sense absolute strain. The piezoelectric sensor emits charge and therefore has the advantage that it can use coaxial cabling, which shields its signal from electromagnetic excitation. Furthermore, a tiny amplifier can be placed with the sensor or close by and thereby further increase the signal to noise ratio. For strain sensing above 50 Hz and of low strain amplitude, piezoelectric strain sensing is preferred. Mechanical load is best estimated in areas away from stress concentration. Such areas tend to have lower strain which makes piezoelectric sensors good candidates for such tasks.

4.7 PRESSURE TRANSDUCERS

Pressure is comprised of three components:

- Line Pressure (LP) - static, non propagating, pressure
- Kinetic Pressure (KP) - 'wind' pressure that moves with the flow velocity
- Pulsation - 'sound' that propagates as waves with the wave speed in fluid.

A pressure sensor can react to all three components and it is up to the analyst to make sense of what really is measured.

Pressure data can be obtained through the use of dynamic pressure transducers usually piezoelectric pressure sensor where a piezoelectric crystal emit a charge signal that is proportional to pressure. These sensors don't capture down to DC.

Most process pressure measurement is made using a pressure sensor where pressure is proportional to the strain of a membrane that is loaded by the pressure. Membrane strain usually is determined with the use of a full bridge Wheatstone

coupling where the strain sensors are of the semi-conductor type, also referred to as piezo resistive sensors

The use of pressure transducers requires tapping into the piping, which often creates a system modification.

All types of pressure sensors that protrude through a wall to contact the pressurized medium produce signals that are influenced by how they are mounted. A pressure sensor dynamic signal, irrespective of type, is ruined if gas bubbles form in front of its membrane. Its attachment to the wall must be stiff for correct pressure sensing and it should stick a short distance into the flow and be aligned in parallel with the flow to correctly capture pulsation.

Often there are installed pressure transmitters at special positions into the piping. The impact pressure (total pressure) from the pressure transmitter is the sum of the static, LP, and dynamic pressures, KP and pulsation, on a surface or object.

From Figure 14 point B depicts the impact pressure and point A the static pressure. The dynamic pressure is the difference between point A and B, which is the pressure of interest for dynamic vibrations.

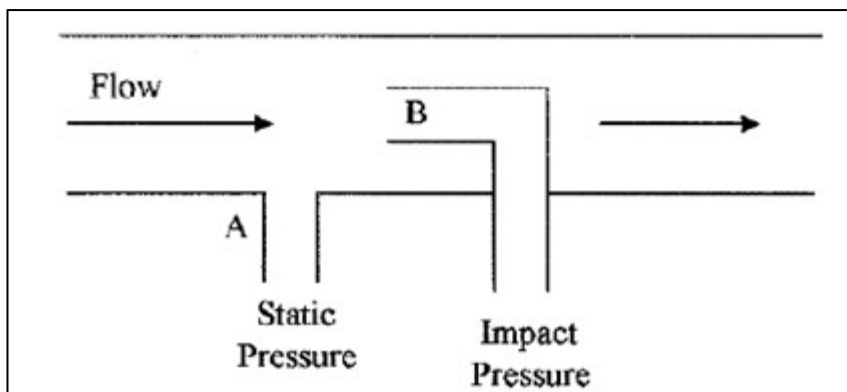


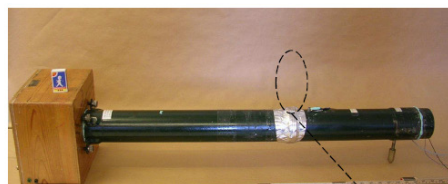
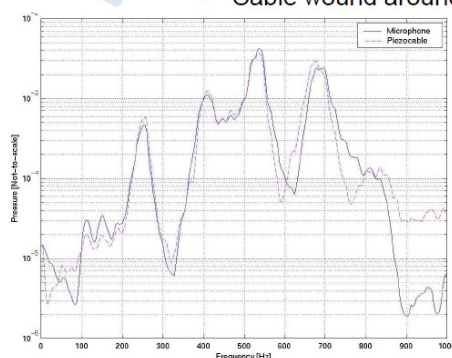
Figure 14 Static and impact pressure from common pressure transmitter.

Pressure data are useful in determining the source of the vibration, as pressure fluctuations are a forcing function for piping vibration.

A non-destructive way of measure pressure pulsation on the outside of pipe wall without protrude through the wall is to wound a piezocable around the pipe. This sensor technique has been verified at ÅF and tested at OKG.

Specials: *pressure pulsation measurement using piezocable*

- Relative pressure pulsation measurements
- Cable wound around pipe (non-destructive application)



Pipe: 1130 mm long, 90 mm diameter & 4 mm thick



Innovation by experience



Figure 15 Verification of piezocable for pressure pulsation at ÅF. Graph shows the pressure response from microphone “----” compared to the response from the piezocable, solid line. Source “ÅF internal material”.

The piezo cable effectively behaves as an extended microphone, converting stress, strain, vibration, impact, sound or pressure change into minute electrical signals. All piezoelectric sensors display a linearly increasing electrical output as the level of mechanical disturbance increases.

4.8 MICROPHONES

Acoustic sound levels can be monitored through the use of microphones. The microphone diameter limits the highest frequency at which a microphone can be considered to pick up sound at a point. The larger microphone diameter the lower frequencies limit. However normal microphones are designed to pick up sounds from 20 Hz. Also, microphone size is a trade-off between sensitivity and frequency range.

The frequency content of the sound measurements can be analyzed, which is helpful in determining sources of vibration. Sound level measured in decibels also can be used as qualitative evaluations of the vibration severity. Acoustic sound levels measured before and after vibration fixes are used as qualitative measures of the vibration fix's effectiveness.

4.9 FLOW VELOCITY SENSORS

Flow velocity can be measured in a number of ways. Here we describe the most common methods suited for water pipes: ultrasonic flow meter and pressure drop measurements.

Ultrasonic flow meters use sound waves to determine the velocity of a fluid flowing in a pipe. At zero flow speed; the frequencies of an ultrasonic wave transmitted into a pipe and its reflections from the fluid are the same. Under flowing conditions, the frequency of the reflected wave is different due to the Doppler Effect. When the fluid moves faster, the frequency shift increases linearly. The transmitter processes signals from the transmitted wave and its reflections to determine the flow rate.

Temporary flow measurements can be made using portable ultrasonic flow meters with clamp-on transducers. Clamp-on transducers are especially useful when piping cannot be disturbed, such as in power and nuclear industry applications



Figure 16 Ultrasonic flow meter attached by chains. Source “delivered from participating plants”.

Pressure drop measurements use the fact that a known pipe cross-section change force flow to travel faster through the constriction. This velocity change causes a pressure difference upstream/downstream the constriction that can be sensed using a relative pressure sensor that senses upstream/downstream pressure or from two pressure sensors that independently sense upstream/downstream pressure. This arrangement can be fooled by pulsation where acoustic waves in the pipe affect the pressure difference reading and/or pulsation in the tubes leading to the pressure sensor(s) may experience local acoustic resonance. The remedy is low pass filtering signals and keeping pressure sensor lines short.

4.10 ACOUSTIC EMISSION SENSORS

Acoustic Emission, AE, sensors are a complement to traditionally pipe sensor transducers described above. The term AE applies to both the physical effect whereby high frequency elastic waves are generated in materials by naturally occurring processes in response to a lower frequency stimulus and to the technology that is used to detect and process such signals. In general AE signals have a high signal to noise ratio for the detection of energy loss processes such as impacts, friction, turbulence etc. The detection of such signals has found

widespread use in machinery and process pipe monitoring. AE methods can also be used to detect structural degradation (crack growth, delamination, corrosion etc.) although this can be complicated by lower signal to noise ratios and on large structures it will usually be required to simultaneously monitor the outputs of multiple sensors.

Nowadays there is AE-sensor, which is working in enveloping scheme which responding to elastic waves within 86 dB range or better. This is “slowing down” the measured signal from 100kHz to 10 kHz, still maintaining information about energy content (pipe system) and not sensitive to low frequency disturbances. This sensor can measure AE-envelope time traces in a continuously way.

The AE-envelope sensor is DC coupled which means that it both capture the slow and fast varying trends in the steam pipe, for instance slowly increase/decrease of air flow, along with the sudden impacts of pulsation hitting the probe.



Figure 17 AE-probe mounted on a hot cracker tube pipe. The probe enters the main pipe in 30 degrees and registers the change in the process. Source “example figure from non-nuclear industry”.

Both acceleration and shock pulse sensors are reflecting the change in the process by varying the overall magnitude of the signals. The AE-envelope sensor shows this change directly via the DC offset. This is what makes a huge difference in tracking the process flow. The AE-envelope signal reflects the changes in the process directly, while both high-frequency accelerometers and shock pulse signals are mixing different responses and eventually causing the rise of overall amplitude. Of course, information can be re-gained in the frequency domain, but this requires extra computation power.

5 Measurement point location selection

From a conservatism point of view, it is difficult to know whether the actual vibrations at the worst location are much higher than those at the measured locations. This problem can be partly addressed with the help of simulations. E.g. investigating the simulated mode shapes gives insight on where the sensors should be placed and what is the relation between the worst locations and the locations actually measured.

In addition measurement point locations or at least number of positions are limited by accessibility of the measurement locations and areas.

The maximum stress and maximum deflection are generally not at the same point. An experienced vibration specialist may in some extent foresee the most critical positions but in a complex piping system it is advisable simulations of mode shapes and stresses are performed in advance.

In OM-3 a simplified method of pipe vibration evaluation is described (4). The maximum allowable vibration amplitude for a piping system are evaluated by dividing the piping system into characteristic or analogous beam segments. It is assumed that the vibration measurements are carried out on the characteristic piping span while vibrating at its natural frequency. In that method it is assumed that the selected theoretical mode shape exactly matches the measured mode shape.

Much of the data required to predict pipe movement is derived from feedback and relates to particular conditions and geometry design guidelines will also reduce the vibration risk.

5.1 STRUCTURAL SIMULATIONS

Spreadsheet calculations offer a fast way for approximate root cause analysis. They may be useful in estimating the order of magnitude of different phenomena and approximating the frequencies at which they occur.

Structural simulations are typically carried out using a Finite Element software, such as Ansys, ADINA, Caepipe, Pipetress, Abaqus or equivalent. Structural simulations make it possible to investigate several topics that would be impossible or very difficult to do experimentally.

For example as the number of sensors possible to install is limited, there is a chance that the locations of maximum vibration velocities are missed in the measurements. When using simulation models, these maxima are found more easily with the simulations (1). Dynamic FE-simulations of a pipe system will give the mode shapes and positions with high deflection of the pipe system. A relative measure of deflection a "scale factor" or a vibration quality index value Dynamic Susceptibility (DS) may be utilized as guidelines when measurement positions are selected and measured vibration levels are judged.

With the simulations, also the stresses can be estimated at non-accessible pipe areas where strain measurements are not feasible.

5.2 FLUID SIMULATIONS

Computational fluid dynamics (CFD) has also been widely used for analyzing pipe vibration problems.

Thermohydraulic simulations can be seen as a special type of CFD simulation. They are typically used for simulating water hammers and other fast transient phenomena. Software often used for the thermohydraulic simulations include RELAP5 and Trace. Most of the thermohydraulic simulations performed in the past have been 1-dimensional but recently the use of 3-dimensional simulations has increased (1).

CFD simulations make it possible to investigate several topics and comparing design solutions that would be impossible or very difficult to do experimentally.

5.3 ACOUSTIC SIMULATIONS

The most typical acoustic simulation type is the modal analysis for investigating acoustic natural frequencies.

Most of the FE solvers used for structural simulations are also in different extend suitable for acoustic simulations. However, also specialized acoustic simulation software exist, e.g. VA One and MSC Actran. The acoustic simulations can be performed using e.g. the FEM (finite element method), BEM (boundary element method) or SEA (statistical energy analysis) approaches.

5.4 ACCESSIBILITY OF THE MEASUREMENT LOCATIONS

Different boundary conditions for pipe measurement location like heat and radiation determines which transducers and cables are acceptable to use.

Accessibility of the measurement locations: It may not be easy or possible to access the locations desired to be measured, especially during the operation.

Organizing the required measurement cables for the locations, especially inside the containment, may require a vast amount of planning and other work.

5.4.1 Taking measurements in radiation areas

Performance requirements for wire and cable installed near radiation areas usually include:

1. Reliability.
Whenever large amounts of energy are transmitted, a service interruption is always expensive.
2. Thermal stability.
Wire and cable must often be installed in regions of high ambient

temperatures. In addition, power cable temperatures may be increased by conductor losses.

3. Moisture resistance.

In nuclear power plants, wire and cables sometimes must be placed in moist locations. Also, water may condense on the walls of conduit housing wire and cable.

4. Radiation resistance.

In many nuclear power plants, the only practical location for some wire and cable is in a region appreciable nuclear radiation.

5.4.2 Permanent installations – radiation areas

Ultimately, the ability for a product to survive radiation comes down to different tests and the data they provide. Tests that look at how well electronics can survive TID (total ionizing dose), SEE (single event effects) and ELDR (enhanced low dose rate) conditions. Radiation hardened does not mean a product can survive a specific amount of radiation; it only means that it can survive some radiation. Silicon-based microelectronics breaks down under exposure to radiation. Radiation-hardened components designed nuclear applications can survive up to 100 Mrad

There are no electronics built into Charge Output accelerometers, they can operate and survive exposure to very high temperatures up to 600 °C for some models. It is important to note that measurement resolution and low frequency response for charge output, acceleration sensing systems are dependent upon the noise floor and discharge time constant characteristics of the signal conditioning and readout devices used.

Charge converters are designed to convert the high impedance output of a charge mode piezoelectric transducer to a low-impedance voltage output. This allows long cables to minimize noise.

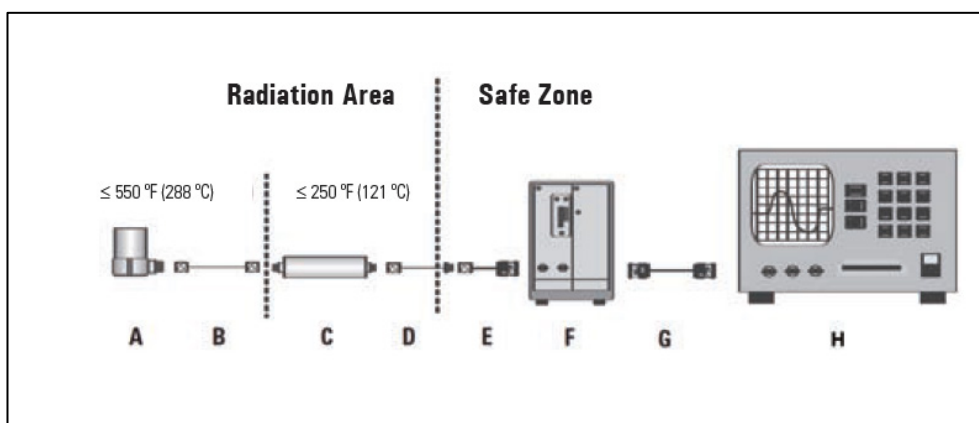


Figure 18: Typical permanent instrumentation line in a high temperature radiation area. Source “example figure from IMISensors”.

- A: Charge accelerometer/pressure sensor radiation hardened
- B, D: Radiation hardened cables with appropriate connectors
- C: fixed charge amplifier
- E and G: cables with appropriate connectors
- F: ICP converter
- H: measuring system

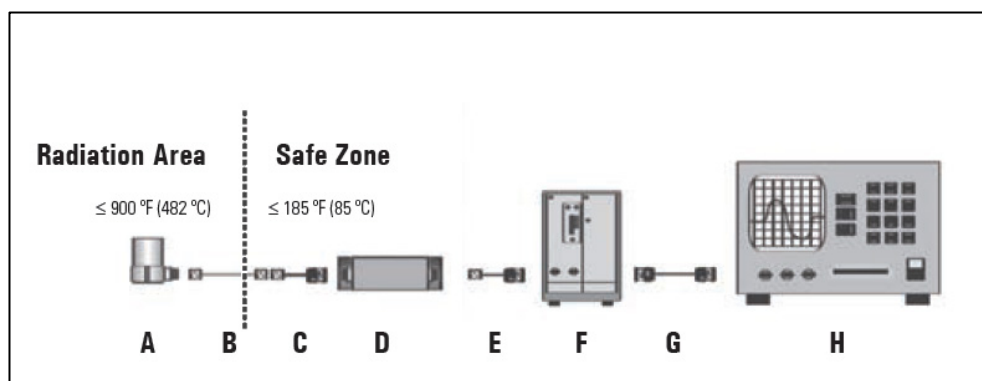


Figure 19 typical permanent instrumentation lines for very high temperature radiation area. Source “example figure from IMISensors”.

A: Charge accelerometer/pressure sensor radiation hardened and very high temperature

B, D: Radiation hardened cable

C: differential charge amplifier

E and G: cables with appropriate connectors

F: ICP conditioner

H: measuring system

5.4.3 Short term / baseline measurements – radiation areas

Depending on limitations due to human radiation exposure both time, location and distance must be considered. The tests must be planned in close co-operation with the radiation technicians at the plant. If the tests are well planned, a short visit in the radiation zone of some minutes with a handheld analyzer and an accelerometer with magnet may give valuable measurement results. A thorough walkthrough shall be conducted with vibration expert, measurement technician, plant system expert and radiation technician.

For short term measurement in radiation zones it is advisable to use a long, 2-3 m, trash pick up stick to mount sensors with magnetic mounting on pipes. The plants standard measurement equipment can be used since the exposure time is kept at a minimum and is controlled by regulations for human radiations. The impacts on the instrumentations degradation can then be kept at a minimum. It is then possible to reach highly radiation areas, example pipes in containments where human being should minimize its exposure. With aid of this tool very quick measurements can take place where also pipe lines are difficult to access.

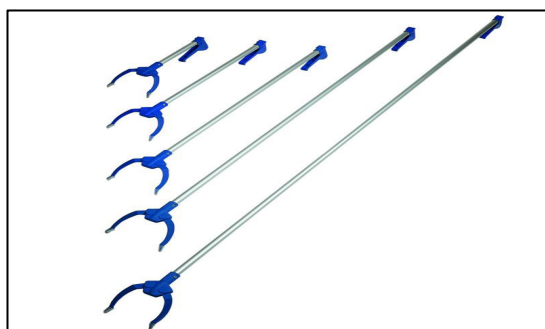


Figure 20 Useful trash pick-up stick to put on accelerometers on pipes in radiation areas.

5.5 SMALL BORE MEASUREMENT POSITION

5.5.1 Accelerations

Many of the failures that occur in piping systems are in the smaller diameter piping connected to larger piping. The structural vibrational modes of small-branch piping are often excited by the structural vibrations of the header piping. Frequently, pressure pulsations in the header piping or vortex shedding at the branch connection also excite acoustic resonances in the branch piping.

Small bore connections (SBCs) and branch attachments connect to the main process piping. These small attachments, typically less than 50-80 mm in diameter, are the most common cause of integrity problems. Even if the main process piping has acceptable vibration, the vibration can be amplified on SBC causing failures. For large facilities there can be thousands of SBCs that pose this integrity risk.

SBC rides on the main pipe – it simply does not bend as is assumed for the main pipe. The piping vibration criteria are applied also for SBC.

One motivation to this may be that if it is worse than the piping vibration – it adds risk for fatigue failure. In many cases, this is so but it is far from a general truth. To exemplify why. Imagine the case where piping vibration is 20 mm/s and small bore vibration is 30 mm/s. In this situation the relative vibration may be either $30 + 20 = 50$ mm/s or $30 - 20 = 10$ mm/s. The former case, is worse than the latter because it involves a relative velocity of 50 mm/s for the small bore to accommodate, where the latter case only involves a relative velocity of 10 mm/s. Therefore, it is prudent to assess SBF risk using more than a single measurement channel.

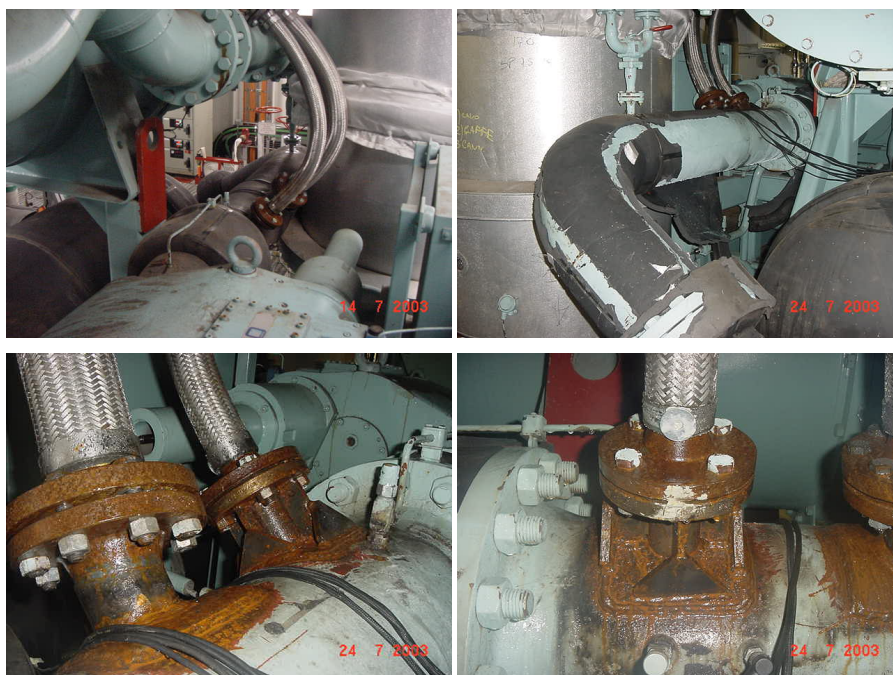


Figure 21 Suction side of chiller compressor consisting of two small bore connections DN50 & DN80 connected to main pipe. A countermeasure of extra stiffening plates are made to SBC DN50. Source "example figure from non-nuclear industry".

Figure 21 shows an example of pipes with SBC after the countermeasure of extra stiffening plates were installed to the smaller DN50 connection.

To understand the pipe vibration pattern at a specific load case a wireframe is created out of used sensor accelerometer positions in Figure 22 for animation purposes.

In the example showed below was very difficult to know if the main pipe itself had global modes, which affected the SBC vibrations or if the high detected vibrations at the flanges of the SBC were local. The most efficient way to determine this was to perform a multichannel ODS where you can easily determine the vibrations relative phase behavior for bending, torsion, shell modes and how the main pipe modes affects the SBC. By taking measures on different positions around a pipe you can find out if the pipe has shell modes, like ovalisation deformation. Shell modes are often higher up in frequency, above 150 Hz.

However, sometimes you don't have access to a multichannel system. Then you need to have at least a two channel monitoring system where you can measure the relative phase in each direction between top flange and base of the SBC. If these two positions in phase, the magnitude of the relative vibrations can be subtracted and generally less hazardous than the top flange value first show. The opposite, if the two positions are out of phase the relative vibration magnitude is additive and should be handled more conservative.

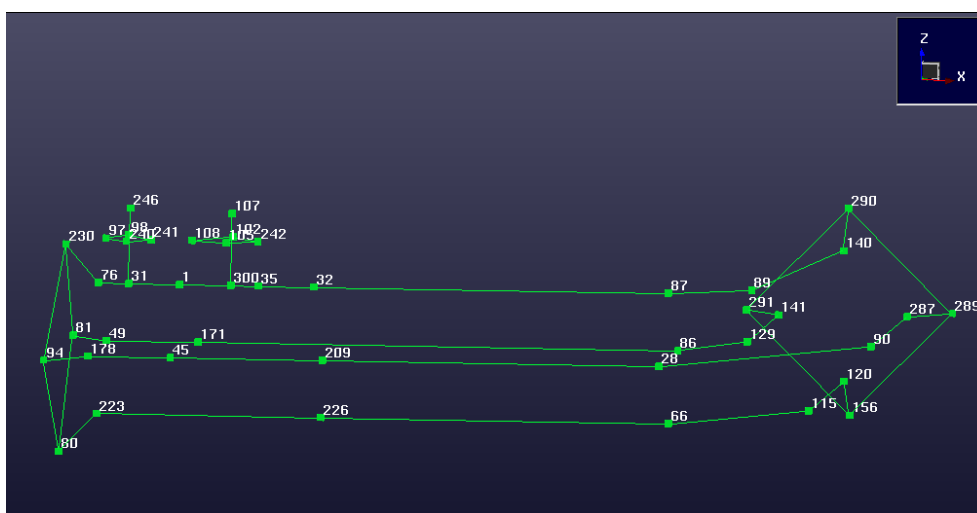


Figure 23 Wire frame of the suction pipe to the chiller compressor in Figure 21 with possible accelerometer locations for multi-channel measurements like modal testing and operational deflection shapes, ODS. Source "ÅF internal material".

5.5.2 Use of strain gauges

Ideally, to determine what vibration levels are acceptable, stress levels resulting from the vibration should be considered.

When a mechanical system vibrates, it is moved from its normal or equilibrium position. Considering the top section of a piece of pipe, Figure 24, the vibration alternately puts the top of the pipe in tension and compression, causing stresses in the pipe. Vibration causing large amounts of tension or compression can result in

high stresses in piping, which can potentially damage the pipe. Totally eliminating all the vibrations in a given system would not be necessary or practical from a design and/or economic standpoint. However, it is necessary to reduce vibration to a level where failure will not occur.

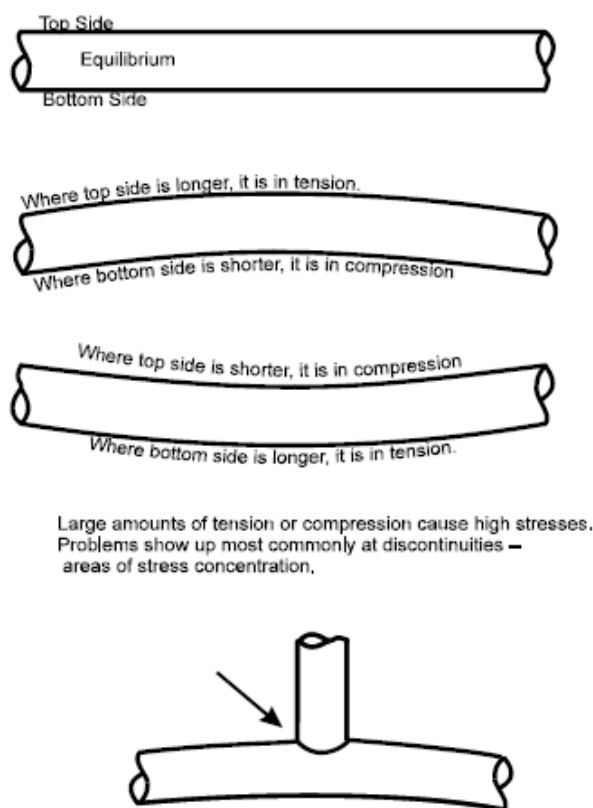


Figure 24 Stress in a vibrating pipe.

If there is a low frequency problem it is always recommended to use strain gauges. When dealing with SBC low frequency problem the frequency behavior is better revealed in terms of strain compared to acceleration. Recommended positions are seen in Figure 25 and Figure 26

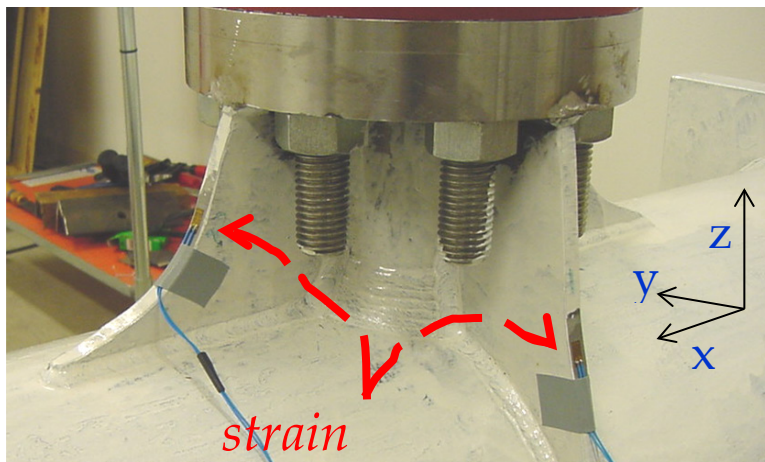


Figure 25 Example of recommended dynamic strain sensor positions at highly stressed locations at T-section / SBC. Source "ÅF internal material".

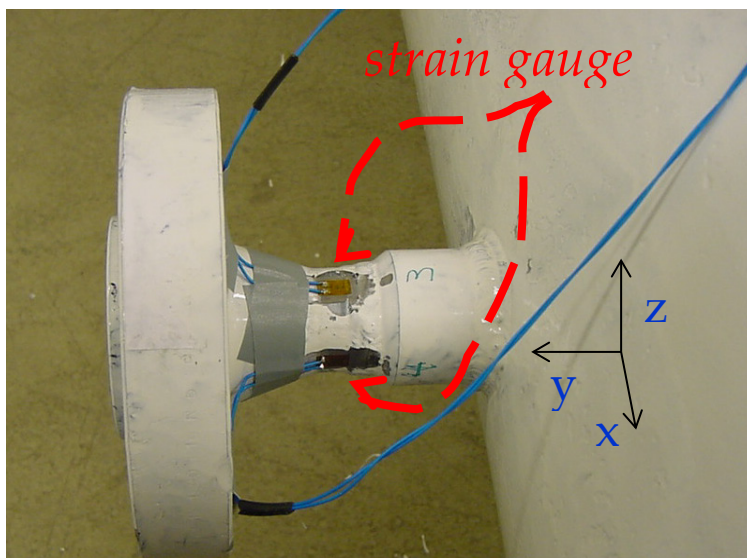


Figure 26 Example of recommended dynamic strain sensor positions at highly stressed locations at SBC. Source "ÅF internal material".

6 Testing for the transducers before installations

The whole measurement chain (transducers, cabling and measurement equipment) shall always be tested and preferable with a calibrator.

6.1 SHORT TERM MEASUREMENTS

With proper handling and usage industrial accelerometers do not need frequent re-calibration. Transducers of today have often-maximum sensitivity drift less than 1% over the life span of the sensor. If exact accuracy of vibration levels is required, the sensors should be re-calibrated annually. Otherwise, sensors need to be re-calibrated only if exposed to mistreatment (over shock, extremely high temperatures) or if required by regulations.

6.2 LONG TERM MEASUREMENTS

6.2.1 Accelerated vibration tests in test rig.

Lifetime of test equipment in a shaker test rig can be compared with calculated life cycles. Data may be utilized for verification of calculated life cycles.

The origin of a test specification which takes into account the real operation is measured in terms of acceleration. These are taken at the power plant in operation. The aim is to record worst-case vibration. Normally tri-axial accelerometers are used measuring Peak Hold limit spectra. Multi-channel time data records provide input for the tailoring of the test profile. For a Peak Hold limit spectra to be unambiguous, parameters like frequency resolution and windowing as well as amplitude scaling must be specified. Requiring FFT analysis of acceleration using a frequency resolution of typically 2-3 Hz, Hanning window, peak hold averaging. Scaling shall be 'peak' which is analogue with swept sine shaker test

A selected number of "core" transducer components are tested, for a specified defined life time, and the test profile simulates the environmental conditions. The tests can be performed for low cycle fatigue i.e. thermal cycling and high cycle fatigue due to vibrations.

6.2.2 Shaker test profiles.

These are swept sine or random vibration or a combination thereof. Swept sine profiles are normally given in 'peak' acceleration. Random profiles are given in Power Spectral Density (PSD). Test duration is a parameter which enables fatigue analysis with respect to component life time. Shaker tests can be compared to accelerated endurance tests (AET) using Fatigue Damage Spectra (FDS). Simultaneously, Max Response Spectra (MRS) will describe the maximum instantaneous vibration load. Both MRS and FDS spectra operate on principles similar to shock response spectra, i.e. the response in time domain of a SDOF system to an input consisting of acceleration relative to input, whereas FDS applies

rainflow counting to the response signal, thereby being dependent on the duration. The Wöhler slope of the material subject to fatigue is a parameter in the FDS calculation. The resonant gain factor Q of the SDOF systems is a parameter for both functions.

Max Response Spectra (MRS) and Fatigue Damage Spectra (FDS) are used for comparison between measurements and vibration demands.

MRS applies to damage due to instant overload whereas FDS indicates failure risk due to fatigue, accounting for the duration of the vibration load. MRS and FDS are based on the assumption that damage occurs in resonant systems which is generally the case. This method is designed by C. Lalanne (1984) and is applicable in the design of shaker test profiles (Tailoring approach) as implemented in LMS Test.Lab Mission Synthesis software.

7 Transducer mechanical installations into the pipe

7.1 VIBRATION MEASUREMENTS

The work starts with an inspection when the most appropriate option is selected and exact position of installation is defined. Before any installation a walkdown inspection with relevant personal from the plant, including vibration expertise, shall be performed. The optimum installation positions and routes are to be highlighted and installation routines to be talked through. After the installation is completed, a second walkdown inspection to performed with the same parties. Any deviations to be highlighted and fixed. The (temporary) installation is now considered complete.

Pipe clamps are typical used for the attachment, Figure 27. In a new built plant selected vibration measurement positions at the pipework may be predefined and installed in advance.

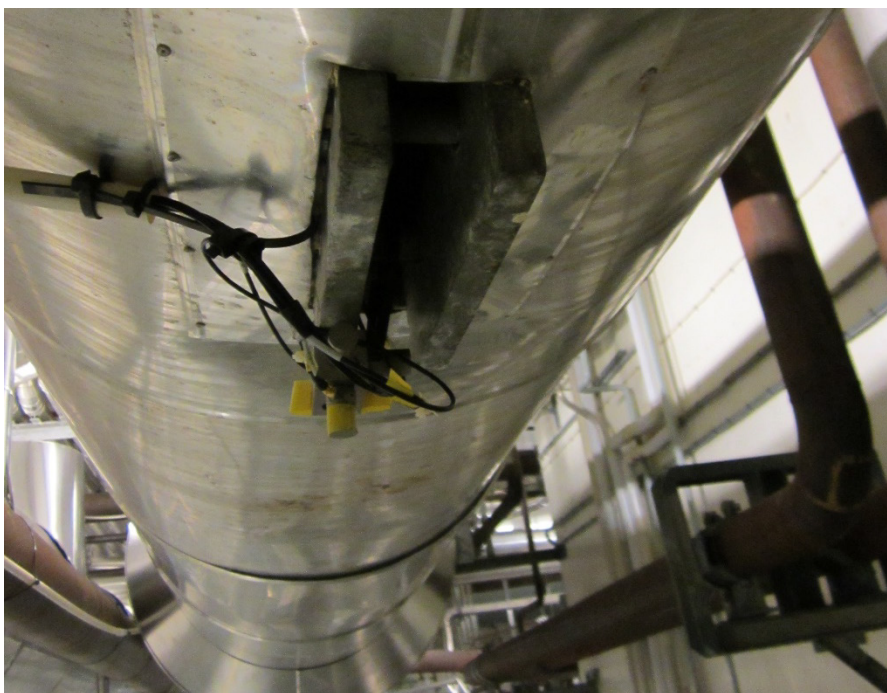


Figure 27 Example of accelerometer mounting at clamp of a pipe hanger support. The accelerometers are bolt mounted. Source “delivered from participating plants”.

How (and where) a transducer is mounted is critical to comparison of measurements. Accelerometers are sensitive to the method of attachment.

Very large differences in bandwidth can be measured between hand-held, magnet attached, epoxy, and stud mounted installations, see Figure 28.

Installation instructions must be followed precisely to obtain the manufactures transducer specifications. Accelerometers not mounted perfectly perpendicular to

the surface or on a flat surface will produce stress risers which will also produce false signals.

There are three mounting methods typically used for monitoring applications:

1. bolt mounting,
2. glue (wax)
3. and magnets.

The bolt mounting method is the best method available for permanent mounting applications. This method is accomplished via a stud or a machined block. This method permits the transducer to measure vibration according to the manufacturer's specifications. The mounting location for the accelerometer should be clean and paint free. Any irregularities in the mounting surface preparation will translate into improper measurements or damage to the accelerometer.

The adhesive or glue mounting method provides a secure attachment without extensive machining. However, this mounting method will typically reduce the operational frequency response range. This reduction is due to the damping qualities of the adhesive. In addition, replacement or removal of the accelerometer is more difficult than any other attachment method. Surface cleanliness is of prime importance for proper adhesive bonding.

In walk-around monitoring/screening programs, **magnetic mounts and probe tips** may be used. The frequency range of both mounting methods is dramatically reduced when compared to stud or adhesive mounts. Magnetic mounts are available with flat surfaces for flat locations or two pole configurations for curved surfaces. This method is not recommended for permanent monitoring. The transducer may be inadvertently moved and the multiple surfaces and materials of the magnet may interfere with or increase high frequency signals. As can be seen in Figure 28 the mounting method has a strong effect on the operating frequency range of an accelerometer.

In Figure 29 an example of neodymium magnets can be seen. Neodymium magnets are the strongest type of permanent magnet commercially available and very suitable when taking screening vibration measurements.

Stud mounts are recommended for low frequency measurements. Use of magnets and probe tips allow the sensor to move at low frequency and disturb the measurement. Handheld measurements can be disturbed by movement of the operators hand (the coffee factor) and cable motion. Stud mounts firmly attach the sensor to the structure and ensure that only vibrations transmitted through the machine surface are measured.

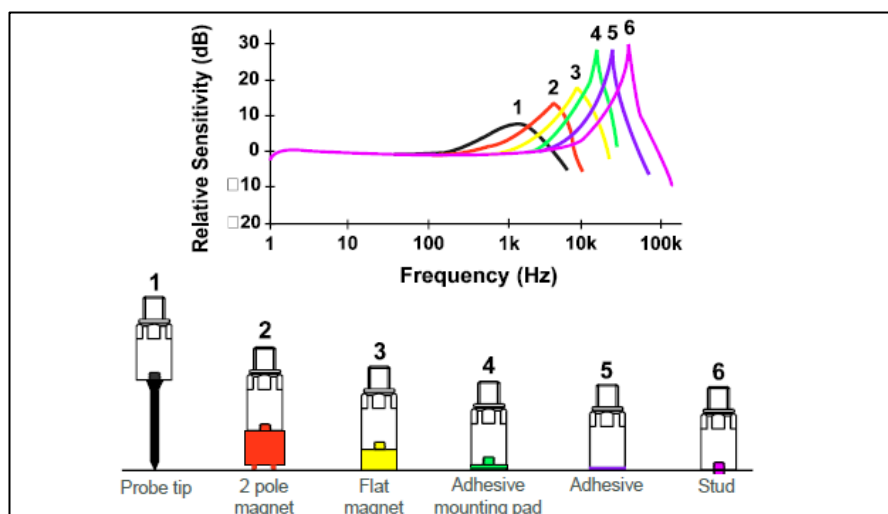


Figure 28: Mounting technique determines mounted resonance. Source "example figure from PCB".

By design, accelerometers have a natural resonance which is 3 to 5 times higher than the advertised high end frequency response. The frequency response range is limited so that a flat response is provided over the operating range. The advertised range is achievable only by bolt mounting. Any other mounting method will adversely affect the natural resonance, and in turn the usable frequency response range.



Figure 29 Example of neodymium magnets (also known as NdFeB, NIB or Neo magnet). Neodymium magnets are the strongest type of permanent magnet commercially available.

7.2 SENSOR MOUNTING EXAMPLES

In Figure 30 an example of mounting of accelerometer on steam valve housing is given (temporary installation during some two years). The mounting base of the accelerometers was assembled to the magnet with a 10-32 UNF / 10-32 UNF stud. The stud was secured with Loctite 243. Super low-noise coaxial cables (Type: AO-0122-D-030 of supplier Brüel & Kjaer) were connected to the accelerometer (connector: 10-32 UNF to 10-32 UNF). An inline charge converter was connected to the low-noise coaxial cable (connector: 10-32 UNF to 10-32 UNF, cable length: 3m). Low-noise coaxial cables (Type: AO-0531-D-0050 of supplier Brüel & Kjaer) were connected to the inline charge converter (connector: 10-32 UNF – BNC, cable length: 5m). BNC cables were connected to the low-noise coaxial cables (connector: BNC – BNC, cable length: 25m). The BNC cables were connected to the measurement system.

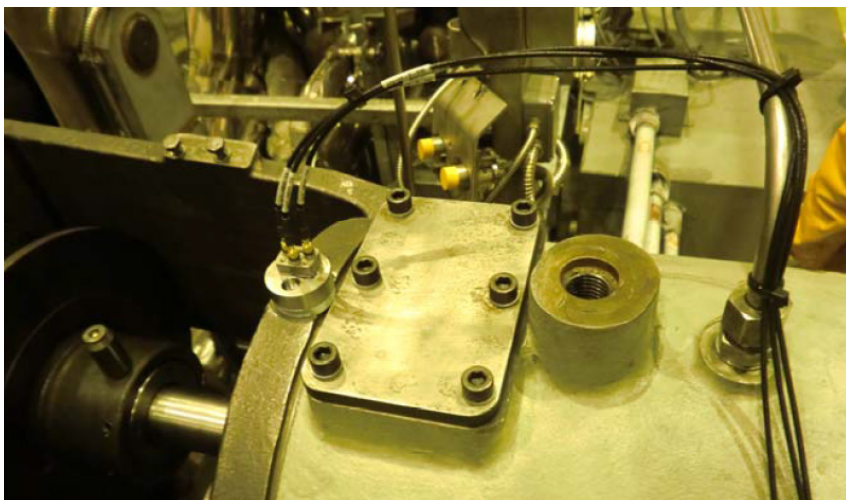


Figure 30 Example of mounting of accelerometer on steam valve housing. Source “delivered from participating plants”.

In Figure 30 an example of mounting of a tri-axial mounting base mounted to an ESV yokes can be seen. An M10 was screwed in the mounting base and an M20 was screwed in an existing threaded hole at the valve yoke. The M10 to M20 adaptor was secured with Loctite 243. M10 washers were used to adjust the position of the triaxial mounting base (so that the axial direction of the mounting base is equal to the axial direction of the valve yoke).

The velocity transducers were mounted with M10 headless screws to the triaxial mounting base. The headless screws were secured with Loctite 243. The triaxial ICP accelerometer was mounted to a mounting base with a 10-32 UNF / 10-32 UNF stud. The stud was secured with Loctite 243. The mounting base was assembled to the triaxial mounting base with an M6 cylinder head screw. The screw was secured with Nord-Lock washers and Loctite 243.



Figure 31 Example of mounting of accelerometer and velocity transducer on a high pressure steam emergency safety valve housing. Source “delivered from participating plants”.

A risk evaluation shall be performed prior to the installation. In Figure 32 an accelerometer installation on a custom made u-clamp can be seen. Because u-clamps are commonly used on exhaust pipes it can be considered a proven technology. The smaller pre load is compensated by the use of metallic lock nuts and Nord-Lock lock washers. Because of the use of lock nuts the u-clamp cannot be separated by vibration only and it can therefore not fall off.

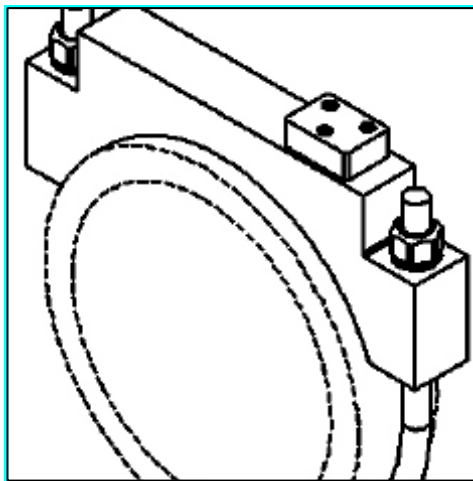


Figure 32 Example of a measurement setup for a temporary installation at a steam valve / pipe. A tri-axial accelerometer was mounted on a custom made u-clamp. The clamp was fastened with (2x) all metallic lock nut & Nord Lock washer. Source "delivered from participating plants".

8 Transducer mechanical installation checking with measurements

Many installation and sensor problems can be detected by measuring the bias voltage of the sensor. The bias voltage will indicate faulty cable routes and failed sensors. Many online systems are capable of trending the sensor bias voltage. Other problems can be detected by analyzing the time waveform and FFT spectrum.

For both accelerometers and pressure sensors the dynamic stiffness of mounting base and measurement position shall be judged by experience or preferable by impact measurements.

8.1 MEASURING THE BIAS OUTPUT VOLTAGE (BOV)

The majority of accelerometers, PiezoVelocity transducers and pressure sensors have a biased output. Biased outputs are characteristic of two-wire sensors used to measure dynamic AC signals

Once installation is complete, it is recommended that the transducer sensor be tested for proper operation. Measure the DC bias output voltage (BOV) by powering the sensor and connecting a voltmeter across the sensor's signal and common leads. The BOV should rest within ± 2 V of the value note on the specification sheet (usually 8 to 12 V).

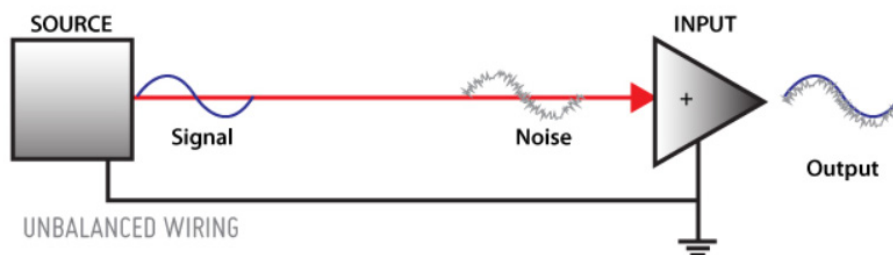
If the BOV equals 0 V and the power supply is properly connected the circuit may be shorted; test the cable connections and power supply. If the BOV equals the supply voltage, the circuit may be open; test the cable connections. If the cable and power supply check as normal, then the sensor amplifier may be defective. To confirm sensor amplifier operation, temporarily replace the suspect sensor with a new unit and recheck the BOV. If the BOV is correct, then the sensor must be checked for vibration sensitivity.

To test for vibration sensitivity, tap the pipe surface near the sensor. Observe the signal on a voltmeter to ensure that the sensor is picking up vibrations. Monitor the measurements of a newly installed sensor to determine if its output is reasonable.

8.2 CABLING

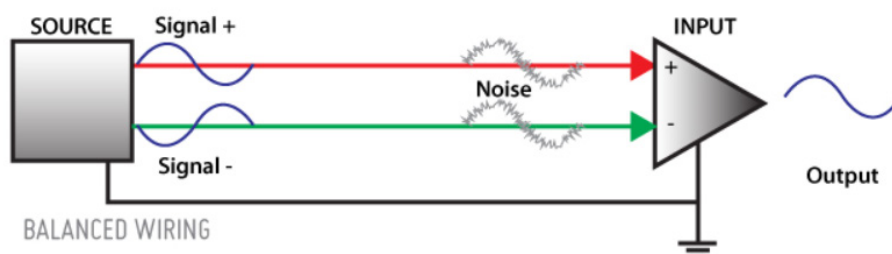
Cabling is one of the most important aspects of vibration sensor installation. Careful attention must be given to six major considerations: cable type, cable length and capacitance, routing, grounding, environment and anchoring.

Unbalanced cables as described in Figure 33 are not very good at suppressing noise from outside interference, unbalanced cables should have a maximum length of 4-6 m. The real secret is that a balanced cable will reject electromagnetic noise (EMI, RFI) but allow the vibration signal to go through. As a result a balanced cable is preferable if there are long cables needed, ~300-400 m.



Unbalanced wiring uses just two conductors and is susceptible to picking up noise.

Figure 33 Example of unbalanced wiring with an output signal detected with noise. Source “example figure from Aviom blog”



Balanced wiring uses two signal conductors plus a ground, allowing noise picked up along the way to be canceled through polarity inversion.

Figure 34 Example of balanced wiring with an output signal detected with noise cancelled out. Source “example figure from Aviom blog”

Always ground the shield at one end only!

8.2.1 Cable length and Capacitance

All cables have capacitance across their leads, therefore the capacitance load on the output of the sensor increases with cable length. Generally, this capacitance is about 9 Pico farads (pF) per meter, depending on the cable construction. After the cable length has been determined, its effect on the sensor operation should be evaluated. Capacitive loading reduces high level, high frequency vibration signals. The effect of this capacitive loading is not a problem for cables less than about 75 m in length between the sensor and the power source.

The easiest solution is to use a lower sensitivity sensor. A sensor with 10 mV/g sensitivity will have a hundred times larger amplitude range than a similar 1 V/g sensor.

N.B. Cable length of velocity sensors is less important as they are employed at low frequencies.

8.2.2 Cable routing and electromagnetic interference

Assure that high quality, well shielded cables are used. Proper cable routing is also recommended. Avoid routing sensor cables alongside AC power lines; cables should cross AC power lines at right angles. In addition, route the cable away from radio transmission equipment, motors/generators, and transformers.

8.2.3 Anchoring

The cabling shall be protected against mechanical damage where necessary as exemplified in Figure 35 and despite that the equipment is not a permanent installation the cabling shall be routed in a professional and orderly manner. In addition, to minimize risk of safety issues like take a false trip over the cables.

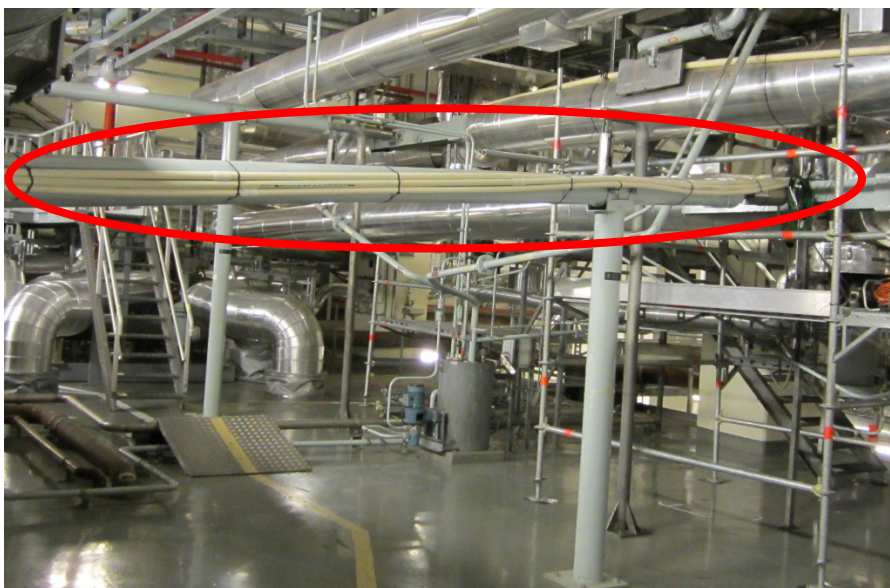


Figure 35 Example of temporary cable routing. The Microdot cables are protected in electric wire tubes (VP-rör). Source “delivered from participating plants”.

When securing the cable, leave enough slack to allow free movement of the accelerometer on the vibrating machinery, see Figure 36. When coaxial cables flex under vibration conditions, there is separation and relative motion between the cable dielectric and the outer shield. The result is “triboelectric” noise at frequencies below about 20 Hz. This can be a severe problem with low-level measurements unless low-noise cable is used.

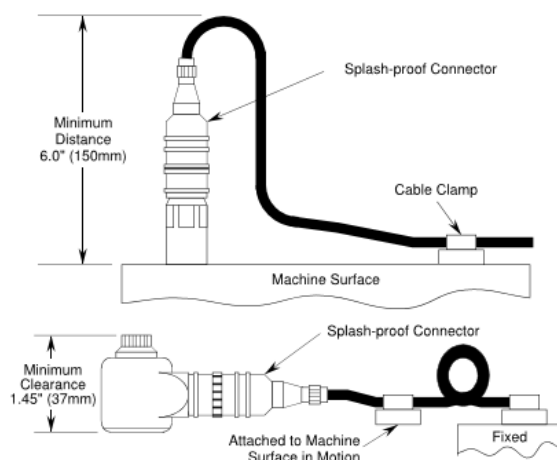


Figure 36 Cable anchoring

8.2.4 Examples of cable types

Super low-noise coaxial cables, BNC or Microdot, (Type: AO-0122-D-030 of supplier Brüel & Kjaer.) could be used for accelerometers. Inline charge converter may be connected to the low-noise coaxial cables.

Other alternatives may be twisted pair low-noise cables (Type: 078G30 of supplier PCB - Synotech) were connected to accelerometers (connector: Microtech to 3 * BNC). BNC cables were connected to the twisted low-noise cables (connector: BNC – BNC, cable length: 25m). The BNC cables were connected to the measurement system.

Examples of connection of cables to velocity transducers: Connecting cables EC were (Type: EC of supplier Vibro-Meter) connected to the velocity transducer (connector: MS to BNC, cable length: 40m). The connecting cables EC were connected to the correction circuit (Type: TSG 212). BNC cables were connected between the correction circuit and the measurement system (connector: BNC – BNC, length: 1m). All connections were inspected after the routing of the cables and secured against loosening by lagging the connectors with tape.

8.3 ANALYZING THE TIME WAVEFORM AND FFT SPECTRUM

8.3.1 Overload

Some common mechanical causes of an overload in the sensor are severe pump cavitation, steam release, impacts from loose or reciprocating parts and even gearmesh noise. High frequency, high amplitude vibration signals can also overload the sensor and in severe cases cause erratic time waveform. However, overload problems are usually detected by observing truncated waveforms and large ski-slope spectrums, see Figure 37.

If the amplifier saturates, intermodulation distortion occurs. This causes low frequency noise, also referred to as wash over distortion. Figure 37 shows a normal

spectrum and what can happen when the signal becomes overloaded due to excessive vibration.

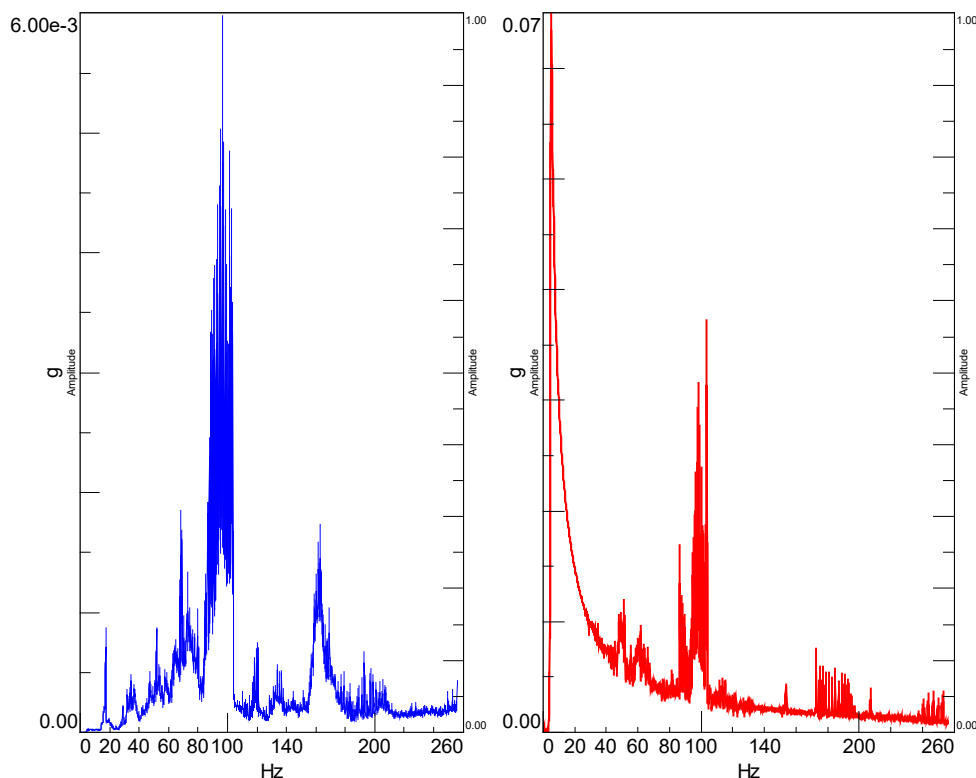


Figure 37 Normal “correct” acceleration spectrum versus overloaded spectrum (ski slope). Source “snapshot from computer program LMS Test.Lab”.

Sometimes the ski-slope signal can be caused by circuitry used to integrate acceleration signals to velocity or displacement.

One way to reduce overload is to use a higher power supply voltage and ensure that the bias voltage is centered between supply voltage and ground voltage. However the bias voltage and power supply are rarely adjustable. For example, if you are using an 18 volt power supply and a 12 volt bias, clipping will occur sooner than if you used a 24 volt power supply.

9 Performing of the actual measurements

Which parameter to choose? The general measurement rule is that the parameter giving the flattest response over the frequency range of interest should be chosen. The useful range, flattest response, will give the biggest dynamic range of the whole measurement set up, see Figure 38. In general, most high frequency sensors have low sensitivities and conversely, most high sensitivity sensors have low frequency ranges. The dependence of inertia on mass governs this relationship. As the mass increases the sensitivity is also increased; however, the usable frequency range is reduced since the sensor more quickly approaches its resonance frequency.

The high frequency range of the sensor is constrained by its increase in sensitivity as it approaches resonance. The low frequency range is constrained by the amplifier rolloff filter. Many sensors have a passive low pass filter between sensor element and the amplifier in order to attenuate the resonance amplitude.

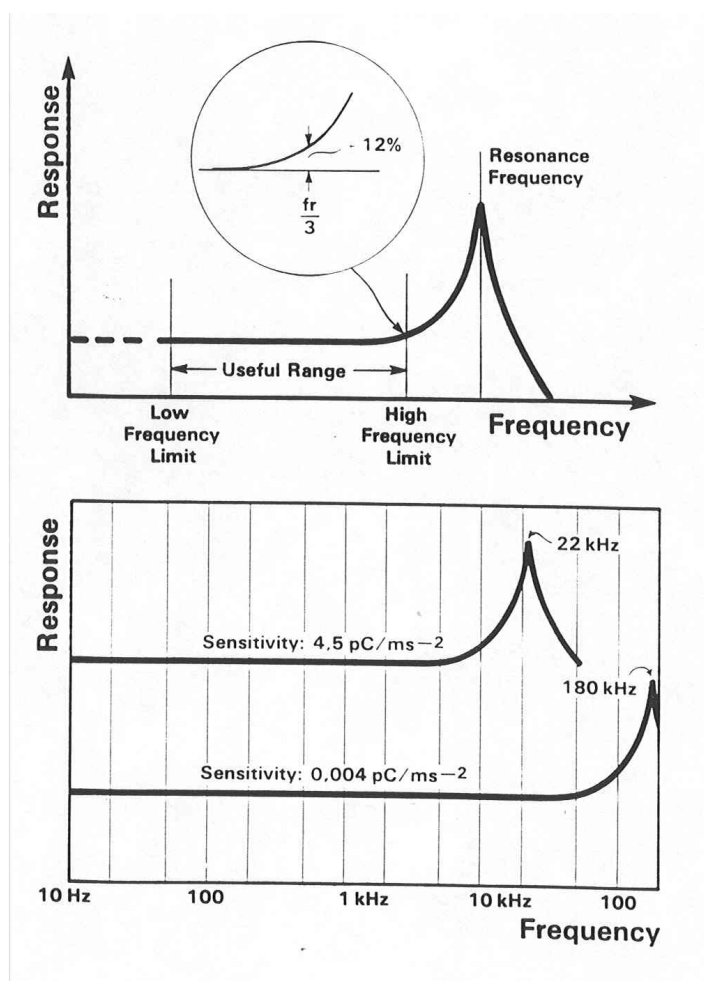


Figure 38 Typical frequency response from various accelerometers. Source "example figure from Bruel&Kjaer".

An advantage of the accelerometer is that its electrical output can be integrated to give velocity and displacement signals. At the lowest frequencies the resulting integrated signal should be handled with caution as the discrepancy could be considerable compared to a “true measured velocity or displacement” due to signal bias etc.

9.1 MEASUREMENT SETUP PARAMETERS

The resolution should be better than 1 Hz, frequency range 0-300 Hz, number of spectral lines greater than 300 (and typically 800 or 1600), Hanning window, RMS average vibration velocity, 10 averages. Use accelerometer or velocity transducer. A displacement proximity transducer is not acceptable for trouble shooting (2).

The author’s experiences are that:

- The frequency range should be as low as possible. In practice the limit is often about 1 Hz depending on type of transducer and analyzer utilized.
- Upper frequency range is depending on vibration requirements (often up to 1000Hz) but in practice up to some hundred Hz. However depending on equipment (pumps, compressors, motors, valves, orifices, bellows) it could be wise to if possible to choose 2 kHz and sometimes even higher but seldom over 10 kHz.
- Filter type selected is by standard a Hanning window but if the vibration signal is a sine tone a Flat top window could be chosen to give a true amplitude.

9.2 STATISTICAL OPERATIONS

Statistical operations must often be made on the measurement data. Suppose that you shall measure transient pipe vibrations from pressure pulsation. It is likely that you get different maximum vales for each measured occurring pulsation. The more occurrence you measure the larger is the probability of measuring a higher largest maximum value. A common rule of thumb (three-sigma rule of thumb) is to use the 95% percentiles of the maximum values.

Averaging in the FFT algorithm is used to reduce the noise in a random signal (5). The standard deviation of the error, ε , in the spectrum is proportional to:

$$\varepsilon \propto \frac{1}{\sqrt{nBT}}$$

where B is the effective noise bandwidth of each narrow band window ($\approx 1.5 \cdot \Delta f$ for Hanning window), T is the effective averaging time and n the number of averaging. A specification of noise bandwidth is specified in Table 5.

Table 5: Noise bandwidth of different windows in the FFT algorithm.

Window	Noise bandwidth [Δf Hz]
Rectangular	1.0
Hanning	1.5
Kaiser-Bessel	1.8
Flat top	3.8

To exemplify the above let's say that we have:

- Steady-state random signal with bandwidth $f=400\text{Hz}$
- FFT analysis
- 800 spectral lines
- Hanning window
- Number of average, $n=10$
- $B=1.5 \cdot \Delta f = 0,75 \text{ Hz}$
- $T=10 \cdot 2=20 \text{ sek}$
- $BT=0,75 \cdot 20 = 15$

This example will result in a standard deviation error ε :

$$\varepsilon \propto \frac{1}{\sqrt{nBT}}$$

$$= 0,26 \text{ (c:a 2 dB)}$$

10 Presentation of the measurements results

Best practices on how to present the results depending in much extent on the purpose of the measurements, the source, the equipment and the frequency range of interest.

It could often be helpful to start the commission by writing the report. What is the purpose of the survey? If the survey is based on a test specification report the presentation of data hopefully is predefined.

The measurement report shall present the results in a condensed and clear manner. The measurements shall be so well described that another observer can repeat the measurements.

10.1 PRESENTATION OF RESULTS – ACCELERATION/VELOCITY/DISPLACEMENT

Piping vibration requirements and guidelines are often given in vibration velocity as vibration energy is closely connected to the vibration velocity (2). But at lower frequencies displacement may be of more of interest. At frequencies up to 10 Hz vibration requirements might be given as displacement.

- Displacement (large displacement at low frequencies and small displacements at high frequencies for the same amount of energy)
- Velocity (Velocity gives a more uniform weighting over the required range and is most directly related to the resulting dynamic stress and is therefore most commonly used as the measurement)
- Acceleration (acceleration is weighted such that the highest amplitude occurs at highest frequency)

Requirements stated as acceleration, often in g ($\sim 10 \text{ m/s}^2$), are common for instrumentations as pressure and temperature sensors or electrical equipment. In Figure 39 the relative amplitude of the parameters; displacement - velocity - acceleration are compared.

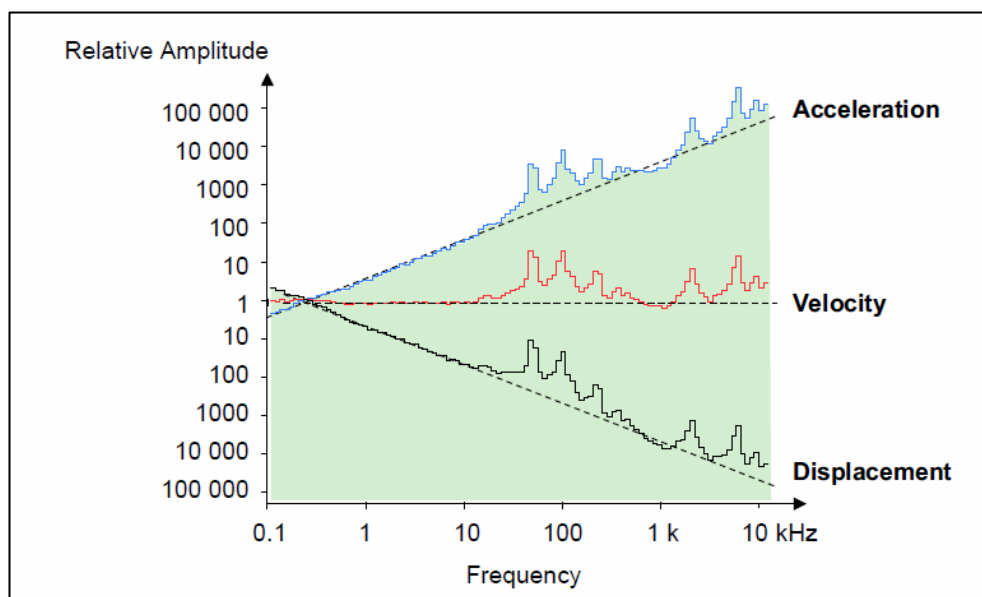


Figure 39 Vibration parameters, Acceleration-Velocity-Displacement

10.2 PRESENTING RESULTS FROM SCREENING OF VIBRATION LEVELS

The measurements shall be so well described that another observer can repeat the measurements. There is a lot of information from a pipe vibration measurement which preferable should be grouped together in order to be traceable, not just the vibration level with corresponding spectrum. This additional information is typically an isometry marked with position of sensor, pictures of sensor mountings and type of used sensor as well as cabling but also the flow chart, used calculation models (ex. Pipe stress) etc. Preferably the information is grouped together in a condensed html report, Figure 40, which can be accessible by the users at the power plant. The advantage is that hopefully that next time the measurement can be repeated in the same way and that this will minimize the preparation time to carry out a new test.

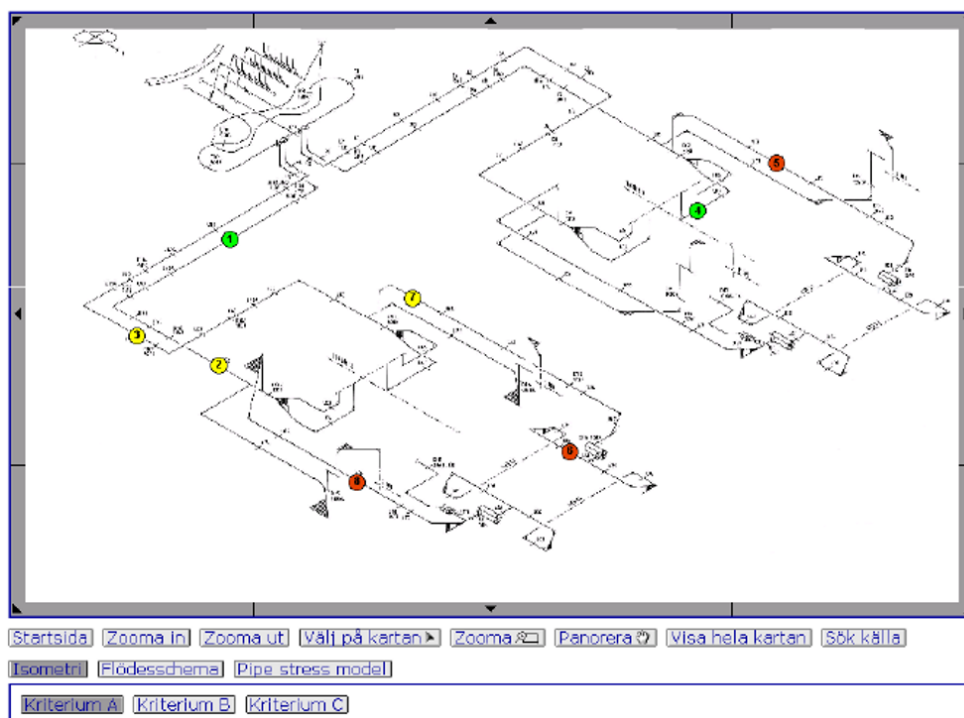


Figure 40 Example of vibration mapping of steam pipes reported in a html based report. Source "ÅF internal material".

10.3 BANDWIDTH AND RESOLUTION

The setting for "Lines" affects the number of frequency points used in the PSD calculations for the random control loop. Increasing the number of lines makes the frequency resolution for the PSD finer. This provides better information for general analysis and can be helpful in controlling highly dynamic structures. However, with higher line resolution the time to acquire a frame of data increases. For example, a 2000 Hz with 400 lines has a time history frame time of 200 milliseconds while a 2000 Hz test with 1600 lines will have a frame time of 800 milliseconds. This increase in frame time will have the effect of making the control loop somewhat more sluggish as simply takes longer to acquire the data used in the control spectrum averaging process. However, in the event of sudden change in the overall RMS level of the control spectrum the random controller uses a special algorithm to allow fast re-equalization.

10.4 POWER SPECTRAL DENSITY (PSD)

There is a need to normalize the spectrum to the frequency bandwidth chosen. If the measured spectrum isn't normalized the amplitude is depending on the bandwidth used. Compare with noise measurements for instance where octave band levels and 1/3 octave band levels not are the same.

Power Spectral Density (PSD) is a measure of a signal's power intensity in the frequency domain. In practice, the PSD is computed from the FFT spectrum of a signal. The PSD provides a useful way to characterize the amplitude versus frequency content of a random signal.

Random vibration is often experienced in the real world. It is motion at many frequencies at the same time. The amplitude at these frequencies varies randomly with time. The usual way to describe random motion is in terms of its Power Spectral Density.

The name "Power Spectral Density" comes from the study of random variations of the power absorbed in an electrical circuit. Although developed for electrical engineering applications, the same theory is applicable to mechanical vibration applications. Vibration testing typically uses acceleration measurements so "Acceleration Spectral Density" but "PSD" is a name more widely adopted by the industry.

10.5 RMS (ROOT MEAN SQUARE)

Corresponding to the Random Profile PSD there is a RMS (Root Mean Square) value. The PSD profile defines the test in terms of the amplitude versus frequency characteristics. The RMS is calculated by integrating the area under the PSD profile and then taking the square root of the result. Therefore, the RMS represents the overall severity of the test.

RMS is proportional to signal energy and is evaluated using an integration time that rarely is defined within the criteria. The standardized RMS integration times that can be found on instruments are: Slow (1 s), Fast (125 ms) and Impulse (35 ms). The RMS value will change depending on the integrations setting. Note that these integration times are defined with respect to human hearing and imposed by what instrumentation hardware is available. Therefore, they are poorly adapted to assess piping vibration risk. As a rule, the shorter the integration time, the closer the RMS value is to the peak value.

Since the RMS value has its source in an integration process, it is typically a stable value over the course of a test. The fluctuation in individual frequency values in the control PSD can be quite large but the RMS is relatively stable.

10.6 PEAK

Most piping vibration will not be sinusoidal or harmonic; it would be better described as quasi-random—a distinction that becomes important because much of the available instrumentation measures the root mean square (rms) of a vibration signal, which is a time average of the waveform magnitude.

The rms reading for a purely sinusoidal vibration can be converted to a peak amplitude by multiplying rms by 1.414, the Crest factor. For any vibration that is not composed of a purely sinusoidal motion, this simple relationship is not applicable, Figure 41.

The Crest factor is the peak amplitude of the waveform divided by the rms value of the waveform. In other words, crest factor indicates how extreme the peaks are in a waveform. Crest factor 1 indicates no peaks, such as direct current, DC. Higher crest factors indicate peaks, for example sound and vibration waves tend to have high crest factors.

For piping vibration, peak values need to be measured because allowable fatigue are in terms of peak stress. Therefore, a method of obtaining true peak vibration levels is needed, which can be obtained either by using instrumentation that senses true peak values or by statistically converting rms measurements to peak values.

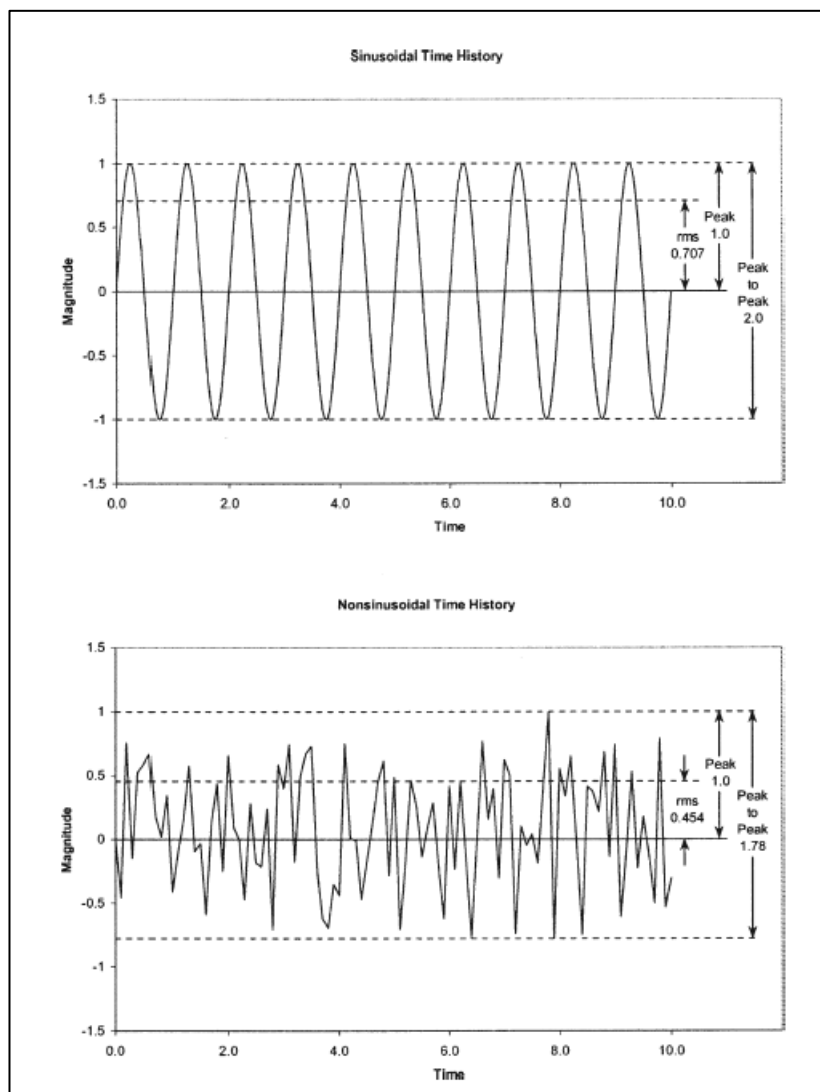


Figure 41 RMS versus PEAK-TO-PEAK measurements for a sinusoidal and non-sinusoidal time history.

10.7 OVERALL VIBRATION LEVEL

The overall level of pipe vibration is a measure of the total vibration amplitude over a wide range of frequencies, and can be expressed in acceleration, velocity or displacement. The overall level can be measured with an analog vibrometer or it can be calculated from the vibration spectrum by summing up all the amplitudes over a frequency range. In comparing overall vibration measurements, it is important that they encompass the same frequency range.

Sometimes overall levels are expressed in a decibel scale for vibration acceleration and velocity. It's then important to know the used relative reference level to be able to recalculate it back to a linear format overall level.

Acceleration level, L_a dB (relative reference $1 \mu\text{m/s}^2$), is defined as:

$$L_a = 10 \cdot \log(a^2/a_0^2) = 20 \cdot \log(a/10^{-6}) \text{ dB}$$

Velocity level, L_v dB (relative reference 1 nm/s) is defined as:

$$L_v = 10 \cdot \log(v^2/v_0^2) = 20 \cdot \log(v/10^{-9}) \text{ dB}$$

This means that an increase/decrease in acceleration/velocity level of 20 dB gives a ratio factor of 10 in difference. Other conversion ratios is found in Table 6.

Table 6 Linear and dB factor increase/decrease of vibration velocity/acceleration

Acceleration/Velocity ratio linear	Acceleration/Velocity ratio in dB
100 000 000	160
10 000 000	140
1 000 000	120
100 000	100
10 000	80
1000	60
100	40
10	20
1	0
0.1	-20
0.01	-40
0.001	-60

To exemplify the above let's say that we have:

- Measured a vibration velocity OA-level of 50 mm/s rms between 2-1000 Hz. After a modification, the level was reduced to 5 mm/s rms. The OA-level has then decreased a linear factor of 10, which corresponds to a 20 dB decrease, see Table 6.

11 Evaluation of the measurement results - reliability and analysis

Checking the consistency of the data shall always be done at least in some depth. Evaluation of the measurement result reliability and tolerances in the interesting frequency range should be performed. But most important is always to note the measurement and load condition, the speed of machinery, flow, pressure together with photos of the installation and surrounding pipework and vibration sources.

What other sources are expected to contribute to the results? How wide is the actual frequency range? Is the low frequency values correct? Is all the data reliable or are there some outliers? Is each of the measurement sensors expected to work properly, or is there a chance that some of them are giving erroneous signals? Is there noise, ski-slope, random peaking or other disturbances in the measurement results?

11.1 MEASUREING CORRECT TIME SLOT

Selecting the timing, to event and length, for measurement should be taken with care. It may not reveal the true vibration problem. The OA-level in Figure 42 will differ a lot if the time series is taken in modulation maximum or modulation minimum.

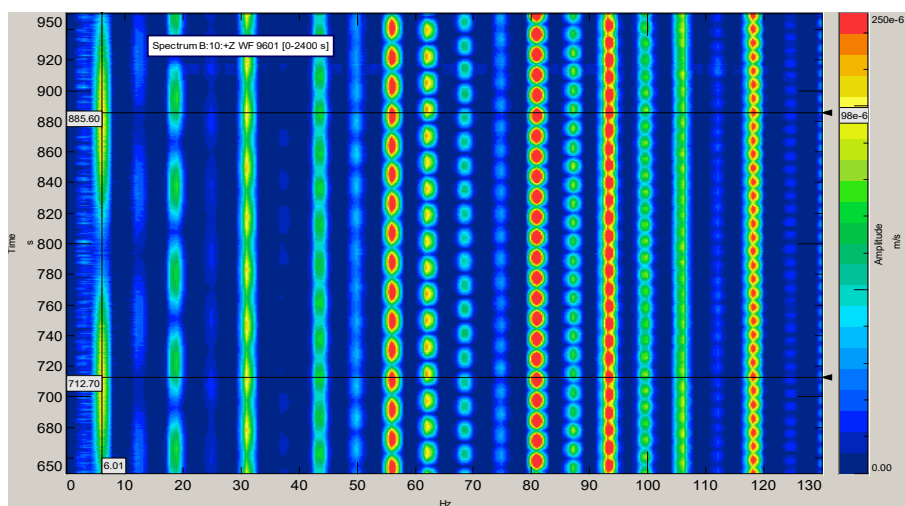


Figure 42: Pipe response from modulation between two different vibration sources. Source "snapshot from computer program LMS Test.Lab"

11.2 PROCESSING OF THE DATA

The reliable frequency range should be determined and the data filtered accordingly. However, caution should be taken in order to prevent filtering away physical vibrations from the signals.

All FFT-analysis parameter should always be annotated on result data curves. This is especially important for comparison with measurements made with other

independent data systems. If there are discrepancies in-between too independent measurement the signal process parameters should in first place be checked. A too high/low level might be caused of different spectral Window, amplitude format etc. This is illustrated in Figure 43.

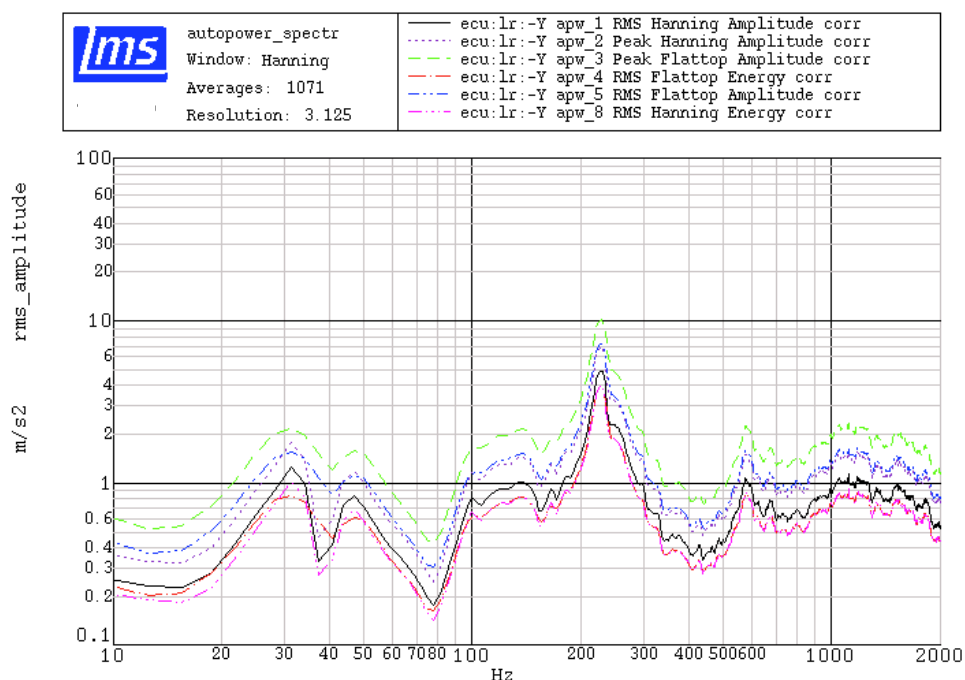


Figure 43 Calculated Autopower spectrum with different windows and amplitude correction. Source "snapshot from computer program LMS Cada-X".

11.3 HOW TO DISPLAYING RESULTS FROM FFT SPECTRUM

A first result from an FFT analysis in a broad band analysis is often shown in a display with linear x- and y-axis as in Figure 44. The vibration data range over several orders of magnitude i.e. from extremely low levels to extremely high levels, a logarithmic scale is often a more logical choice for the representation of the amplitude of vibration motion.

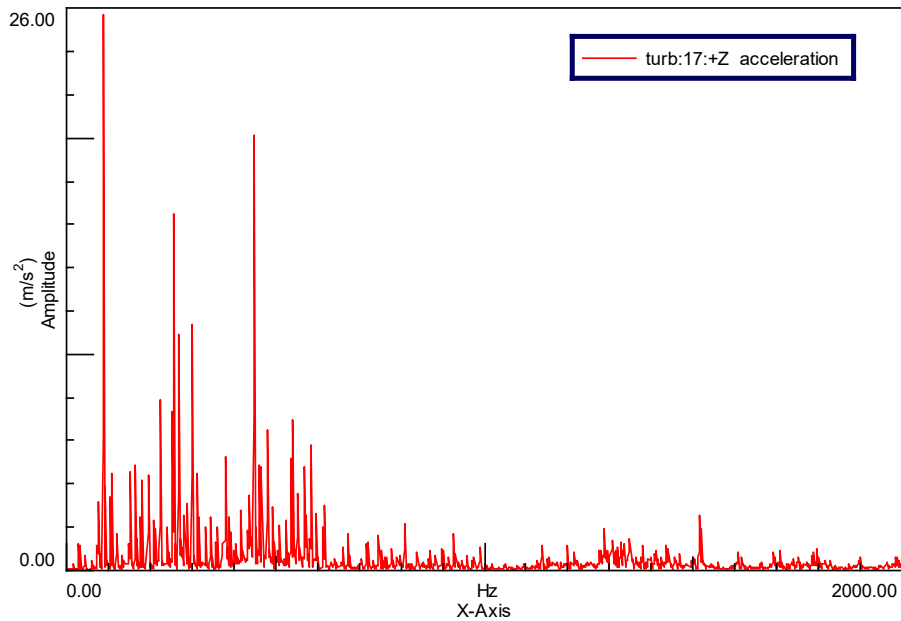


Figure 44 A FFT spectrum in a display linear x [Hz] and y [m/s²] axis. Source “snapshot from computer program LMS Test.Lab”.

Displaying the same data as in Figure 44 in a logarithmic display where both x and y are logarithmic axis will often give a more detailed overview in full measured frequency range, see Figure 45.

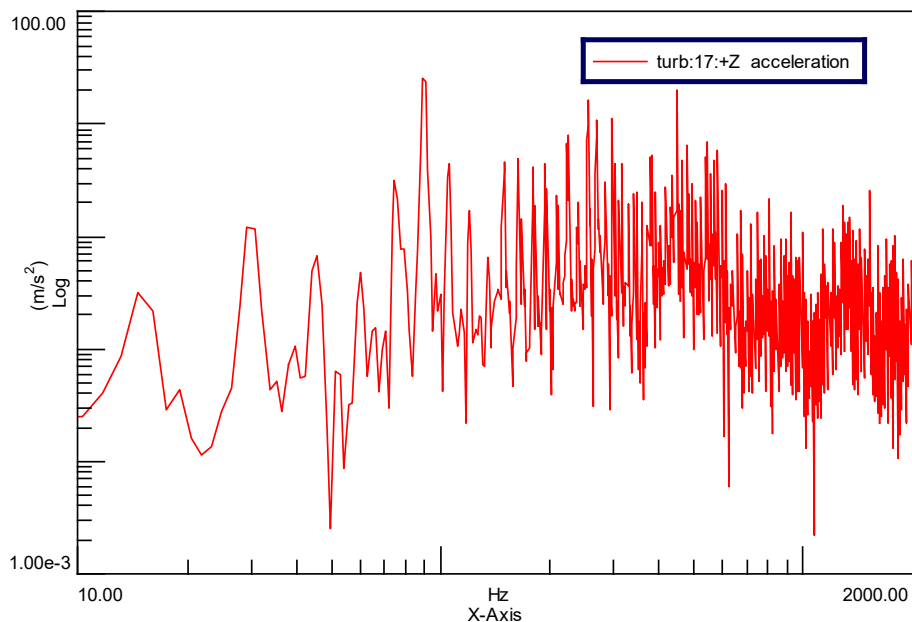


Figure 45 A FFT spectrum in a display with logarithmic x [Hz] and y [m/s²] axis. Source “snapshot from computer program LMS Test.Lab”.

11.4 TIME WAVEFORM AND FFT SPECTRUM FAULT ANALYSIS

Overload problems from high frequency and high amplitudes are usually detected by observing truncated waveforms in time domain and large ski-slope spectrums in frequency domain. Some common mechanical causes of an overload in the sensor are severe pump cavitation and steam release.

Harmonics of AC line power frequency usually indicate interference from motors, power lines and other emissive equipment.

Cable routing faults can also be detected by analyzing the FFT. Multiples of the line power frequency usually indicate improper shielding or grounding. Ground loops are developed when the cable shield is grounded at two points of differing potential. Always ground the shield at one end only! An easy test for ground loops is to disconnect the shield at one end of the cable. If the problem disappears, it was probably a ground loop fault.

12 Best practices on the pipe vibration measurements

A first step in determination how a pipe measurement should be performed is to ask to what purpose the measurement should be carried out. This will help to classify which kind of measurements shall be performed.

Careful attention should be paid to determine if the vibration are steady state random/tone or transient in nature. Also, note whether vibrations may have a varying amplitude or “beating” which is typical of a piping vibration in which excitation is occurring from two sources at slightly different frequency. If there are beating phenomenon or transient vibrations the measurement should be performed in time domain or if possible synchronous time and spectrum domain.

12.1 WALKDOWN/SURVEY THE SYSTEM

When high priority problem arises which might adventure production and/or safety aspects a temporary internal task force group is often set up. Here, people with relevant different technical disciplines are collaborating together to sieve out and map the pipe vibration problem.

The survey should start with a walkdown of the piping system. Walkdown procedures rely heavily on the judgment and experience of the engineers who complete them. Therefore, to ensure that the walkdowns are effective, those completing them should be experienced in a variety of areas related to piping vibration, including experience with the systems and its operation. Surveys of the pipe system is further described in (1).

The extension and content of a walkdown survey is depending on the purpose of the measurements. Is the purpose:

- Trouble shooting?
- Validation or verification or screening measurements of the pipe system?

12.1.1 Walkdown - Trouble shooting of existing piping system

The purpose of the walkdown is to determine if the high vibrations reported are a real problem or not. Often wise the analyst/engineer get as a first input very vague information, like “it vibrates very much” or it “sounds scary”. In addition to the described symptoms it is therefore important to make following observations regarding the nature of the vibrations:

1. Frequency of vibration. Is it low frequency below 10 Hz, medium up to 300 Hz or high frequency?

As a general best practice, select the appropriate vibration sensor:

- a. Use displacement sensors i.e. LVDT for frequencies below 10 Hz. Alternative velocity sensors with electronic linearization to measure frequencies below 10 Hz.

- b. Use mechanical velocity sensors for frequencies up to 300 Hz. Alternative use accelerometers if no risk of higher frequencies out of band overloads exist. However, an accelerometer with an external high pass filter may also be a good choice. Especially if space is the limiting factor and the velocity sensor is not fast enough to capture the signal, for instance a rapid transient signal.
- c. Use accelerometer sensor for frequencies above 300 Hz. However, mechanical velocity transducers with linearization can also be used to higher frequencies depending of the transducer mounting. With bolted transducers, up to 2000 Hz and above can be use.

In addition, it is always a good practice to store the time signal with a sampling rate 5-10 times the highest frequency of interest. Post processing of data will then not be restricted

2. Amplitude of vibration

Validate against norm/standard to check if it's a severe vibration.

- a. Has the amplitude a beating effect? Use a sufficient long measurement time to comprise a couple of beating cycles.
- b. Is it a transient vibration signal? Capture the signal in time domain. Is the signal stationary? It's preferable to stay in frequency domain?
- c. Check vibration signal for overload. If it's a strong shock consider to use a piezo resistive accelerometer instead of usual piezoelectric accelerometer.

3. Location of highest vibration

Where does the vibrations with highest magnitude occur: on pipe wall, pipe support, small bore connection or valve?

- a. Does the vibration of the pipe belong to a local pipe mode or a global pipe mode? It is preferable to check the vibrations with at least a 2 channels system to check relative vibrations to magnitude and phase between different pipe components. However, if you can measure the vibrations at the same time in 3 directions (x,y,z) in a measuring point it will be easier to estimate the highest vibration level in that point.
- b. If it is a valve vibration consider to also measure the dynamic pressure before and after the valve in order to find out if the valve vibration has a pulsation induced source.
- c. If it is a low frequency pipe support problem, below 10 Hz, consider also to measure strain at the pipe support. Dynamic strain measurements by piezoelectric sensors are often suitable and easy to use if the problem has a dynamic nature.

4. Identify which kind of vibrations it is, steady state random, steady state tone or transient vibrations.
 - a. If the signal is steady state random it can be preferably be measured in the frequency domain with sufficient long measuring time in case of a beating effect. To avoid leakage in the FFT algorithm use a Hanning window.
 - b. If the signal is steady state periodic. Think about how to capture the signal in frequency domain with a bandwidth to comprise second or third harmonic of the actual tone. Due to the tonal nature a Flattop window will better estimate the signals amplitude than the Hanning window in order to avoid leakage in the FFT algorithm.
 - c. If the signal is transient it should be measured in time domain or preferable in a synchronous time and frequency domain.
5. Identify mode shape or vibration pattern of local pipe component and global pipe system. This step may requires a deeper understanding of vibration methods.
 - a. If feasible perform a multichannel Operational Deflection Shapes, ODS, during operation. This is an efficient way to visualize the vibration problem by animation of measured pipe points. This also reveals how the vibration problem may be influenced by changing loading conditions.
 - b. During outage it is preferable for operational critical pipe segments to perform an Experimental Modal Analysis, EMA. This could be used to calibrate calculated FE Modal Analysis, FEMA. By having a well calibrated simulation model a simulation of pipe counter measures could be done with higher accuracy i.e. design of pipe supports, damper countermeasures e.t.c.

12.1.2 Walkdown – Validation/verification/screening

In addition to the trouble shooting case, risk of vibration problem and/or vibration failure surveys of the whole pipe system should be conducted/considered.

The walkdown procedure in this case is much depending on if test procedures are documented (in a vibration validation plan or similar) or not. In a test procedure report, operational load, measurement methods and installation of equipment are to be documented. In Figure 46 an example of how to report measurement installation is given.

Securing of the connections

- Secure all bolted connections with the retaining washers (e.g. Nord-Lock®) or bolt adhesive (e.g. Loctite®).
- If possible, secure the magnet against slipping with a standard two component epoxy.

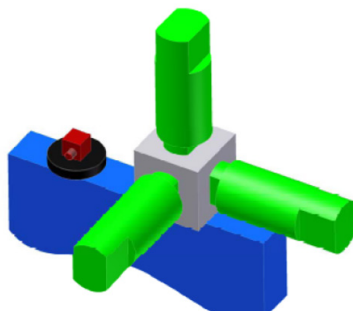


Figure 46 Example of a measurement setup for a temporary installation at a valve. One tri-axial accelerometer together with 3 velocity transducers (6). Source “delivered from participating plants”.

12.2 VIBRATION SOURCES

For the purposes of piping design, monitoring and measuring, vibration is typically divided into three types: steady-state random, steady state periodic and dynamic transient vibrations. However steady-state vibrations exist in a range from periodic to random.

Each type has its own potential causes and effects that necessitate individualized treatment for prediction, analysis, control, monitoring and measuring.

12.2.1 Steady-State Random Vibration

Piping steady-state vibration can be defined as a repetitive vibration that occurs for a relatively long time period. It is caused by a time-varying force acting on the piping. Such a force may be generated by rotating or reciprocating equipment by means of vibration of the equipment itself or as a result of fluid pressure pulses. The steady state vibrations are contributed by the reactor coolant pumps, which drive the coolant through various circuits. These pumps generate periodic and random disturbances in the fluid, which in turn vibrate the system.

Vibrational forces may also result from cavitation or flashing that can occur at pressure reducing valves, control valves, and flash tanks. Flow-induced vibrations such as vortex shedding can cause steady-state vibrations in piping, and wind loadings can cause significant vibrations for exposed piping similar to that typically found at outdoor boilers.

The primary effect of steady-state vibration is material fatigue from the large number of associated stress cycles. This failure may occur in the piping itself, most likely at areas with stress risers such as branch connections, elbows, threaded connections, or valves.

However, this failure can also occur in various piping system components and supports. Fatigue damage to wall penetrations can occur because of vibration in the attached piping, snubbers, and supports; premature failures of machine bearings are another potential consequence.

12.2.2 Steady-State Periodic vibration

The periodic pump-induced pressure pulsations may be produced at multiples of the pump-operating speed and multiples of the number of pump plungers, blades, volutes, or diffuser vanes. A vibration which is show up as a tone i.e. periodic steady state vibration.

The potential pulsation frequencies are defined by the following equations:

$$F = N \cdot X / 60 \quad \text{or} \quad F = N \cdot XY / 60$$

where

F = frequency of pressure pulsation, cycles/sec. (Hz)

N = 1, 2, 3, and so on

X = pump rotating speed, rpm

Y = dependent on pump type: number of pump plungers,

blades, volutes, or diffuser vanes.

Vortex shedding in piping systems is also an important potential source of piping steady-state periodic vibration. The frequency of vortex shedding can be approximated by the following formula:

$$F = S \cdot V / D$$

where

S = Strouhal Number, 0.2–0.5 for flow through restrictions or across obstructions

V = flow velocity, m/s

D = restriction diameter, m.

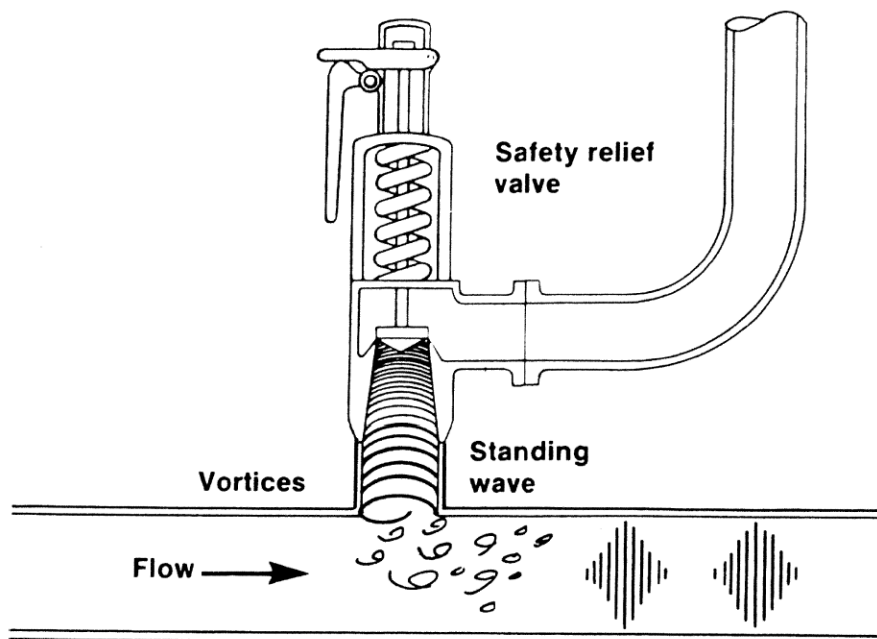


Figure 47 Vortex shedding at a Safety relief valve

The Strouhal number, S , is a function of geometry and Reynolds number. Over a large Reynolds number range a Strouhal number of about 0.2 is then valid regardless of the body geometry (7).

Vortex shedding normally results in low-amplitude pressure pulsations, and no problem occurs unless these pulsations coincide with a piping acoustical resonance. The vortex shedding tends to lock into a close piping acoustical frequency, and the pressure pulsations can then be greatly amplified.

12.2.3 Dynamic-Transient Vibration

The dynamic transient is the second, perhaps more dramatic form of piping vibration, differing from the steady-state vibration in that it occurs for relatively short time periods and is usually generated by much larger forces.

In piping, the primary cause of dynamic transients is a high- or low-pressure pulse traveling through the fluid. Such a pulse can result in large forces acting in the axial direction of the piping, the magnitude of which is normally proportional to the length of pipe leg—that is, the longer the pipe leg, the larger the dynamic transient force the piping will experience (pipe leg is defined as the run of straight pipe between bends).

The transient vibrations in the pipeline arise due to an instant closure of the check valve(s), initiating a water hammer, while switching to new operating condition. The usual causes are rapid pump starts and trips, and also the quick closing or opening of valves such as turbine-stop valves and various types of control valves.

Dynamic transients also occur as a result of rapid safety/relief valve (SRV) opening or as a result of unexpected events, such as water accumulating at a low point in

steam piping during a plant outage. When the steam is returned to the line, a slug of water will be pushed through the piping, resulting in large axial loads at each elbow

Other sources of vibrations are located at the singular points such as cross-sectional enlargements, bends, valves and T-junctions. The presence of these singular points increases the possibility with which such disturbances can excite in resonance beam type flexural modes of the pipe lengths, and may induce vibrations of lower order frequency.

Effects of transient vibrations are usually obvious; large pipe deflections usually occur that damage the support system and insulation as well as cause possible yielding of the piping. Of course, damage can also be sustained by the associated equipment, valve operators, drain lines, and so forth.

12.2.4 Examples of pipe vibration sources

Examples of vibration sources are:

1. Mechanical Induced Sources –
 - Machinery Unbalanced Forces and Moments (High excitation forces, low frequency)
2. Pulsation Induced Sources –
 - Reciprocating Compressor and Pumps, Turbine pulsations (High pressure pulsations, Low frequency)
 - Centrifugal Compressors and Pumps (Low pressure pulsations, High Frequencies)
3. Flow through Pressure Letdown, Valves, Orifice plates (High acoustic energy, mid to high broadband frequencies)
4. Flow turbulence (broadband source, low frequencies)
5. Cavitation and flashing (wide range of pressure fluctuations)
6. Vortex shedding (Pressure pulsations at distinct frequency bands, frequency proportional to flow velocity)
7. Acoustical resonance (Tonal excitation frequencies)
8. Water- and Steamhammer (Dynamic-transient vibration are short-duration events—typically less than 1 sec, but with dramatic effects.)

12.3 OPERATIONAL LOADS TO BE EVALUATED

It is essential to conduct a complete functional analysis of the system. This must include, in particular, the periodic testing and condition monitoring during operation and the deteriorated ambient conditions environment in accidental extreme conditions, which have been taken into account for the qualification of equipment connected by piping. This procedure shall apply even if the operation time in some configurations are low (of the order of a few minutes per cycle).

The operation of pumps with partial flow or overflow leads to significant flow fluctuations. Partial flow or overflow refers to an operation of the pumps outside of the field of maximum efficiency and leading to a high fluid excitation source compared with the nominal value.

Cavitation is known to lead to excessive vibrations in the pipework circuits (cavitation of orifice plates, cavitation of butterfly valves and vacuum orifice plates (under vacuum conditions)). It is important to note that in cavitation conditions, the operating conditions cannot be ranked. The experience feedback from vacuum conditions or from the operation of plants, does indeed show that changes in vibratory levels are not correlated with the increase or decrease in cavitation indexes from the literature.

The recommended flow velocity values are initially derived from economic analyses (function of the reduction in material by reduction of the piping diameter and the resulting expected increase in pump performance). The experience feedback shows a safe dynamic behavior of the piping when these 'economical' velocity values are met.

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Besides references listed above a number of internal ÅF Sound and Vibration reports, vibration measurements and investigations have been utilized in this work.

Appendix A: Questionnaire

Pipe vibration measurements - KK50427

SAMMANFATTNING

Frågorna i detta dokument är främst relaterad till mätningar av rörvibrationer men också vibrationsproblem och verifiering/validering.

Mottagare av detta dokument är medlemmar i referensgruppen i projektet KK50427.

SUMMARY

The questions in this document are mainly related to piping vibration measurements but also vibration failure and verification/validation are included.

The receivers of this document are the members of the reference group in the project KK50427.

WALK DOWNS AND PREPARATIONS FOR PIPE MEASUREMENTS

An updated pipework, a new installation of a pump/machinery/valve/etc or requalification of a pipe system may be handled in different ways regarding vibrations. The initial work and measurement preparation are very important.

- a) Do you build a group of different competences who performs the walkdown? Who attends the walk down?
- b) How do you judge a pipework due to risk of piping vibration problem? What do you look for when judging a pipe system at the walkdown? What type of documentation are you requested for (Vibration validation plans, etc)?
- c) Do you use a monitoring system to take control points at the walk downs or is it just the subjective feeling? Do you have internal document describing the walkdown procedure?
- d) Which pipe systems do you found most complicated to investigate?

KNOWLEDGE TRANSFER

- a) When you first hear about a pipe vibration problem where do you search information from?
- b) How do you give feedback to machinery suppliers about outcome of connecting pipe vibrations?
- c) How do you give feedback to pipe designers for improvements?

- d) Are your NPP-site member of any committee or network which have a pipe system vibration forum? If yes which ones?

TAKING MEASUREMENTS

- a) Do you on regular basis measure pipe vibrations in all three directions x, y and z- direction? If not when do you do it and find it important?
- b) Does your site have any fixed vibration sensors mounted on pipes? If yes have the mountings of the sensor been fatigue tested for low cycle fatigue?
- c) How are you handling mounting of sensors and measurements on isolated pipes? Do you have fixed mounted vibration measurement positions?
- d) Do you include machinery and foundation into the measurement plan of pipe investigations?
- e) How do your site cooperate between simulation and test department when constructing countermeasures like modifications of pipe support?
- f) How is your site measures temperature on pipes?
- g) How is your site measures flow velocity in pipes?
- h) How is your site measures dynamic pressure in pipes?
- i) When you have pipe vibrations below 10 Hz how do you measure these?
- j) Strain measurements when do you perform them?
- k) How does your site handles measurements in hot environments > 150 deg C?
- l) How does your site handles measurements in radiation environment?
- m) Lessons learned. Do you have some examples on outcomes which not was expected/predicted?

MEASUREMENT EQUIPMENT

- a) Which instrumentations/methods are you using for pipe vibrations:
 - i. Regular basis, short and long term measurements
 - ii. Trouble shooting
- b) Who takes care of the calibration of equipment and sensors?
- c) Which pressure measurement equipment and instrumentation are you using?
- d) Which flow speed measurement equipment are you using?
- e) Which strain measurement equipment are you using?
- f) Are you using cable shielding against electrical disturbances? And if yes. What kind/type?

- g) When you measure pipe vibrations below 10 Hz which sensors, cables, amplifiers etc are you using?

SETUP PARAMETERS

- a) What frequency range and resolution are you utilizing when taking vibration measurements?
- b) Which spectrum amplitude format do you use (PSD, peak,RMS) and when do you use it?

STANDARDS AND DOCUMENTATION

Which standards, guidelines or internal documents are you utilizing when deciding method, validation or verification measurements?

Examples of standards and guidelines are:

1. ASME ASME OM-SG-2007 Standards and guides for operation and maintenance of nuclear power plants,
 2. Guidelines for the Avoidance of Vibration Induced Fatigue Failure in Process Pipework 2008 second edition,
 3. VDI 3733-1996, Noise at Pipes (is there a later version?),
 4. Companion Guide to the ASME Boiler and Pressure Vessel Code, Volume 2, Second Edition, ch37, PIPE VIBRATION TESTING AND ANALYSIS, David E. Olson
- a) Which standards, guidelines or internal documents are you utilizing when deciding method, validation or verification measurements?
- b) Which requirements of vibration levels and frequency range are you utilizing?

What vibration measurement positions are according to you suitable hangers/pipe shell/valves?

- for vibration verification purposes?
- for vibration validation purposes?

7. IN-SITU AND LABORATORY MEASUREMENTS

- a) What kind of experience do you have from laboratory measurements? How was the agreement between test and full scale/plant and how was it verified?
- b) What kind of laboratory measurements/tests are, according to you, appropriate? When is computer simulation to prefer? (Is flow simulations by CFD to prefer versus physical model scale tests for instance.)

Have you carried out in-situ measurements, for instance changes of loads of equipment or increased flow to investigate a coming uprate conditions? How was the tests planned and how were the safety, risk and validation handled?

PIPE VIBRATIONS

The objective of the project "Pipe Vibrations – Measurements" is to assemble knowledge and experience in the area of piping vibration measurements at the nuclear power plants. The vibrations of the pipes concern the pipe structure, pipe support and valves. By setting up a guideline for pipe measurements based on experience the problem will be resolved in the most efficient way and selection of appropriate countermeasure could also be verified according to best practice.

Energiforsk is the Swedish Energy Research Centre – an industrially owned body dedicated to meeting the common energy challenges faced by industries, authorities and society. Our vision is to be hub of Swedish energy research and our mission is to make the world of energy smarter!