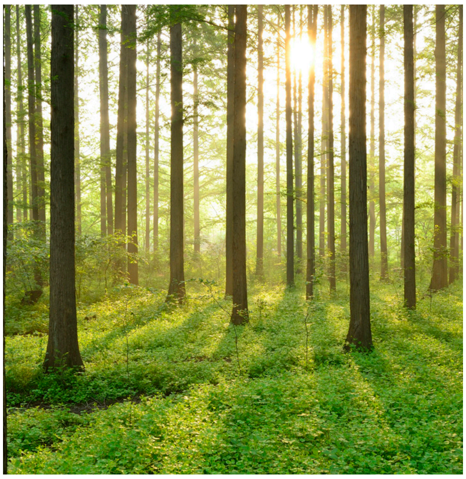
SURVEY OF VIBRATION DAMPERS

REPORT 2020:690



NUCLEAR

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NUCLEAR APPLICATIONS

Energiforsk

Survey of vibration dampers

– Analysis and mitigation

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Foreword

The project “Survey of vibration dampers- analysis and mitigation” assembles knowledge and experiences in the area of vibration dampers. Problems encountered that are related to dampers and how they were examined and mitigated are gathered. Furthermore, experience from vibrations dampers in the Nordic nuclear power plants are summarized.

In this project, the DIAM (Detection Investigation Analysis Mitigation) matrix tool developed by professor Rainer Nordmann and Paul Smeekes has been used to summarize the experiences of vibration dampers in the Nordic nuclear power plants with respect to damper, damper function and damper problems.

In a parallel project, in-depth information on viscodampers was collected in Energiforsk report 2020:667 “Vibration elimination using viscodamper technology” by V. Kostarev et al.

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

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

Sammanfattning

En viskös vätska som honung flyter inte så lätt, eftersom dess viskositeten är hög. Ett visköst flöde kräver att arbete tillförs för att få det att strömma. En vätska med noll viskositet kräver däremot ingen energi för att den ska strömma. Tillförs vibrationer i en viskös vätska kommer viskofluiden verka hindrande för vibrationerna och istället omvandla vibrationsenergin till värme.

I denna rapport ligger huvudfokus på vibrationsdämpare som använder viskösa vätskor eller viskoelastiska material där ofta skjuvning i materialet omvandlar vibrationer till värmeenergi. Bland dessa dämpare är speciellt viskodämpare väl representerade i kärnkraftverkens rörsystem.

Att avhjälpa rörvibrationer med viskösa och/eller viskoelastiska dämpare är motiverat om rörsystemet uppvisar resonanta förstärkningar. Normalt är materialdämpningen låg för konventionella stål- och aluminiumkomponenter, en förlustfaktor på ~0,01 %, men det finns speciella dämpmaterial där materialförlustfaktorerna är så höga som 300 %, vilka kan användas till att designa en dämpare specifikt avstämd till det aktuella rörsystemet. Rörsystemets respons vid dess resonanser kan då kraftigt begränsas vid excitation av dess strukturella resonanser.

Viskoelastiska dämpare ger både en hastighetsberoende kraft och en förskjutningsberoende elastisk reaktionskraft som gör dem användbara för ”påstick på rör”-applikationer där de naturligt kan integreras i elastiska förband. Renodlade viskodämpare ger däremot enbart en hastighetsberoende kraft och kan därför inte bära någon statisk belastning. Det gör dem därför perfekta för åtgärder mot resonanta rörsystem eftersom de inte förändrar någon övrig dynamik samtidigt som de responderar på excitationer utan någon fördröjning.

Det här projektet har samlat in erfarenheter av vibrationsdämpande komponenter från de fem nordiska kärnkraftverken (TVO, OKG, FKA, RAB, Fortum Loviisa). Tillsammans med konsulterfarenhet hos Efterklang® inom process- och kärnkraftsområdet har underlag anskaffats för att skriva denna rapport. Erfarenheter från kärnkraftverken erhölls från intervjuer med vibrations- och underhållsspecialister vid kraftverken. Som grund för intervjuerna användes en enkät där frågorna har grupperats i sektioner.

Rapporten belyser kärnkraftverkens dämparerfarenheter för rörsystem men beskriver också olika typer av vibrationsdämpare, deras kapacitet, design och behov av underhåll etc.

Följande slutsatser kan dras:

Genom införing av modal dämpning i form av viskodämpare och viskoelastiska dämpare erhålls ett rörsystem som har:

a) Högt motstånd mot transienta vibrationer till exempel orsakade av tryckpulsationer i rörsystemet.

b) Övergång från ett onormalt driftläge till normal drift utan återställningstid.

c) Verkar förlåtande för överbelastning.

d) Verkar vibrationsdämpande i alla frihetsgrader.

e) Minskat underhåll jämfört med traditionella vibrationsdämpande åtgärder tex. snubbers.

f) Snabbare avklingning av otvingade vibrationer.

g) Förlängd utmattningslivslängd pga. minskade spänningar och töjningar orsakade av resonanta vibrationer.

h) Tillåter långsamtgående rörelser till exempel termiska expansioner.

Summary

A viscous fluid such as honey does not flow readily, it has a large viscosity. A viscous flow requires energy dissipation. Zero viscosity requires no energy to flow. This means that a viscofluid can convert vibration energy to heat and as a result reduce vibration response.

In this report main focus is on vibration dampers uses energy dissipation caused by a hysteresis loops between loading and unloading of different materials. Among these dampers especially viscodampers are frequently used at the NPPs pipe systems.

Control of pipe vibrations by viscous and/or viscoelastic materials are most suitable where there is a resonant problem in the pipe system. Normal material damping is small for conventional steel and aluminum constructions, loss factor ~0.01 %, but there are special damping materials that can have material loss factors as high as 300 %. Designing such materials into a damper the damping controls the response at resonance.

Viscoelastic dampers provide both a velocity dependent force and a displacement-dependent elastic restoring force which makes them useful for small bore applications on pipes where they can be incorporated in bracing members. Pure viscodampers provide just a velocity dependent force and cannot bear any static load and make them perfect for resonant pipe vibration without effecting any reinforcements into the pipe system. Both types respond without clearance, time delay, or minimal response deflection.

This project has gathered experience from five Nordic nuclear power plants (TVO, OKG, FKA, RAB, Fortum Loviisa) together with Efterklang® consulting experience in process and the nuclear field used to write this report. Experiences from the five nuclear plants were obtained from interviews with vibration and maintenance specialists at the power plants. As the basis for the interviews a questionnaire was used in which the questions have been grouped into sections.

The report highlights NPPs dampers experiences for pipe systems but also describe different vibration damper types, capabilities, design and maintenance issues etc.

The following conclusions can be drawn:

By adding modal damping to the pipe system by mounting viscodampers and viscoelastic dampers, the pipe system obtains:

a) High resistance under shock load

b) Transition from an emergency case to normal operation with no recovery time

c) Permissibility of overloading

d) Reaction in all degrees of freedom

e) Limited maintenance compared to traditional snubbers.

f) More rapid decay of unforced vibrations

g) Faster decay of freely propagating structure-born waves.

h) Reduced amplitudes at resonance of structures subject to steady periodic or random excitation with accompanied reduction in stresses and increases in fatigue life.

i) Allow for slow movements (i.e. for instance due to thermal effects).

List of content

List of abbreviations

B	Bulk Modulus
BWR	Boiling Water Reactor
c	Speed of Sound in Fluid
d	Damping resistance
D	The amount of energy dissipated per cycle of loading per unit volume
CFD	Computational fluid dynamics
E	Modulus of Elasticity
E´´	Lost Energy
E´	Reversible Energy
EMA	Experimental Modal Analysis
F	Forsmark
f	Frequency
G	Shear Modulus
FE	Finite Element
FEM	Finite Element Method
FEMA	Finite Element Modal Analysis
FKA	Forsmarks Kraftgrupp AB
L	Loviisa
LVDT	Linear Variable Differential Transformer
NPP	Nuclear Power Plant
O	Oskarshamn
ODS	Operational Deflection Shapes
OKG	Oskarshamns Kraftgrupp AB
OL	Olkiluoto
PWR	Pressurized Water Reactor
Q	Amplification factor
R	Ringhals
RAB	Ringhals kraftgrupp AB
rpm	Revolution per minute

RPV	Reactor pressure vessel
SBC	Small Bore Connections
SSM	Statens Strålskydds Myndighet
TVO	Teollisuuden Voima Oyj
v	Fluid velocity
VEM	Viscoelastic Material
VVER	Vodo-Vodyanoi Energetichesky Reaktor; Water-Water Power Reactor
ε	Strain
μ	Viscosity
σ	Stress
Φ	Phase angle between Stress and Strain
η	Loss factor
ζ	Fraction of critical damping
Φ	Phase angle between stress and strain
ϱ	Density
τ	Shear

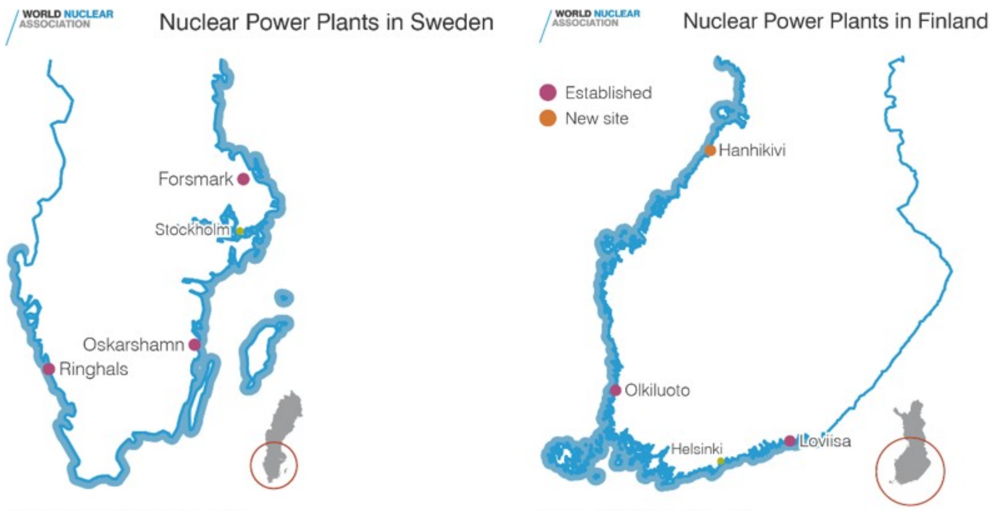
1 Introduction

1.1 OBJECTIVE

The objective of this project is to assemble knowledge and experience in the area of vibration dampers. Problems encountered, that are related to dampers and how they were examined and mitigated, should also be gathered. The information is assembled in this report and can be used to increase awareness of vibration dampers when working with maintenance and quality assurance in an LTO perspective.

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 L)



Source: World Nuclear Association

Source: World Nuclear Association

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

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

- Rami Vanninen (TVO)
- Petri Lemettinen (Fortum Loviisa)
- Kent Andersson (OKG)
- Magnus Adolfsson (FKA)
- Stefan Melby & John Lorentzon (RAB)

1.2 INTRODUCTION TO VIBRATION DAMPING

Damping is dissipation of vibrational energy through conversion into heat.

The use of vibration dampers is to reduce resonant vibrational amplitudes in structures, either to reduce vibrations to increase fatigue life and/or reduce structure born noise has been receiving considerable attention in recent year. This interest is mainly due to a technology that has matured not only in analysis, but also in materials and manufacturing processes. Previously, for most cases, damping has been considered as a last resort because of its complexity. The most commonly used approaches to solve vibration problems are source modification, stiffening modification, mass modification, isolation etc. The complexity of damping is dependent of combining both material and vibration technology to ensure the success of the damping amplification. Since damping is effective only for structures with resonant vibration behavior especially those with low to medium damping values, a good definition of vibration characteristics of the structure is required as a first step before damping can be considered.

There are different sources of damping in a structure. This can come from:

- Sound radiation
- Structure-borne transmission
- Friction (e.g., at joints)
- Finishing materials
- Material damping
- Damping treatments (damping devices and layered treatments)

In this work the main focus will be towards material damping with focus on the viscoelastic material damping and damping treatments.

1.3 SCOPE OF WORK

1. Assemble information and reports from the five participating nuclear power plants (FKA, OKG, RAB TVO and Fortum Loviisa).
2. Group the information and documentation into problem areas. Hence the structure of the work shall not be plant specific but focusing on the different problem areas encountered.
3. Available types of dampers and their function including advantages/ disadvantages, maintenance needs including life cycle costs shall be presented. These shall be compared for the different damper types.
4. Make a qualitative risk analysis of how different types of dampers are affected by being installed in a nuclear environment. Factors such as irradiation affecting viscous properties or expected life length should be considered. Other factors that can be included in the analysis if for example that irradiation might make it difficult to perform installation of certain types of dampers and that specific fire requirements can be applied in some environments.
5. Make a technical report with a description of the encountered problems, the applied investigation techniques and mitigation activities related to vibration dampers (if applicable both the chosen mitigation activities and optional analyzed alternatives shall be handled, and the decision tree discussed). Make

use of the established Energiforsk DIAM methodology (Detection Investigation Analysis Mitigation).

1.4 CONDUCTING THE WORK

Efterklang® in house experience from evaluation of vibration dampers together with reports and information from the NPPs were used. Five 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 face-to-face meeting 2020-01-24 with Stefan Melby and John Lorentzon
- OKG face-to-face meeting 2020-01-30 with Kent Andersson, Carl Möller and Thomas Probert.
- TVO face-to-face meeting 2020-02-11 with Rami Vanninen
- Fortum face-to-face meeting 2020-02-11 with Petri Lemettinen
- FKA skype meeting 2020-03-31 with Magnus Adolfsson, Ylva Vidhög, Adnan Qadour and Andreas Andersson.

As a result of the meetings with the five power plants, a summary of their experience of the vibration dampers installations were collected.

All five power plants have a lot in common but also have a lot of discrepancy. The result is described in the following Chapter 4

In conjunction with the meetings, sites were encouraged to share pictures of site-specific vibration dampers mountings to the project, results of damper measures, problems and lessons learned.

2 Vibration problems in piping

2.1 EFFECTS OF DAMPING

Materials are considered to have good damping properties based on their ability to dissipate unwanted vibrational energy into heat. Most engineering structural materials have little damping capabilities and therefore exhibit high resonant vibration levels when excited. Material damping is small for conventional steel and aluminum ~ 0.01 % which is normally used in pipe structure. Friction and non-linearity at interfaces tend to generate damping ~1%. Such damping comes “for free” but is hard to predict.

This level of vibration is affected not only by the damping of the material but also by the structural damping. The two mechanisms of damping should not be confused, because material damping and/or add-on damping devices can be effective only when they are significantly higher than the structural damping.

To illustrate the way damping materials dissipate energy, consider the two extremes of lightly damped systems and highly damped systems. On one hand, the perfectly elastic materials are considered to have stiffness properties without any damping capabilities. Although, this is only an approximation, because such materials actually have some damping properties even though at times it seems too small to be measurable. Such systems exhibit a unique behavior that whenever a load is applied to them and then removed, all the energy stored in the system becomes recoverable. The amount of energy dissipated during deformation by such materials is, for most cases, very small and usually assumed to be zero. On the other hand, there exists a family of materials exhibiting a Newtonian fluid behavior. For such materials, the energy is not recoverable after the application and removal of a load because all the energy is being dissipated into heat. Materials with good damping properties lie in between those two extremes because they possess both stiffness and damping properties at the same time. By adding special damping treatments which uses stiffness and damping properties at the same time, the material loss factor can increase significantly.

2.1.1 Material properties of interest for damping treatment

Two properties are needed to describe the behavior of damping materials to include a stiffness property and a damping property. This is, in contrast to, the single property that describes the behavior of elastic or Newtonian systems.

For an elastic system, the stress, σ, is proportional to the strain, ε, and the constant of proportionality is the modulus of elasticity, E. For a cyclic loading the stress is always in-phase with the strain as seen in Figure 2.

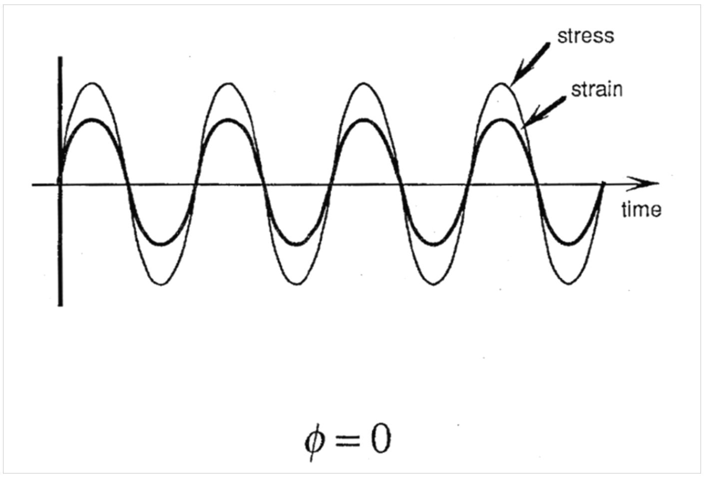


Figure 2: Example of a purely elastic material where stress is proportional to strain and an applied load is completely recoverable. Phase difference, ϕ, between strain and stress is in-phase.

For a viscous system the cyclic stress, σ, is proportional to the rate of strain, ε. The constant of proportionality is the viscosity. In this case the stress is out-of-phase with the strain by 90˚, depending on the specific material and its environment as seen in Figure 3. The complex modulus of damping material is simply defined as the constant of proportionality between the cyclic stress and strain.

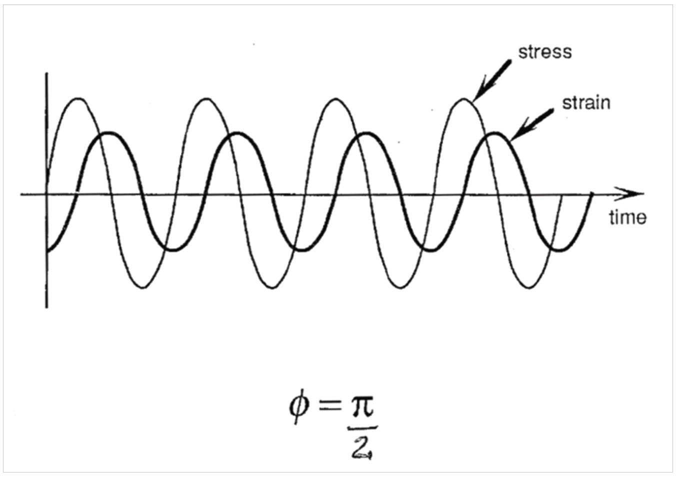


Figure 3: Example of a Newtonian fluid (viscous material) where strain is proportional to rate of stress and none of applied load is recoverable. Phase difference, ϕ, between strain and stress is out-of-phase by 90˚.

A viscoelastic material is a combination of the elastic and viscous properties. The cyclic stress, σ, is proportional to the rate of strain, ε, and the constant of proportionality is both the viscosity and the modulus of elasticity, E. In this case the stress is out-of-phase with the strain by a phase angle between 0˚ and 90˚, depending on the specific material and its environment as seen in Figure 4.

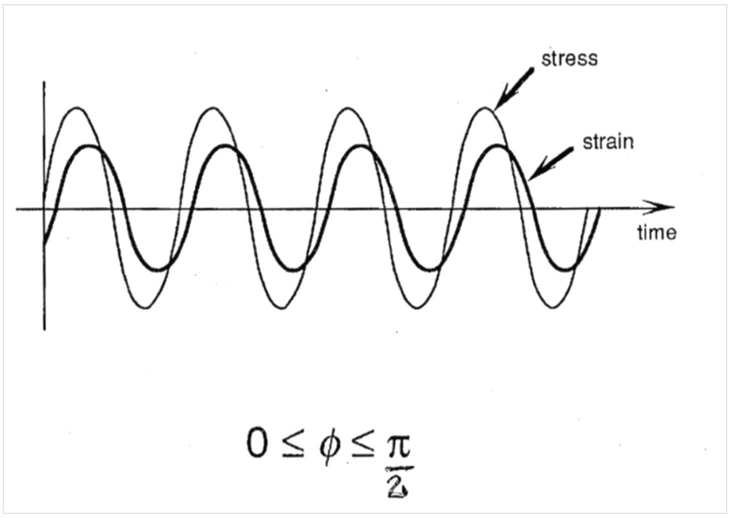


Figure 4: Example of a viscoelastic material which has both elastic and viscous components of modulus. Here some of the applied load is recoverable and some is dissipated as heat. Phase difference, ϕ, between strain and stress is in range of 0-90˚.

2.1.2 Measures of damping Loss factor, amplification factor and fraction of critical damping

When a structure is subject to oscillatory deformations, the structure can be described by the combination of kinetic and potential energy. In the case of real structures, in every deformation cycle, some of this energy is lost and this is called material damping.

A measure on the damping capability is the loss factor, η. The loss factor is defined as the ratio of the lost energy, E´´, to the reversible energy E´ according to Figure 5 and Equation 1.

$$\eta = 2 * \zeta = \frac{1}{Q} = \frac{1}{2 \cdot \pi} \frac{\text{lost energy}}{\text{reversible energy}} = \frac{E''}{E'} = \tan \Phi \qquad \textbf{Equation 1}$$

η: loss factor

E´´: lost energy

E´: reversible energy

ζ: fraction of critical damping

Q: amplification factor

Φ: phase angle between stress and strain

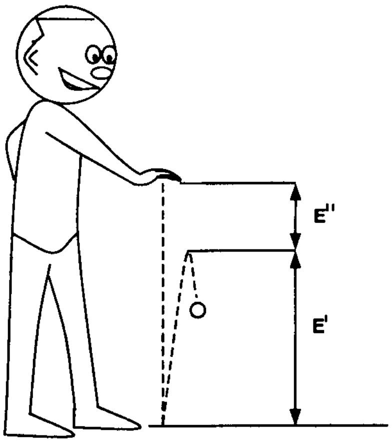


Figure 5: Example of lost energy E´´ and reversible energy E´.

In this report the main focus is put on viscoelastic materials and viscofluids which are the materials used in viscoelastic dampers and viscodampers.

The relationship between the moduli of classical elasticity are carried over to viscoelasticity simply by replacing the real moduli by the corresponding complex moduli. For homogeneous isotropic materials, only three moduli are needed to describe all states of stress, namely Young's modulus E, shear modulus G, and bulk modulus B. These three moduli represent respectively, extensional deformation, shear deformation, and compressive deformation as illustrated in Figure 6. The E- and G moduli deformations represent shape changes without volume changes while the B moduli represents volume changes without shape changes.

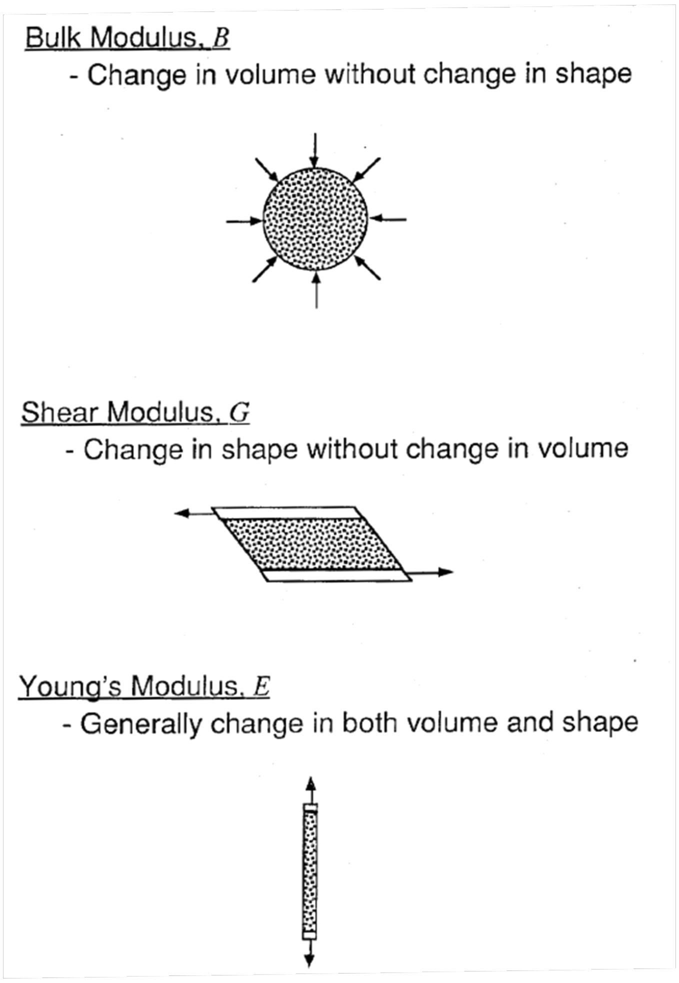


Figure 6: Types of Moduli Bulk, Shear and Young's (tension and compression).

The corresponding complex modulus for Young's and Shear can be expressed in terms of a real (in phase) and an imaginary (out of phase) part for:

$$\boldsymbol{E^{*} = E' + i \cdot E'' = E'(1 + i \cdot \eta)} \qquad \textbf{Equation 2}$$

The in-phase part, E´, is called the "Storage Modulus" and the out-of-phase "Loss Modulus", E´´.

For cyclic stress in a tension/compression deformation, having a peak stress amplitude, σ_0, and a frequency ω with a resulting strain amplitude ε_0 "Storage and Loss modulus" are defined as

$E' = \frac{\sigma_0}{\varepsilon_0} \cos \Phi$ and $E'' = \frac{\sigma_0}{\varepsilon_0} \sin \Phi$.

2.1.3 Energy dissipation

Damping is the conversion of mechanical energy of a vibrating structure into thermal energy. If we want to quantify the level of damping in a structure the absorbed energy per cycle must be determined. By plotting the instantaneous stress versus strain for a given cycle of motion the elliptically shaped hysteresis curve is generated. One possibility to quantify the level of damping is to determine the area, D, captured within the hysteresis loop in Figure 7.

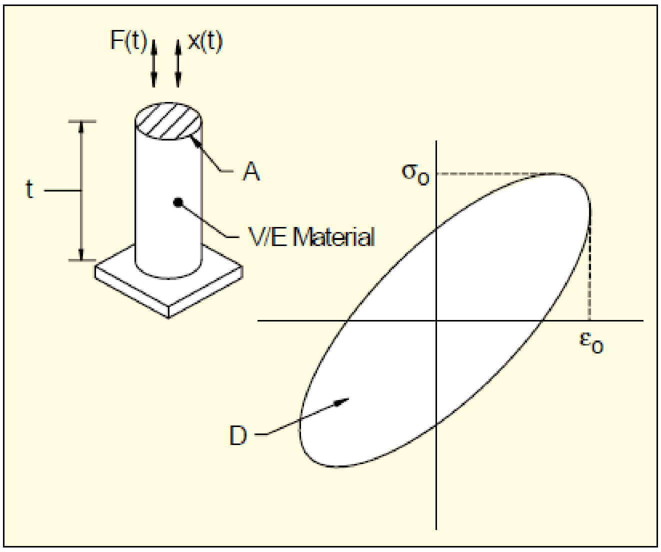


Figure 7: Typical stress-strain hysteresis loop for force-excited SDOF system. Area of ellipse, D, represents level of damping.

The amount of energy, D, dissipated per cycle of loading per unit volume of material is (Lazan, 1968):

$$D = \int \sigma d\varepsilon \qquad \text{Equation 3}$$

Using the complex modulus representation for the material properties, the above integral becomes (for uniform strain):

$$D = \pi E \eta \varepsilon_0^2 \qquad \text{Equation 4}$$

In order to maximize the amount of energy dissipation it is necessary to maximize every term in the above equation. It should be noted here that the product Eη which is the product of the real part of the Young's modulus E and the loss factor η of the material, is basically a material property.

The term ε_0 is the peak amplitude of strain in the material and is a function of the way the material is used. In other words, ε_0 is a property of the treatment. Therefore, using even the best damping materials in an inappropriate configuration will result in a poor damping performance. The opposite is also true, i.e. if the best treatment is used but without an appropriate material, poor results will be obtained. Clearly, understanding the basic characteristics of the properties of damping materials and treatments is very important before an application can be successful.

2.2 VIBRATION SOURCES

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.

Pipe systems may be excited by various dynamic forces from inside or outside during normal operation, as well as in emergency cases. These undesirable loads are due to variety of phenomena, such as valve actuations, pressure pulses and general operational vibrations. Especially in the nuclear power plants, the safety-related piping systems and some other components must be restrained in such a way as to minimize their rapid dynamic displacements without any marked resistance to slow heat expansion. Typical shock restraints that have been used for years for these purposes are mechanical and hydraulic snubbers that lock up at a certain velocity or acceleration, acting at the moment as a quasi-rigid support.

2.2.1 Steady-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.

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

2.2.2 Steady-State periodic vibration

Periodic vibrations in pipe systems occurs whenever we have repeating phenomena such as a reciprocating pump or a repeating pressure pulsation at a distinct frequency.

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.

Example of pipe transient are hydraulic hammers originates often from rapid valve closures, pump start-up/shutdowns, vapor collapses, safety valve blow downs etc.

The estimate of the reacting force F of the pipeline follows:

$$\mathbf{F = \Delta P * A \sim= \rho * c * \Delta v * A} \qquad \textbf{Equation 5}$$

where

ϱ: density,

c: speed of sound in the fluid,

Δv: change in fluid velocity

A: pipe area of impact

2.3 RESONANCE

Dynamic response of a structure essentially depends on three parameters:

- Mass (m)
- Stiffness (k)
- Damping (D)

Mass and stiffness are associated with storage of Kinetic and Strain energy respectively. Damping on the other hand, is related to the dissipation of energy. Damping, in essence, affects only those vibration motions that are controlled by a balance of energy in a vibrating structure. Vibration motions that depend on a balance of forces are virtually unaffected by damping.

However, at resonance, where the excitation frequency matches the natural frequency, the spring and inertia effects cancel each other out and the applied system’s energy (and amplitude) increases until steady state is reached, at which the energy input per cycle is equal to the energy lost per cycle due to damping.

The resonance, ω_n is equal to the square root of the stiffness over the mass as shown in Figure 8.

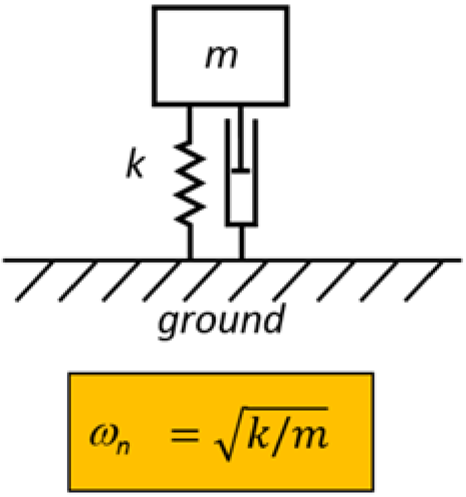


Figure 8: Single Degree of Freedom Mass-Spring-Damper system.

A resonance can be increased by:

- decreasing mass
- increasing stiffness

This holds true for all structures, even more complicated ones.

A 'Spring-damper' modification can be used to alter the stiffness between two points as shown in Figure 9.

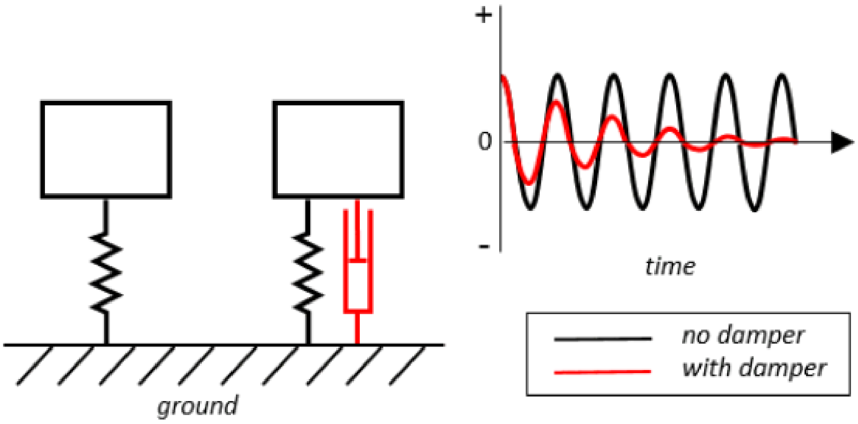


Figure 9: The amplitude over time of a mass-spring system and the change in amplitude over when a damper introduced.

Added damping at resonance frequency results in:

- More rapid decay of unforced vibrations
- Faster decay of freely propagating structure-born waves.
- Reduced amplitudes at resonance of structures subject to steady periodic or random excitation with accompanied reduction in stresses and increase in fatigue life.
- Reduced rate of build-up of vibrations at resonance.

3 Vibration damper types

There are many types of vibration dampers. In this report we will have main focus to passive pipe dampers using a damping material which increases the loss factor of the assembled structure. However other standard vibration damper types will also be mentioned and described.

Most structures receive its damping ´by accident´ which means that damping is not a controlled parameter in the design phase. Normal material damping is small for conventional steel and aluminum, with a loss factor of ~0.01 %, but there are special damping materials can have material loss factors as high as 300 %. Designing such materials into a damper, see Figure 10, the damping controls the response at resonance. A successful designed damping device can increase the damping by a factor "X" reduce stress, noise and vibration by a factor "X". Therefore, guessing the damping wrong by a factor "X" implies that your design is off by a factor "X".

Thus, increasing damping reduces dynamic fatigue.

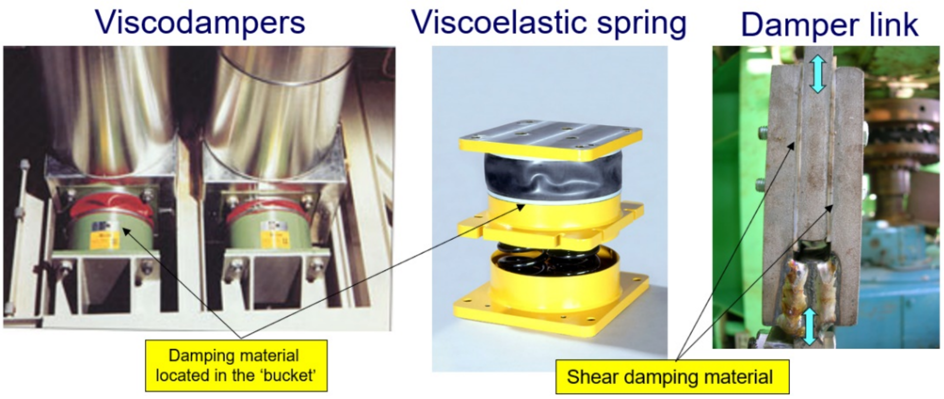


Figure 10: Example of different dampers which use a shear damping material which increase loss factors to assembled structure.

The viscodamper in Figure 10, left picture, is the most common pipe damper to control pipe vibrations at resonances below f=50 Hz at the NPP's.

Viscoelastic dampers may also be used in connection with spring devices, see Figure 10, middle picture, e.g. for the base isolation of a heavy equipment foundation in plant installations. In this case, they will help to reduce the high oscillations rising while passing through the resonance range in the start-up phase of the equipment.

The viscoelastic damper link, Figure 10, right picture, can be used to small bore pipe application, i.e. valves, where the pipe element is subjected to a high cycle fatigue in a frequency range of 10-1000 Hz.

3.1 AVAILABLE DAMPERS – PASSIVE AND ACTIVE DAMPERS

Vibration dampers are broadly subdivided into two groups based on the requirement of external power supply: passive and active dampers.

Passive dampers commonly include passive elements such as metallic or non-metallic springs, viscous and friction-based dampers and pneumatic/hydraulic elements etc.

On the other hand, active damping is less common in industrial applications and includes dampers such as active hydraulic network, electromagnetic damper, sensors and control systems. Due to requirement of external power supply for the active dampers this makes them unappropriated for NPPs where redundancy is of main concern.

3.1.1 Passive Dampers for piping

Viscodampers, see section 3.2, are comparable with mechanical and hydraulic snubbers. However, they are more favorably priced and give a number of technical advantages. For example, they react simultaneously in all degrees of freedom, restrict operational vibrations and require almost no maintenance. However, they cannot take any static load.

The use of snubbers (also called shock absorbers) is preferred in thermally operating piping systems. In a dynamic event, snubbers instantaneously form a (nearly) rigid restraint between the protected component and the structure. Resulting dynamic energy can, instantly, be absorbed and harmlessly transferred while the operational slow displacements due to thermal expansion and contraction must not encounter any noticeable resistance. Through this special function of the shock absorbers, thermal displacements during normal operation remain unhindered (offers very little resistance to pipe movement). However, when a sudden impact load act upon the snubber an internal braking device engage, thus controlling the movement of pipe. Snubbers is said to be “lock up” and in this condition the snubber acts as rigid restraint. When the load has dissipated, the snubber unlocks and again allows gradual movement of the pipe. Depending on the internal working mechanism of snubbers they are divided in two types:

1. Hydraulic Snubbers
2. Mechanical Snubbers

Similar to an automobile shock arrestor the hydraulic snubber is built around a cylinder, see Figure 11, containing hydraulic fluid with a piston that displaces the fluid from one end of the cylinder to the other.

Figure 11: Pipe system secured with snubbers

Displacement of the fluid comes from the movement of the pipe causing the piston within the cylinder to move resulting in high pressure in one end of the cylinder and a relatively low pressure in the other. The velocity of the piston will dictate the actual pressure difference. The fluid passes through a spring-loaded valve, the spring being used to hold the valve open. If the differential pressure across the valve exceeds the effective pressure exerted by the spring, the valve will close. This causes the snubber to become almost rigid and further movement or displacement is substantially prevented.

The hydraulic snubber is generally used when the axis of restraint is in the direction of expansion/contraction of the pipe. The snubber is therefore required to extend/retract with the normal operation of the pipe work. The snubber has low resistance to displacement/movement at very low velocities. The resistance to normal thermal movements (pipe velocity less than 1 mm/s and with amplitude of vibration less than 3 mm/s) is less than 2% of the rated load of the snubber.

Mechanical snubbers are used for the same application as the hydraulic snubbers. It's retardation of the pipe motion is due to centrifugal braking within the snubber. A split flywheel is rotated at high velocity which causes the steel balls to be forced radially outwards. The flywheel is forced apart by the steel balls causing braking plates to come together thus retarding the axial movement/displacement of the snubber. Rotation of the flywheel is generated by the linear displacement of the main rod acting on a ball-screw or similar device.

Mechanical snubbers are used in cases of applications where human access is restricted, for instance due to high radiation atmosphere in the nuclear plant.

3.1.2 Active dampers

Sometimes the range of excitations is too wide, or the problem area is too constrained to design a passive isolation system. In active vibration control, the response of the structure is measured with a transducer. The response information is received by a control system, for example a PID-controller, which commands the actuator to provide a counter force on the structure. Active systems consist of an actuator with reaction mass and a control unit with a sensor, see Figure 12.

Structural vibrations are continuously detected in order to generate damping forces, which in return reduce the vibrations of the structure.

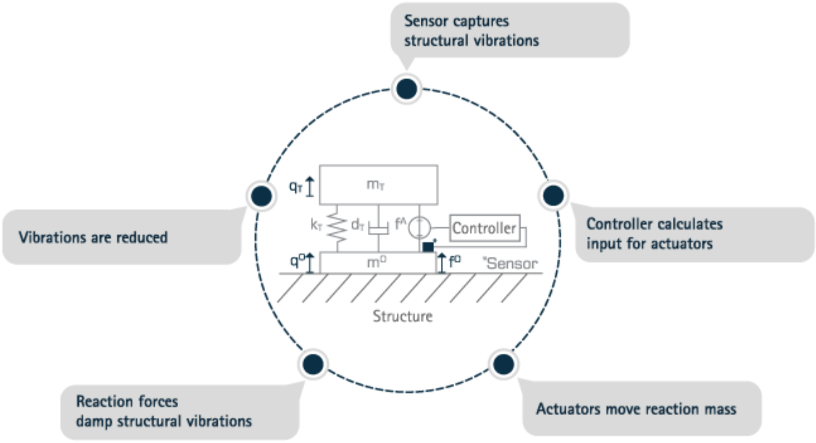


Figure 12: Example of an active damper system for a tuned mass damper

The actuator can be a hydraulic piston, a piezoelectric device or an electric motor. Active vibration control can provide better, and more adaptable vibration mitigation compared to passive methods, but it is a significantly more expensive mitigation method, more difficult to implement and potentially less reliable. However, in some cases it can be the only option. (Inman, 2007, p. 443-445.)

3.2 VISCOUS DAMPERS

These standard products work with relative deformation in six degrees of freedom, i.e. all linear and torsional vibrations, between a piston and a housing filled with viscous liquid, see Figure 13.

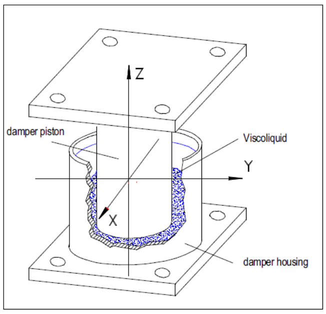


Figure 13: Viscodamper

The main suppliers for these are GERB and VICODA.

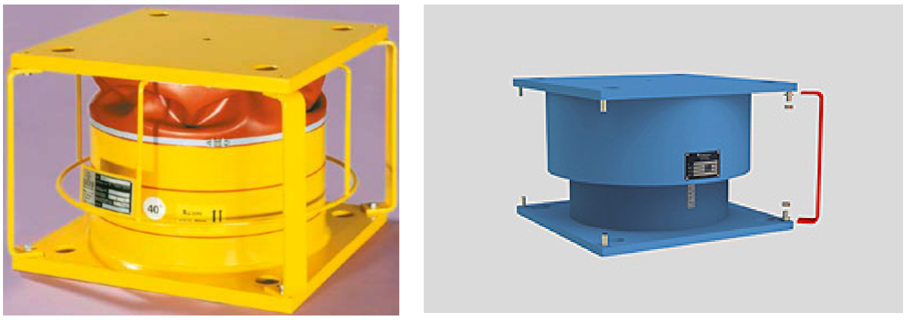


Figure 14: Viscous dampers, left picture from GERB and right picture from VICODA.

To really understand how a viscous damper works, we need to first explain what shearing is. Shearing itself can be described as the normal force resisting movement. In fluid mechanics, shearing (τ) is equal to the viscosity (μ) multiplied by the change in velocity per distance as described in Equation 6.

$$\tau = \mu * [dv/dy] \qquad \textbf{Equation 6}$$

The greater the viscosity the greater the shear force and secondly, as the change in velocity increases, so does the shear force (note, it is the rate of change in velocity, not the velocity itself).

In the viscodamper the fluid in-between the piston and the housing experience a shear force that opposes the cyclic motion and helps to dissipate the vibration energy as heat.

These products are efficient up to approximately 50 Hz, with deformation amplitudes above approximately 0.1 mm for nominal loads up to 100 kN. It comes in a number of sizes and with viscous liquids that either is designed for a narrow temperature, or less highly damped versions that are more temperature tolerant. Viscodampers often use ‘bitumen’ or silicone oil as damping fluid. These damping media has different characteristic depending on temperature and nominal loading, see 3.2.1

Figure 15: The silicone/bitumen can be extremely thick, and viscosity depends on temperature. In picture silicone folds back and forth on itself almost like a ribbon. This is an example of high viscosity.

To use such a standard product efficiently, one must analyze the structure with the damping elements represented physically at the locations you design with.

As viscodampers without spring elements do not support any static loads they have to be used in combination with other support elements, as spring hangers, gliding bearings etc.

3.2.1 Supplier VICODA and GERB types of Viscodampers

When comparing different suppliers for viscodampers there are main interest of comparing damping resistance [kNs/m] at nominal load for desired operating temperature.
At the NPP’s, GERB viscodamper type VES is the most commonly used. Therefore, a comparison to its competitor VICODA type VD is made in this section.
The damping resistance is defined as the ratio between maximum damping force and maximum velocity. This value is frequency dependent and best describes the dissipative properties of the viscous elastic dampers.
Another quantity is the equivalent stiffness which is defined as the ratio of maximum damping force and maximum displacement. This value is frequency dependent and is used in calculation programs that cannot work with velocity proportional damping values.

Vicoda offers three main types of viscodampers (specifications from VICODA data sheets)

VICODA type VD with bitumen based fluids, allowing high damping parameters (up to damping resistance = 554 kNs/m at 5 Hz) for operational temperatures +20°C to +80°C in a limited temperature range of Δ T=10°C.

VICODA type VM with polybuten based fluids, allowing medium damping parameters (up to damping resistance = 416 kNs/m at 5 Hz) for operational temperatures from -10°C to + 40°C.

VICODA type VL with silicone oil-based fluids, allowing lower damping parameters in a wide range of operational temperatures from -30°C to + 110 °C.

GERB viscodampers are categorize the following four types (specification from GERB data sheet):

GERB type VES for nuclear facilities according to KTA guideline 3205.3 und TÜV performance specification. (Dampers type VRD are identical in construction but will be delivered without tests and documentation). These are supplied with damping fluids for 20 °C, 30 °C, 40 °C, 50 °C, 60 °C and in special cases for 70 °C and 80 °C.

GERB Type RRD and RRD..TU for conventional power plants and chemical facilities. These are applicable for operating temperatures between - 30 °C and + 130 °C.

GERB Type RHY for general industrial applications. These are applicable for operating temperatures between - 10 °C and + 40 °C.

GERB Type VD..TU approved by VO Bezopasnost (Russian Nuclear Regulator) for the protection of pipes and components especially in case of earthquakes.

Depending on the application and temperature range GERB is using different damper designs and damping fluids. However, GERB does not reveal which viscous fluid they are using but can deliver safety material data sheets upon request. Their model VES are performance tested by the German TUV for use as standard part in nuclear power plants which often facilitates the administration of introducing a new product in the plants.

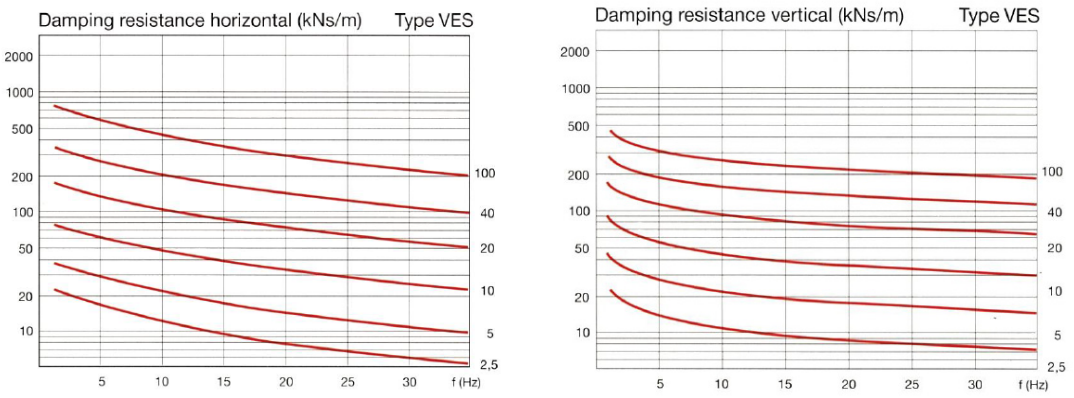
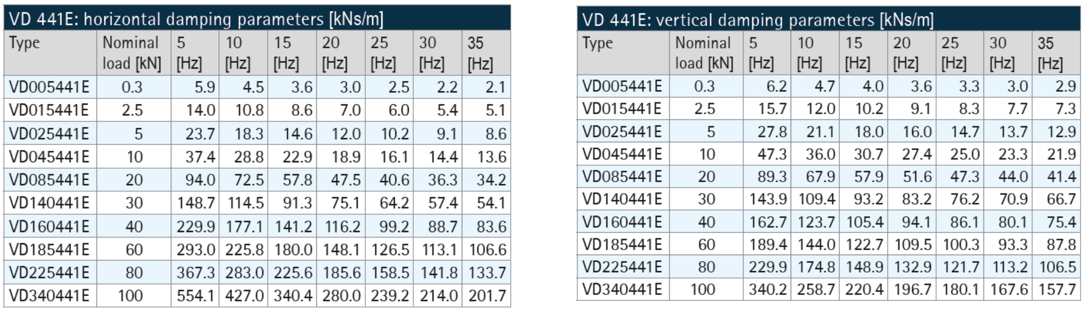


Figure 16: Difference between horizontal (left) and vertical damping (right) resistance [kNs/m] of GERB viscodamper type VES. Nominal load from 2.5 -100 kN and



VD 441E: horizontal damping parameters [kNs/m]

Type	Nominal load [kN]	5 [Hz]	10 [Hz]	15 [Hz]	20 [Hz]	25 [Hz]	30 [Hz]	35 [Hz]
VD005441E	0.3	5.9	4.5	3.6	3.0	2.5	2.2	2.1
VD015441E	2.5	14.0	10.8	8.6	7.0	6.0	5.4	5.1
VD025441E	5	23.7	18.3	14.6	12.0	10.2	9.1	8.6
VD045441E	10	37.4	28.8	22.9	18.9	16.1	14.4	13.6
VD085441E	20	94.0	72.5	57.8	47.5	40.6	36.3	34.2
VD140441E	30	148.7	114.5	91.3	75.1	64.2	57.4	54.1
VD160441E	40	229.9	177.1	141.2	116.2	99.2	88.7	83.6
VD185441E	60	293.0	225.8	180.0	148.1	126.5	113.1	106.6
VD225441E	80	367.3	283.0	225.6	185.6	158.5	141.8	133.7
VD340441E	100	554.1	427.0	340.4	280.0	239.2	214.0	201.7

VD 441E: vertical damping parameters [kNs/m]

Type	Nominal load [kN]	5 [Hz]	10 [Hz]	15 [Hz]	20 [Hz]	25 [Hz]	30 [Hz]	35 [Hz]
VD005441E	0.3	6.2	4.7	4.0	3.6	3.3	3.0	2.9
VD015441E	2.5	15.7	12.0	10.2	9.1	8.3	7.7	7.3
VD025441E	5	27.8	21.1	18.0	16.0	14.7	13.7	12.9
VD045441E	10	47.3	36.0	30.7	27.4	25.0	23.3	21.9
VD085441E	20	89.3	67.9	57.9	51.6	47.3	44.0	41.4
VD140441E	30	143.9	109.4	93.2	83.2	76.2	70.9	66.7
VD160441E	40	162.7	123.7	105.4	94.1	86.1	80.1	75.4
VD185441E	60	189.4	144.0	122.7	109.5	100.3	93.3	87.8
VD225441E	80	229.9	174.8	148.9	132.9	121.7	113.2	106.5
VD340441E	100	340.2	258.7	220.4	196.7	180.1	167.6	157.7

Figure 17: Difference between horizontal (left) and vertical (right) damping resistance [kNs/m] of VICODA type VD. Nominal load 0.3-100 kN.

Both Gerb viscodamper type VES, see Figure 16, and Vicoda VD viscodamper, see Figure 17, generally show a higher damper resistance in horizontal direction compared to vertical direction for the load range 2.5-100 kN. As a result, the damping performance must be higher in the horizontal direction compared to vertical direction for the standard viscodampers. This means that you cannot expect uniform damping capabilities in all preferred directions.

Note that, due to different viscous liquids between the two suppliers the difference in damping resistance between the Vicoda VD and GERB VES. For the horizontal direction Gerb type VES gives roughly 5-20 % higher damping resistance at 5 Hz depending on load range, but for the vertical direction Vicoda VD and GERB are dynamically equal.

3.3 VISCOELASTIC DAMPERS

One efficient way of using viscoelastic material is to apply it as a structural shearing element, either between plates as a damping over an area, or as a more concentrated link between locations of relative deformation.

To obtain high damping, the viscoelastic material must be given the right level of shearing strain, not too little, not too much, and the dynamic stiffness of the damper must be in correct proportion to the stiffness of the connecting structure. A requirement for effective damping of structures is that the damping material must be applied such that it takes up a significant portion of the dynamic strain energy. Hence the thickness and the size (area) must be adapted to the vibration magnitudes and dynamic stiffness of the structure in question.

Figure 18: Damper link with Small Bore Fitting (SBF) bracing with glued saddle plates

Since damping is usually best achieved when the damping material is subjected to large cyclic deformations, the location of the damping material on the vibrating structure is important. Therefore, a knowledge of the vibrational mode shapes of interest is necessary to determine the location where the maximum bending stresses occur.

3.3.1 Single layer viscoelastic damper

The shear deformation in the viscoelastic layer is the mechanism by which the energy is dissipated for a constraining-layer type of damping treatment. To illustrate this case further, consider two extremes of the middle layer damping properties shown in Figure 19.

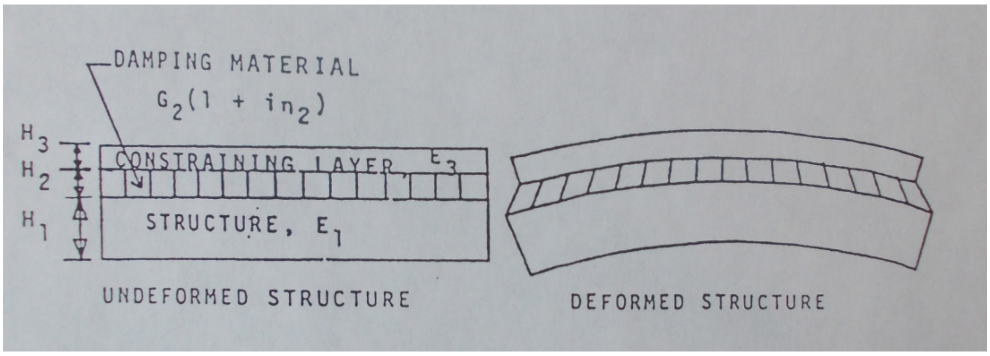


Figure 19: Constrained layer damping treatment

At low temperature, where the material is in its glassy region, both the structure and the constrained-layer become rigidly coupled. In this case, whenever the system is subjected to cyclic bending, little deformation occurs in the middle layer and hence the energy dissipation is also small. On the other hand, at high temperature where the material become almost uncoupled. The energy dissipation in this case is also minimal, even though the shear deformation in the middle layer is low. Between these two extremes, the material possesses an optimal modulus value, so that the energy dissipation for the constrained layer goes through a maximum. The maximum shear deformation in the middle layer is a function of the modulus and the thickness of the constraining-layer, the thickness of the damping layer, and the wavelength of vibration in addition to the properties of the damping material.

The performance of the constrained-layer damping treatment depends to a large extent on the geometry and type of constraining-layer. Usually it is desirable to have the constraining-layer as stiff as possible to introduce the maximum shear strains into the viscoelastic layer. However, the constraining-layer stiffness should not exceed that of the structure. Therefore, the maximum amount of shear strain is usually accomplished whenever the constraining-layer is of the same type and geometry as that of the structure to be damped.

As might be expected, the performance of a constrained-layer damping treatment is only as good as the method of attachment to the structure. Some materials are self-adhesive and therefore can represent some of the easiest and best attachment methods to the structure. However, the majority of constrained-layer damping material are not self-adhesive, and they require fastening to the structure. For most cases, a structural epoxy layer is required.

A general rule of thumb for the adhesive layer between the constrained-layer damping material and the structure is that it be as thin and stiff as possible. Otherwise, if a soft adhesive layer is used between the constrained-layer and the structure, most of the shear deformation will occur in the adhesive layer, detracting from the performance of the damping material.

3.3.2 Sandwiched viscoelastic damper

Multiple constrained-layers are commonly used to increase the damping achieved for a given structural applications.

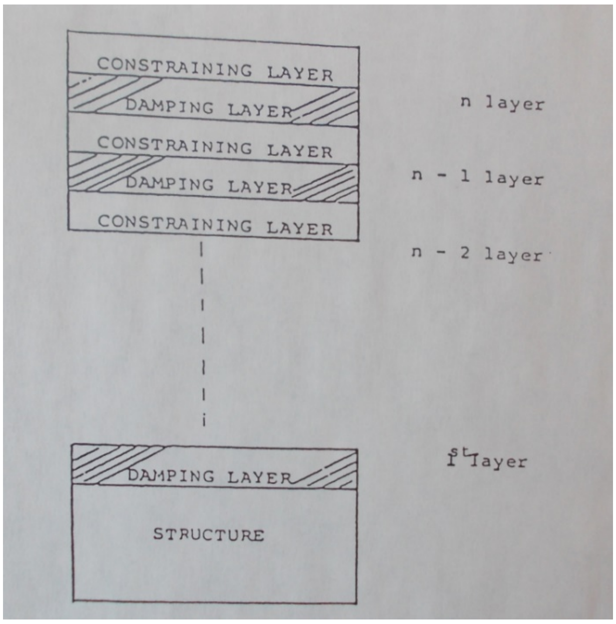


Figure 20: Elements of n constrained-layers on a structure

Usually, by increasing the number of layers, more damping can be introduced for a given mode of vibration. However, as a result of may tests on the performance of multiple constrained-layers, it was found that most of the shear deformation occurs in the first damping layer (closest to the structure). In other words, all subsequent layers work mainly to increase the stiffness of the constraining layer to which the first damping layer is subjected.

Another reason to go for a sandwiched damping treatment is to expand performance with temperature. Figure 21 illustrates the variation of modal loss factor with temperature when two different constrained-layer treatments are applied to each side of the structure. The same effects can be achieved by staking the layers on top of the other as with multiple layers, but to observe thee two different peaks, it will be necessary to utilize damping layers that have considerable different properties, and in the proper stacking sequence.

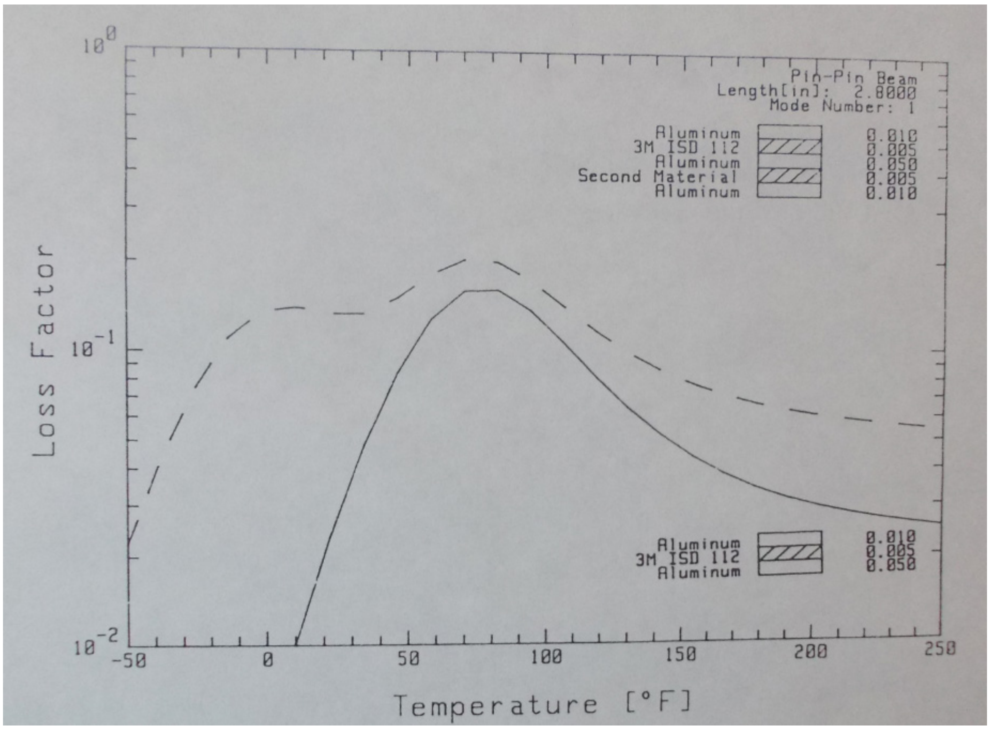


Figure 21: Effects of multiple on the performance of the constrained-layer treatment

Figure 22: A designed (no commercial) damper link to a small-bore application with expanded performance to temperature

A designed sandwich damper links can be used to suppress low amplitude vibration up to higher frequency in a broad temperature range as seen in Figure 22

3.4 FRICTION DAMPERS

Friction dampers dissipates energy of the vibrations through friction. An example of friction damper is the Stockbridge damper, SBD.

The Stockbridge damper, SBD, is composed of a mass part and messenger cable parts, as shown in Figure 23. The messenger cable is comprised of several steel wire strands and can dissipate the energy of the vibration through strand friction. Both sides of the SBD play a different role. The left part of the SBD reduces the *y*-direction vibration of the piping system, while the right part of the SBD suppresses the *z*-direction vibration of the piping system.

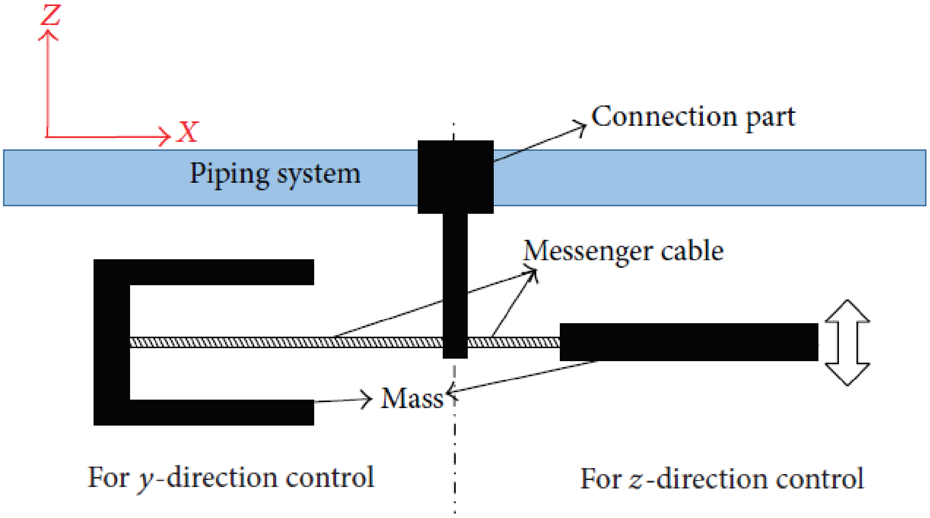


Figure 23: Components of Stockbridge damper

An advantage of the Stockbridge damper is that it is installed directly to the pipeline and require, in comparison to viscoelastic dampers, no rigid abutment to be effective.

3.5 MASS TUNED DAMPERS

The basic design parameters for a mass tuned damper, see Figure 24, are determined by the mass ration between the damper mass, m1, and the mass of the vibrating object, m2. There is a benefit of greater mass ratio which increase the damper loss factor. However, for a given damper loss factor there is a value of mass ratio beyond which there is no added benefit. The resonance frequency and the damping loss factor are determined by the viscoelastic properties.

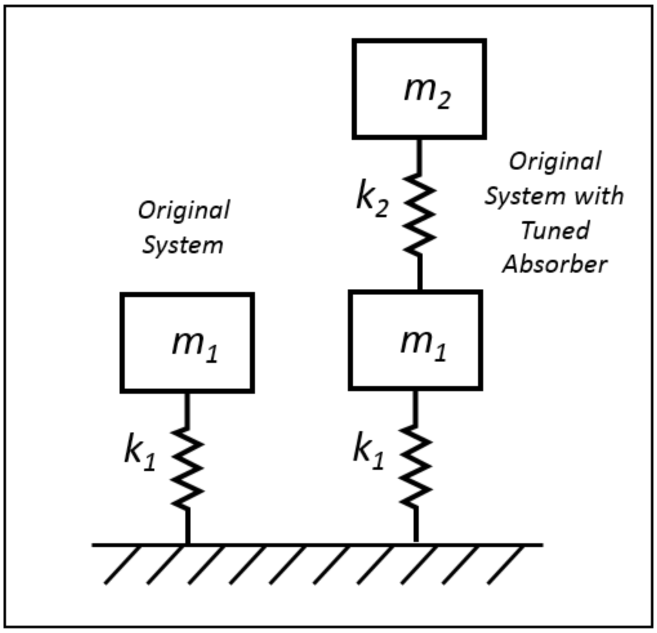


Figure 24: Original system and a modified system with a tuned absorber, tuned with a mass and spring.

A tuned absorber takes the original frequency of the original system and divides it into two modes. The frequency of the first mode is lower than the original system. The frequency of the second mode is higher than the original system as shown in Figure 25.

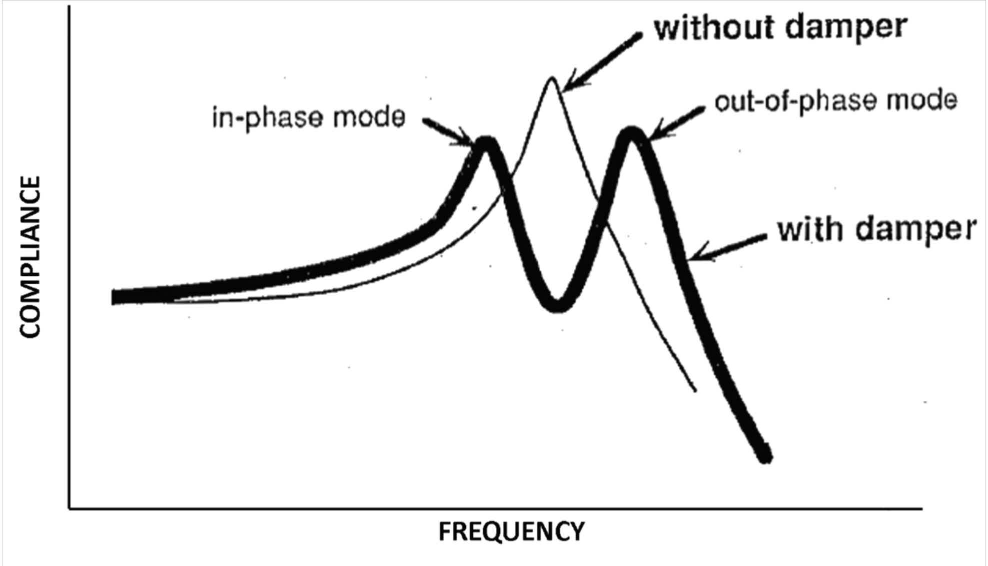


Figure 25: Effect of tuned damper on SDOF system.

The mode shape of the lower frequency would have both the original system mass (m_1) and the tuned absorber mass (m_2) move back and forth *in phase*. The two masses would move back and forth *out of phase* in the higher frequency mode. If the tuned absorber mass and stiffness is carefully selected, the motion on the original system can be forced to zero by the absorber as can be seen in Figure 25.

If not tuned with correct added mass and stiffness to the system, it can be tuned too low or too high as illustrated in Figure 26 with amplification instead of reduction of vibration.

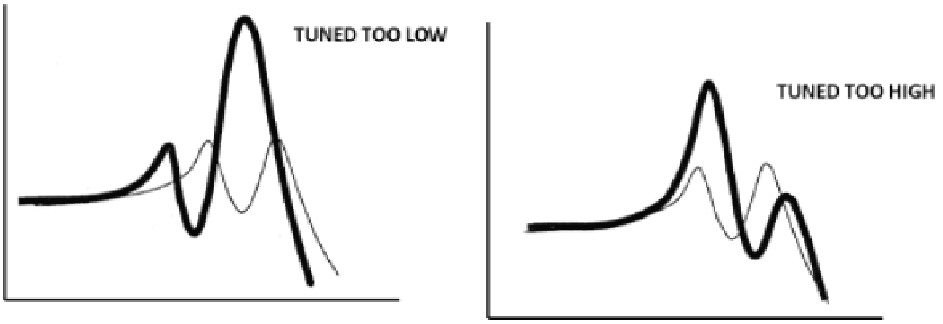


Figure 26: Effect of tuning errors compared to ideal tuned mass damper. Left picture tuned to low. Right picture tuned too high.

A tuned damper can be optimized for best dynamic stiffness at dominant resonance frequency by adding mass and stiffness to the global system. As a result, the vibration reduction at resonance will become optimized but with the side effect that the in-phase and out of phase modes in proximity to the tuned resonance will get amplified, see left picture in Figure 27. For a process with different load ranges this will turn into a problem rather than to a solution. A way to mitigate the problem is to add damping to the tuned system i.e. add mass, stiffness and damping. This will minimize the resonance response to be more broad-banded as can be seen in left picture of Figure 27.

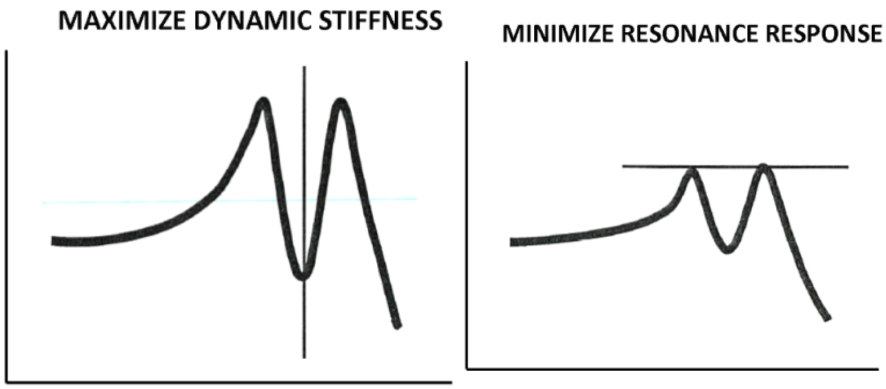


Figure 27: Possible goals, "Maximize dynamic stiffness" or "Minimize resonant response".

When the structural properties change, or there is insufficient installation space for passive tuned dampers, the tuned damper can preferable be transformed into an active device instead. However, none of the NPP's have active dampers installed so this is not a preferred solution.

There are passive mass tuned dampers with minimized resonance response available.

A commercialized mass tuned damper which has been installed at a pump unit at TVO comes from Finish Vibrol Oy. This is a passive non-linear mass tuned damper with a uniqueness to be more broad-banded tunable compare to a regular mass tuned damper. It may be used to reduce vibrations in machinery, engines, pipes and structures on a wide frequency range. It works in three directions and its mass can be varied from 0,1 kg to over 1000 kg depending on the application. (Vibrol, 2018.) An example of mounting is seen in Figure 28. The installation adds damping both lateral and vertical direction.

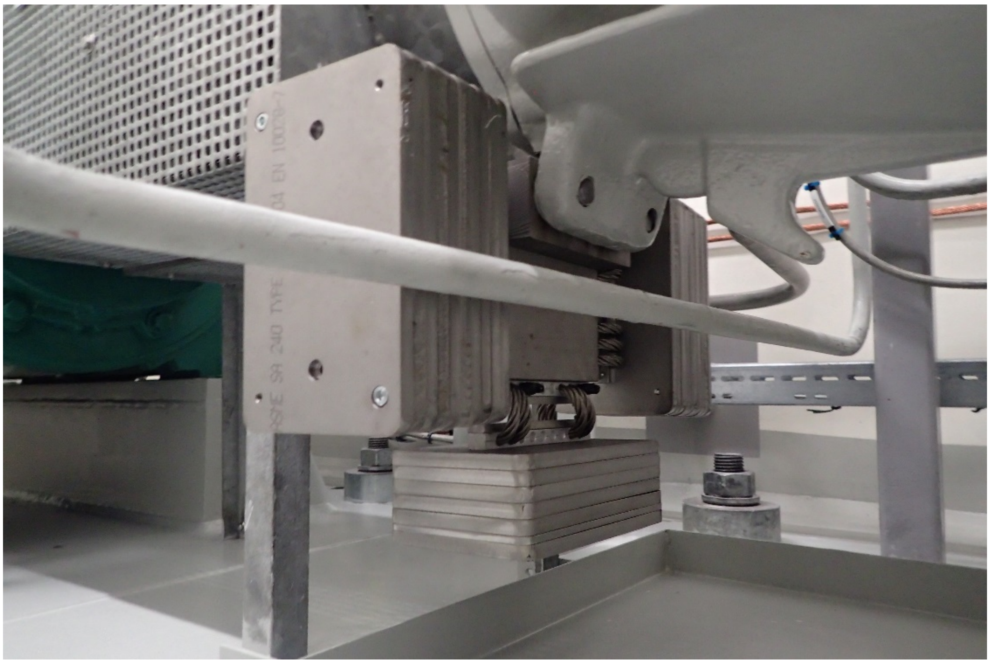


Figure 28: ReKi™ mass tuned damper from TVO.

The principal design of another dedicated passive vibration absorber (TMD, tuned mass damper) for piping consists of a cantilever beam with a concentrated mass at the end, vibrating in a cylinder. The vibration velocities are damped by a viscoelastic fluid within the cylinder as sketched in Figure 29. The bending eigenfrequency depends on the stiffness of the member which in turn depends on the length *L* of the cantilever beam. For tuning purposes this length *L* is adjustable.

For energy dissipation the vibrating mass of the dynamic absorber moves in a highly viscous fluid. The absorber can be attached to the pipe in various positions and the direction of the absorber vibration adapts itself to the motion of the pipe.

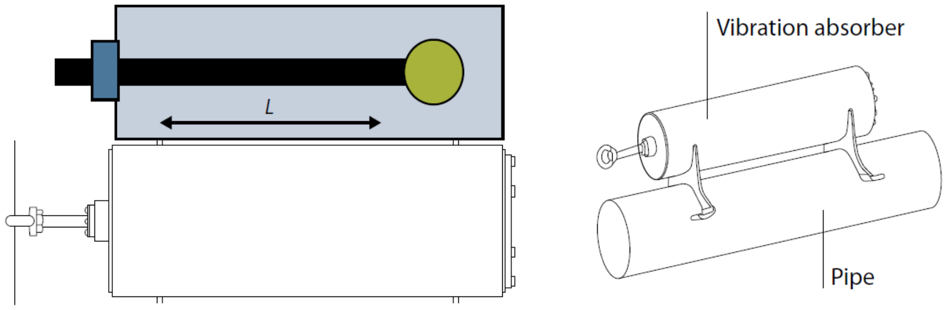


Figure 29: Principal design of an alternative tuned mass damper filled with viscous fluid.

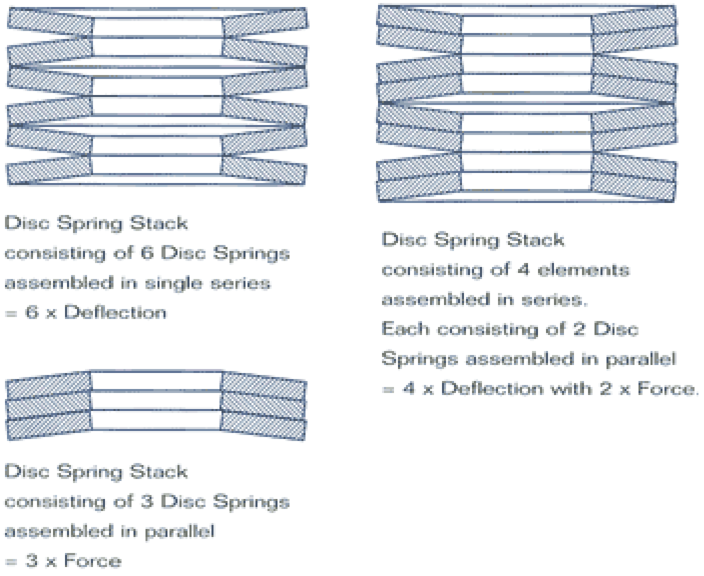
Tuned mass dampers (TMD) are installed directly to the pipeline and require, in comparison to viscoelastic dampers, no rigid abutment.

3.6 YIELDING DAMPERS

Yielding damper can cope with large movements capacity but is not used in the NPP as a damper against pipe vibration. However, they have quite good damping effects which has been experienced by the paper and automotive industry for many years.

They dissipate energy through its plastic deformation (yielding of the metallic device) which converts vibratory energy and consequently declines the damage to the primary structural elements. yielding dampers are economical, effective, and proved to be a good energy dissipator.

An example how they can be arranged is by a disc spring stack with leaf springs can be seen in Figure 30.



Disc Spring Stack
consisting of 6 Disc Springs
assembled in single series
= 6 x Deflection

Disc Spring Stack
consisting of 4 elements
assembled in series.
Each consisting of 2 Disc
Springs assembled in parallel
= 4 x Deflection with 2 x Force.

Disc Spring Stack
consisting of 3 Disc Springs
assembled in parallel
= 3 x Force

Figure 30: Example of disc spring stack arrangements.

3.7 EDDY CURRENT DAMPERS – MAGNETIC DAMPERS

The Eddy Current Damper, ECD, is a passive damper which does not require an external power supply or any other electronic devices. They are used often together with regular vibration dampers to add extra damping where viscous fluid is not suitable due to a big temperature range etc.

The working principle is following:

When a conductive material is subjected to a time-varying magnetic flux, eddy currents are generated in the conductor. These eddy currents circulate inside the conductor generating a magnetic field of opposite polarity as the applied magnetic field. The interaction of the two magnetic fields causes a force that resists the change in magnetic flux. However, due to the internal resistance of the conductive material, the eddy currents will be dissipated into heat and the force will die out. As the eddy currents are dissipated, energy is removed from the system, thus producing a damping effect.

The conductive plate, Figure 31, gets its vibration velocity from the vibration structure and could be attached to for instance a regular spring damper, MTD etc.

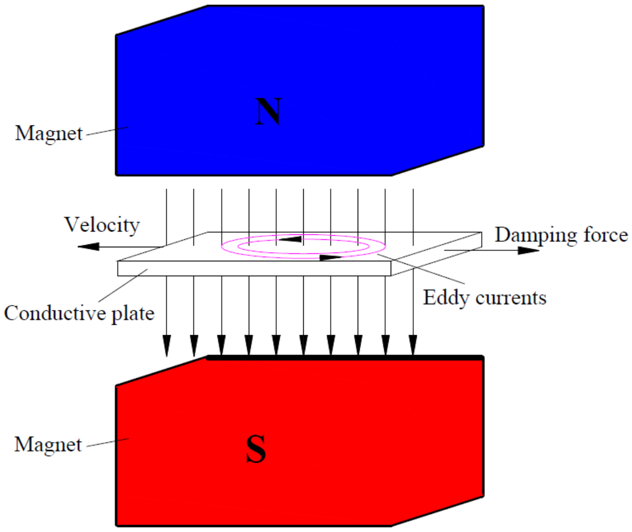


Figure 31: Generation of eddy current damping in a conductive plate.

The strength of the damping depends upon the strength of the magnetic field, the surface area, and conductivity of the conductive plate, and the rate of change of the magnetic flux

The damping force generated by the eddy currents is proportional to the relative velocity, which can be regarded as a linear viscous damping. In the regard of those points, eddy current dampers have been proposed to provide the additional damping for a TMD system.

A commercialized product which adds eddy current damping to a TMD system comes from Vicoda, see Figure 32.

Case study

Passive neutralizing of a compressor aftercooler pipeline

Plant type	Chemical plant
Customer	Origin Energy Limited
Country	Australia
Year	2015
Technical details	Significant vibrations of a compressor aftercooler pipeline (DN250)
VICODA solution	Installation of TMDs Mass 350 kg Natural frequency 6.4 Hz (5.9 Hz) Damping 20 % of the critical damping Vibration amplitude ± 9 mm

Figure 32: Commercialized mass tuned dampers innovated with eddy current damping from Vicoda

VICODA TMDs can be equipped with innovative eddy currant dampers which have a number of advantages compared to conventional damping elements:

- Damping characteristics independent of temperature
- Damping characteristics independent of the shape of the vibrations and thus applicable in different operating states
- High durability, free maintenance and proven reliability due to the contact-free energy transmission

4 NPP vibration damper experience

Interviews of each NPP's vibration specialists has been undertaken during the period January-March 2020 in order to collect the experience and know-how of the use and implementation of vibration dampers in all five NPP sites.

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

The interviews were performed both face to face as well as in digital meeting rooms such as Skype.

The collected experience from the different NPP's show that they are all, at different extent, working both in similar ways as with the same type of damping measures. When it comes to viscous dampers, all are using the Gerb type damper. GERB viscodampers type VES are performance tested by German TÜV for use as a standard part in nuclear power plants and fulfills KTA Safety Standard 3205.3 that makes it possible to install it as a standard product without any SSM approval in nuclear environments. However, SSM has no jurisdiction in Finland. For hydraulic dampers and mechanical dampers the main types are Lisega snubbers and PSA dampers.

There are some differences in perception regarding the expected lifespan of the Gerb dampers. It varies between 20 and 40 years. In addition, it is mostly unknown what the viscofluid composition is but there is an understanding that it is some kind of bitumen-based liquid.

Maintenance of the dampers are similarly performed in the different NPP's. Viscodampers are visually inspected and when needed controlled by vibration measurements while snubbers and mechanical dampers are governed by SSM regulations.

All have positive experience regarding the viscodamper performance, and design and selection processes are very similar.

4.1 RESULT FROM INTERVIEW WITH RINGHALS

4.1.1 About the NPP

Ringhals consists of four reactors and is one of few nuclear power plants to have both boiling water and pressurized water reactors.

The first reactor (R1) is a boiling water reactor, built by Asea-Atom, and has an installed electrical capacity of 881 MW. It began operating commercially in January 1976.

The three remaining reactors (R2, R3 and R4) are pressurized water reactors manufactured by Westinghouse. R2, which has an installed electrical capacity of 900 MW, was in operation between May 1975 and December 2019. R3 has an installed electrical capacity of 1,063 MW and began commercial operation in September 1981 and R4 – with an installed electrical capacity of 1,123 MW – went commercial in November 1983.

Ringhals 1 - Electricity Capacity 881 MWe, Reactor type BWR, Commissioning Year 1976

Ringhals 2 (offline) - Electricity Capacity 900 MWe, Reactor type PWR, Commissioning Year 1975

Ringhals 3 - Electricity Capacity 1,063 MWe, Reactor type PWR, Commissioning Year 1981

Ringhals 4 - Electricity Capacity, 1,123 MWe, Reactor type PWR, Commissioning Year 1983

4.2 TYPE OF DAMPERS INSTALLED

RAB have mostly hydraulic dampers, ‘snubbers’ of brand Lisega and viscodampers of brand GERB installed. 90% of all the snubbers are an oil filled version. They are all installed at piping and the first ones has been in use since 1997.

Ringhals has no mass tuned dampers installed and therefore no experience of this type of damper.

4.2.1 Background to different pipe mitigation countermeasures

Ringhals 3 main steam pipelines, from steam-generator to turbine/compensator has been equipped with viscous dampers of type GERB. These were installed shortly after the change of steam generators in 1996/97.

After this several capacity increases have been done in steps between 1997 and 2011 (8%, 10%, 11% and 13%). The same damper types have been used for each capacity increase without any further tuning efforts.

The selection criteria for viscous dampers at RAB are that the vibration problem has a frequency below 100Hz, and that the pipe system consists of larger pipe dimensions. The vibration type where viscous dampers have been installed have been caused by random pipe vibration.

The snubber dampers, hydraulic dampers (Lisega) are at RAB generally used as countermeasures for water-shocks and valve-closures.

Vibration countermeasures at small bores are made by constructional changes, e.g. adding additional supports.

4.2.2 Design of dampers

The design of dampers at RAB is usually outsourced to the entrepreneur/supplier to fulfill guaranty-requirements, for example at the steam-generator change, Siemens/KVU were responsible for vibration damper installation and design. At the capacity increase 2009-2011, external consultants were contracted for re-qualification of the NPP.

Any FEM/CFD analysis carried out in order to design a damper is outsourced to the main supplier.

4.2.3 Installation examples

The examples below of viscous damper installations in RAB show typical installation examples. Dampers are usually installed supporting the pipe either by supporting beams connected to the roof (Figure 33) or to the wall (Figure 34).

Figure 33: Example of a number of viscous dampers and how they are connected to supporting construction.

Figure 34: Example of one type of viscous damper and how it is connected to the pipe and supporting steel beam.

4.2.4 Maintenance

Regarding control of viscous dampers, it is mainly periodic visual inspection on site and there has so far not been any laboratory or test bench control performed of the viscous dampers. However, the snubbers have been tested at the supplier test bench.

4.2.5 Experiences and lessons learned

The experience made at R3 main steam lines is that the viscodampers are functioning adequately for all relevant and existing load cases. The main purpose of this installation was to dampen the vibrations caused by pressure pulsations or vortex shedding at the steam generators outlet.

When it comes to installation complexity, the pipe system in the reactor unit/system is considered the most complex. However, it is usually here that there are the least vibration issues to handle. The turbine unit and its subsystems are where the majority of the vibration issues are found.

Since Vattenfall has decided that no further capacity increase shall be made at RAB, it can be expected that the vibration issues that might occur in pipe-systems should mainly be caused by wear and tear and component changes.

4.3 RESULT FROM INTERVIEW WITH FORSMARK

4.3.1 About the NPP

Forsmark is the youngest of Sweden's nuclear power plants and was commissioned in the 1980s. Construction began in the early 1970s and the first transport of nuclear fuel reached Forsmark in 1977, but commercial operation was delayed until 1980.

Forsmark 1 - Electricity Capacity 984 MWe, Reactor type BWR, Commissioning Year 1980

Forsmark 2 - Electricity Capacity 1,120 MWe, Reactor type BWR, Commissioning Year 1981

Forsmark 3 - Electricity Capacity 1,167 MWe, Reactor type BWR, Commissioning Year 1985

4.3.2 Type of dampers installed

Forsmark has several types of dampers:

- Viscodampers (Gerb VES)
- Hydraulic dampers, (Lisega snubbers)
- Mechanical dampers, (Pacific Shock Arrestor or PSA-dampers).
- Regular constant hangers and spring hangers installed all over the NPP.

Forsmark have approximately hundred viscous dampers installed at F1, F2 & F3. These are all type Gerb-VES. They are installed at the different system areas for example main steam lines, condenser systems, reheating- and the feedwater system etc.

Hydraulic dampers are installed in all three blocks F1,F2 & F3 and are of many different sizes, but all are Lisega type snubbers. In total, there are approximately five hundred hydraulic dampers installed at Forsmark. They are mainly used as velocity/acceleration restriction dampers i.e. in the turbine system since oil is generally avoided in the reactor enclosure. The snubbers, or hydraulic dampers are installed at the main steam lines, the condenser-and evacuation systems, the condensate, the reheating system, as well as a few at the reactor system.

Figure 35: Example of hydraulic type dampers.

When it comes to mechanical type dampers, they are about 80 of the type PSA (Pacific Shock Arrestor). They are installed at both F1, F2 & F3 and are of several different sizes. They are also installed in F1 and F2 at various reactor systems.

Figure 36: example of mechanical type dampers.

4.3.3 Background to different pipe mitigation countermeasures

At maintenance of F3, large vibrations were discovered in the turbine-hall. The vibrations were verified and compared with earlier made design calculations. The test and calculated result did not coincide. Thereafter, through an iterative process by measurements and update of the calculations with the correct damper points the damper design could be found with great success.

Damping of a factor larger than ten was achieved. See results before and after dampers in Table 1.

Table 1: Vibration levels with and without dampers (mm/s rms).

F3-421 L2	**No damper [mm/s rms]**	**With damper [mm/s rms]**
Measurement Point	**960624 1150 MW**	**970826 1156 MW**
1X	16	4.3
2X	40.8	3.3
3Z	9.8	8.3
4X	8.5	6.5
5Z	24.7	9.5
6Z	9.9	3.7

Another example is the F3 steam line system, see Figure 37. Between the valve and the pump, it was very tight and lack of space. Along the pipe after the pump (flow direction), very high vibrations and pressure pulsations were found. Twenty new viscodampers were, during 1986, installed to resolve the problem.

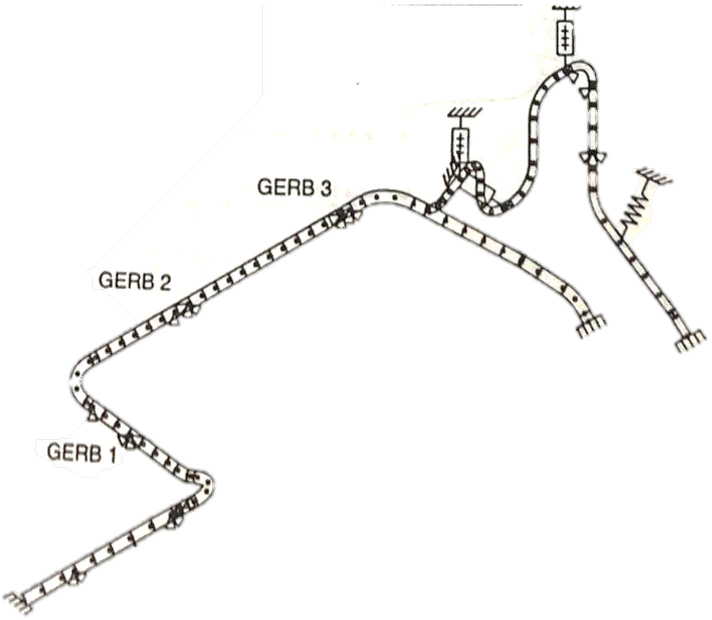


Figure 37: Example steam line in the turbine hall near the turbine on Forsmark 3

As early as in the 80s during F3 commissioning an oilpump/reciprocating pump was found to give pressure pulsations and high vibrations in the piping. Gerb dampers were installed after the condensate pumps on F3 and also in the piping after the oilpump/reciprocating pump. In both cases higher frequencies were damped (pressure pulsations) with good result – not just below as expected 50 Hz.

Also, in F1 and F2, already the first year after commissioning (1983), vibration issue was discovered on the main steam lines on F1 and F2 and spring-mounts and more suspension points were added. During the outage 1992 several damages on the suspension hangers and pipe isolation were discovered and they had to be replaced. The suspensions and piping had been submitted to both vibrations and shocks and the measures taken then was to control the movement of the pipes by installing several stops and stearing plates/glide plates in transversal to the pipeline and in x-y directions. In addition, to further diminish the movements several viscous dampers were installed and after 1 or 2 years the fluid in the dampers were replaced for optimization of the damping effect.

During the same outage in 1992 of F1 and F2 some hydraulic dampers near the turbines were found that had major oil leakage. Some were totally drained from oil and some were mechanically deformed. According to the supplier, Lisega, the root cause was too high vibration levels. Measurements made in 1993 on different load cases showed vibration levels up to 25mm/s. More sensors were mounted to monitor the issue and during the outage 1997 three viscodampers per pipeline were installed as countermeasures and with good result.

Before the capacity increase of F2, the steam lines were equipped with a lot of vibration sensors (three-axial) both in the reactor enclosure as well as in the steam lines outside the enclosure. It was then discovered that some points showed vibration levels that were a bit too high. In the area of 11-12 mm/s at some positions just below the HP turbine after changing to new HP:s. The rest of the steam lines and also in the containment (RI) maintained vibration levels below 8 mm/s rms. Calculations were made, and several more permanent measurement points were added. After that it has been seen that the vibration levels are quite constant and only a couple of dampers have been adjusted since. Most dampers were still working well and could handle the increase of vibrations and did not need replacing.

At outage 2001 at F3 there was a viscous damper that was sent to Gerb (supplier) for changing of the fluid.

4.3.4 Design of dampers

For the design of viscous damper installations both entrepreneurs and in-house expertise have concluded what damper to be used and how it should be designed.

Since the piping temperatures can vary greatly, for instance. at the main steam line, the pipes can be around T=270-280 ˚C, and therefore, when the pipes are isolated, the dampers might be submitted to a room temperature up to T=30-35 ˚C. In addition, the pipe clamps can distribute the heat to the damper, that increase the damper design temperature.

For other areas such as Condensate, a 'normal' room temperature is below T=30 ˚C and for the feedwater system and the Bohr system it is even lower.

For design of dampers at FKA, both measurements and calculations of mode shapes are used. Combining in-house expertise together with suppliers the correct damper design can be done. However, some of the earliest dampers, that were installed when the site was first started, has been discovered to have the wrong temperature span and therefore later had to be replaced.

The number of dampers installed is dependent of the length of the pipeline, for example in F3 there are 3 dampers per pipeline (from the reactor wall to the turbine).

Verification of the damper design is done by measuring the vibration levels before and after installation. There are also, in some cases, a combination of measurements and simulations. Measurements usually performed are vibration level measurements as well as impact testing to check the resonance frequencies before measures as well as after to see if they have changed after damping is applied.

Installation of the dampers are usually a collaboration between the supplier and Forsmark. In the 90's it is probable that Staal constructed the fixtures (clamps) with double fixtures with a welding knob on the pipe to prevent from the fixture to glide.

One example of installation design is the dampers at the steam lines. They are installed at an angle in cold conditions to later be at a correct 'straight' angle in warm conditions. There are also calculations on how large movement each pipe and fixture point should move when the plant is running. It is important to take this into account when designing and installing the damper fixtures.

4.3.5 Installation examples

Visco-damper installation is usually done like the examples showed below in Figure 38 to Figure 41.

Figure 38: Installation example of viscous dampers and supporting structures.

Figure 39: Installation example of viscous dampers and supporting structures.

Figure 40: Installation example of viscous damper and supporting structures.

Figure 41: Installation example of viscous damper and supporting structures.

4.3.6 Maintenance

Viscous dampers:

For the viscous dampers there are no specific maintenance routine except general walk-throughs and visual inspection.

Work to develop such routines are ongoing. The preliminary plan is to regularly change the fluid that is designed to have the right elasticity when a specific operational temperature occurs.

The lifespan of the fluid is according to the manufacturer 30 years (in GERB data sheet 40 years), however the fluid is sensitive to pollution such as water and oil. Therefore, it is vital that the sleeve is intact during its lifespan.

Hydraulic dampers:

The maintenance of these dampers is controlled by the SSM regulations. There it is stated that the dampers are to be functionality checked every ten years. In Forsmark this means that the damper is removed from its position and is replaced with a new damper or renovated. Each year Forsmark replaces approximately 50 hydraulic dampers and the ones that are removed are thereafter sent to the manufacturer for a verification function test. The damper is then renovated and sent back to Forsmark to be used as a replacement part for the next year outage. Besides this functionality check there are continuous visual inspections done were one looks for oil leakage, unnormal wear and tear in connection points etc.

There is also, in the SSM regulations, written that when a new damper is installed it has to be checked for functionality after 3 years. This has been done i.e. for F3 when a couple of new Lisega dampers were installed.

Mechanical dampers:

As for the hydraulic dampers, maintenance is governed by SSM. Every 10 years the damper should be functionality checked. The procedure is the same as for the hydraulic dampers however since many of them are placed in the reactor enclosure and are therefore contaminated by radiation these cannot be sent to the supplier.

A collaboration with OKG has been made where technicians from USA are sent for with their own test equipment and the functionality tests can then be made in Sweden in safe areas. Some of the tests has been done at KG or at Westinghouse.

4.3.7 Experiences and lessons learned

Viscous dampers:

FKA have had good experience regarding the viscodampers. The fact that the damping works in all three directions is much appreciated and has been verified by measurements, at for example F3. The first dampers were installed in the 80’s and there have been very few problems with them.

2007 a couple of viscodampers was found to have ‘’crushed or cracked’’ mass/fluid (see Figure 42 below). After investigation it was found that the fluid was designed for much higher temperatures than was needed and were thereafter changed for correct damper design. The fluid was to stiff and was hardened and crumbled when the pipeline started to move.

At F3 it was discovered in the 90’s that the fluid design temperature was faulty, and it was thereafter changed.

According to the manufacturer the lifespan of the damper is 30 years, but it is sensitive for pollution of the fluid by for example oil or water and it is therefore very important to continuously check that the damper sleeve is intact.

All in all, there has been very few issues with the dampers after installation at Forsmark in the 80's and Forsmark is currently investigating if this lifespan can be considered longer than 30 years.

There is no experience of the sensitivity to radioactivity since no viscoelastic dampers are installed in the FKA reactor enclosure where the radioactivity is higher.

The supplier is very secretive to what material the fluid consists of and there is no clear chemical specification to be found. Despite this it is approved by Forsmark to be used inside the plants.

Figure 42: Example of broken sleeve and cracked fluid of viscous damper.

Hydraulic dampers:

Regarding the Lisega dampers, or hydraulic dampers most of them are installed in the turbine areas. Forsmark has very good experience of using them, however they sometimes have to be replaced due to oil leakage, usually found while doing visual inspection. The trend that is found is that there is more often leakage on piping were there are large vibrations, e.g. the main steam lines. Experience has shown that an oil leakage does not jeopardize the damper functionality directly but can lead to that in the long run. The oil is a silicon-based oil named AK 350 and has a flame point of 300°C and will self-combust at 500°C. The hydraulic dampers are preferred over the mechanical dampers by the construction design department since they are cheaper, easier to get a hold of and more flexible.

In other NPPs there has been reported that there has been fire inside the reactor area due to these dampers. One usually wants to avoid oil inside the reactor enclosure. However, in F3, hydraulic dampers, were installed in the reactor enclosure since they have a silicon-based oil that is approved for use.

The major root cause for replacing the dampers are oil leakage. Approximately two to four dampers are replaced each year. It has been noticed that even with a small amount of oil leakage the dampers are still functioning properly.

Mechanical dampers:

Experience of the mechanical or PSA dampers are that they might freeze or get stuck. They are simply described a rod with a flywheel that spins at slow movements such as thermic expansion but because of the weight of the flywheel it also creates damping at fast movements such as water hammering. According to the supplier, the problem has been that the grease used in the damper has aged and separated and therefore become too stiff for the damper to function properly. It is also possible it is due to heat and high vibrations. The supplier changed to a grease with lower viscosity. After that, these issues have not been noticed.

At very high vibration levels the PSA dampers can be worn at the attachment points. This can be identified as a red dust found at the attachment points and this is something one looks for when visually inspecting the dampers.

Even though the hydraulic dampers are usually preferred, the mechanical dampers will continue to be used on the reactor side to avoid oil inside the enclosure.

Both the hydraulic and the mechanical dampers has been in operation since the start. Approximately ten years back a project was made to change all the hydraulic dampers to a more modern version. However, the mechanical dampers are identical to the ones installed when starting the NPP.

4.4 RESULT FROM INTERVIEW WITH OKG

4.4.1 About the NPP

Three of Sweden's nuclear power reactors are located here; Oskarshamnsverket 1, 2 and 3, owned and operated by OKG. They are generally called units O1, O2 and O3.

These three reactors have a combined installed gross power output of 2,603 MW and at maximum power the reactors account for circa ten per cent of the electricity generation in Sweden. However, a decision on premature shutdown of units O1 and O2 was made in 2015. The decision entails that there will be no future investments at unit O2, and the reactor will not be restarted. On 17 June 2017, unit O1 delivered its final kilowatt hours of electricity.

Unit O3 is with the installed capacity of 1,450 MW one of the largest boiling water reactors in the world and will during its lifetime produce 600 TWh, which is enough for the entire electricity consumption in Sweden for approximately four years.

O3 was commercially started in 1985.

4.4.2 Type of dampers installed

OKG mainly have two types of dampers. Hydraulic dampers of type Lisega for example on the high-pressure turbine and viscous dampers like Gerb but also mass tuned dampers and spring hangers and other bracketing. Approximately 32 viscous dampers have been installed over the years. Some probably from the start of O3 in 1984. On O1 and O2 the oldest dampers were installed in the mid 90's. All of them are of the type Gerb VES.

The viscodampers are of different models, for example VES-20 to VES-100 in O3 and VES-5 to VES-50 in O1.

4.4.3 Background to different pipe mitigation countermeasures

During the season 1988-1989 a limitation of maximum rotational speed was necessary on two HC pumps on Oskarshamn 3 due to high vibrations at high speeds. This affected, for some conditions, the ability to reach the expected output of the reactor.

During the outage of Oskarshamn 3, 1989, an investigation was undertaken with the conclusion that the bracketing of one of the pumps were faulty and had to be modified in order to increase the pumps critical speeds and eigenfrequencies.

The eigenfrequency of the pump motor housing was lower than the equivalent pump speed. Resonance frequencies of all eight HC-pumps were identified using measurements both in warm and cold conditions. They were identified around f=21 Hz in warm conditions and f=12 Hz in cold conditions. By simply tightening all screws of the supporting brackets resonance frequency was changed to f=30 Hz, however the goal was f=35 Hz in cold conditions.

Adding a third bracket changed the resonance to f=32 Hz. Bracket modification was made by ABB Atom as a guarantee issue to increase the system eigenfrequencies. In addition to this, OKG installed two viscodampers on another one of the pumps in order to lower the vibration levels. The results showed that the dampers were more effective in tangential direction than in radial direction (the consoles for the dampers were found to be somewhat flexible in this direction) and that the dampers reduced the amplification factor at resonance from 6 to 2 in tangential direction and to 3 in radial direction.

The dampers were of type Gerb VES-30, which conforms to German TÜV standard for nuclear power plants.

In the mid 90's more viscodampers were installed on the HC pumps. However, first the issue was attempted to be solved using a mass-tuned damper without reaching the wanted result.

1989 an investigation was started regarding the viscodampers previously installed on system 311 and system 314. The dampers did not seem to work as expected since vibration levels were still high. The damper supplier Gerb as well as ABB Atom were involved in the investigation.

Dampers were originally designed for temperatures between T=50-70˚C and temperatures on system 314 were higher than T=70˚C on some damper positions and lower than T=50˚C on all dampers on system 311. That would mean that the dampers did not function properly. According to Gerb the lower temperatures could mean that the fluid loses its grip of the piston and then would move in a hole in the fluid and the damper then loses its function.

It was decided to either change the fluid in the dampers or to increase the temperature in the system so that the damper could work properly.

To change the damper fluid the damper either needs to be removed from the pipe in order to be able to turn it upside down or it is necessary to heat the damper fluid to T=150˚C and then drill a hole in the bottom of the damper and let the fluid pour out. Doing this, it is important to remember to plug the hole before refilling the damper as well as protecting the protective sleeve against the heat since it cannot handle temperatures above T=130˚C.

It was also decided that Gerb would investigate the damper relevant damper fluids more in detail in their laboratory and that temperature measurements should be performed in all the dampers in question.

Gerb test bench measurements of the dampers showed that the dampers should work for the temperatures in specified range and it was therefore concluded that further investigations were needed to better understand the issue. Later in 1990 laboratory tests of dampers were performed for vibration profiles according to measurements in O3, system 311 and system 314. The tests were performed in a test bench at Gerb office in West Berlin. The results of these tests were that the dampers did work as expected, in the for OKG specific vibration frequencies and amplitudes. However, the tested dampers were of different design temperature, since tests were done in room temperature and the "liner/washer" used in O3 was not included in the tests. The conclusion of the tests was that the issues with the lack of damping effect at system 311 and system 314 needed to be investigated further. The dampers had wrong design temperature. The actual temperature was lower than the design temperature. They were to be changed to a correct design by measuring the actual temperature in the fluid during operation.

Further temperature tests were performed to test the temperature and load dependency in a laboratory test rig at Efterklang® for a new damper configuration in system 315 and the main steam lines T11 and T14, see section 6.6. These tests clearly correlated with information received from the supplier.

In Oskarshamn 1 (O1) there was since many years, probably already 1971-72, an issue with high vibrations on pipe system 315. Several investigations have been done over the years and root cause was probably found sometime around 1978. The pipe system connects the auxiliary condenser with the main steam lines (pipe system 311) through the 315 steam lines, and back to the reactor enclosure through the two 315 condenser lines, see Figure 43 below.

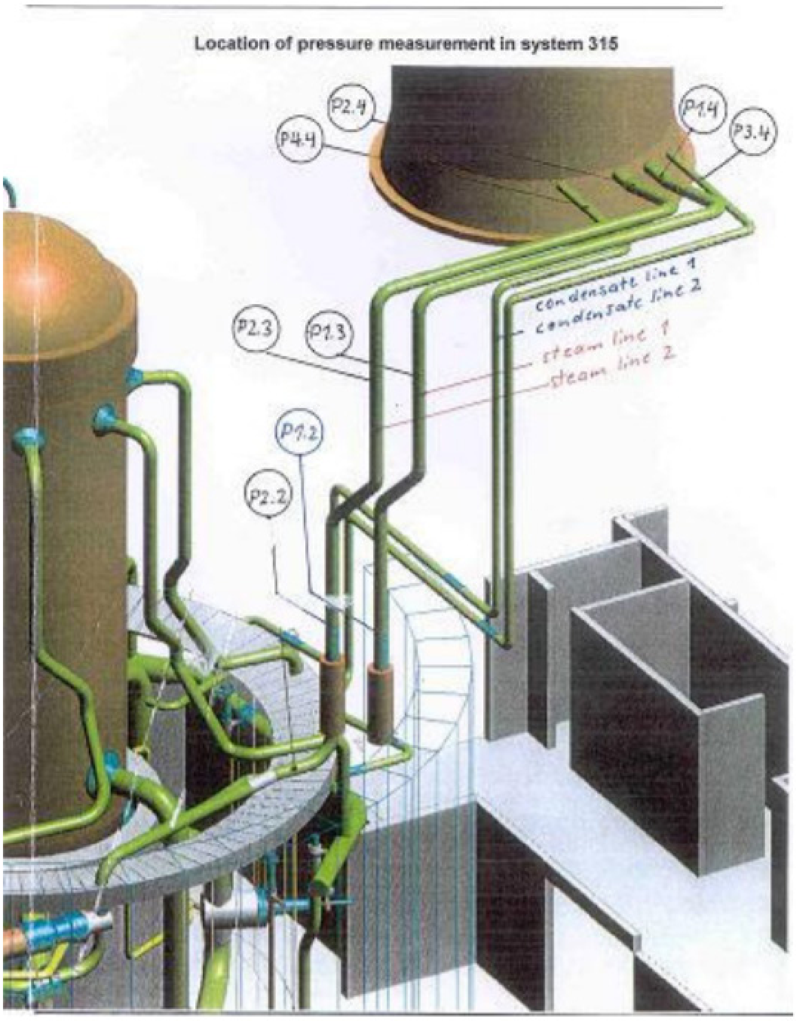


Figure 43 Auxiliary condenser system 315.

The vibration occurred both for normal operation of the plant, where there is no flow through system 315, and also when there is a flow in the system. The vibration problem was subject to many investigations and measurements. These investigations showed that the lines are subjected to resonant bending mode vibration. The bending mode shapes had very little modal damping, in the order of 0.5 to 2.9 % of critical damping, which means that increasing the damping would be an efficient way to attenuate the vibration amplitude.

It was found that the source of the vibrations could be eliminated by closing the valves on the steam lines of system 315, however due to other criteria’s this was not deemed a feasible solution.

The vibrations in normal operation or steady state, were believed to emanate from thermo-acoustic coupling excitation, where heat driven pressure pulses excite acoustic resonance in the system 315. The steam lines are connected to the condensate lines via the auxiliary condenser. The valves on the condensate side are closed. The pressure pulses excite acoustic resonances in the coupled steam and condensate lines, which in turn excite the structural bending mode vibrations.

Root cause was later concluded to be the design of the steam lines in the condenser due to the angle of these. Large angle between the water surface and the piping is optimally designed to get this phenomenon of pressure pulsations.

Vibration velocities measured in normal operation was in the order of 5 - 15 mm/s RMS.

Dominating frequency f=9.5 Hz for the steam lines. Comparison with modal analyses measurements showed that the vibrating steam lines were dominated by the first bending mode. The vibration of the condenser lines showed vibration at f=5 Hz, f=10 Hz and f=30 Hz. Comparison with the modal analyses showed that the first bending mode at f=5 Hz was excited, as well as several higher frequencies.

When measuring during operation of system 315 the initial vibrations were believed to emanate from thermo-acoustic coupling excitation, where heat driven pressure pulses excite acoustic resonance in the system 315. This effect decreases as the system is starting to operate with steady state steam flow. The excitation source will then be emanating from induced forces from the steam flow.

Vibration velocities was measured, for the initial stage, to be as high as 70 mm/s, or even higher. Vibration velocities during steady state steam flow in 315 were measured to be about 10-20 mm/s RMS. Dominating frequencies were around 9.5 Hz for the steam lines. The first bending mode for the steam lines was dominating.

It was concluded that damping needed to be added and viscous dampers were chosen.

A total of twelve dampers of type Gerb VES-5/V40/H40 were recommended to be mounted on the two steam lines. Each steam line to be fitted with

- Two pairs of VES-5/V40/H40 mounted in the ceiling in room 9.59 close to support U964 for steam line no.1 and U965 for steam line no. 2.
- Two pairs of VES-5/V40/H40 mounted in room 7.59 just under the roof.
- Two pairs of VES-5/V40/H40 mounted in room 7.59 as high up as practical, as close to the lower bend on the “knee” as possible.

FEM analysis was made to model the steam line after adding dampers. Figure 44 below shows the steam line no. 2 in the first bending mode after installation of viscous dampers. The blue element lines represent the undeformed model, and the green lines the deformed mode shape at the first bending mode frequency.

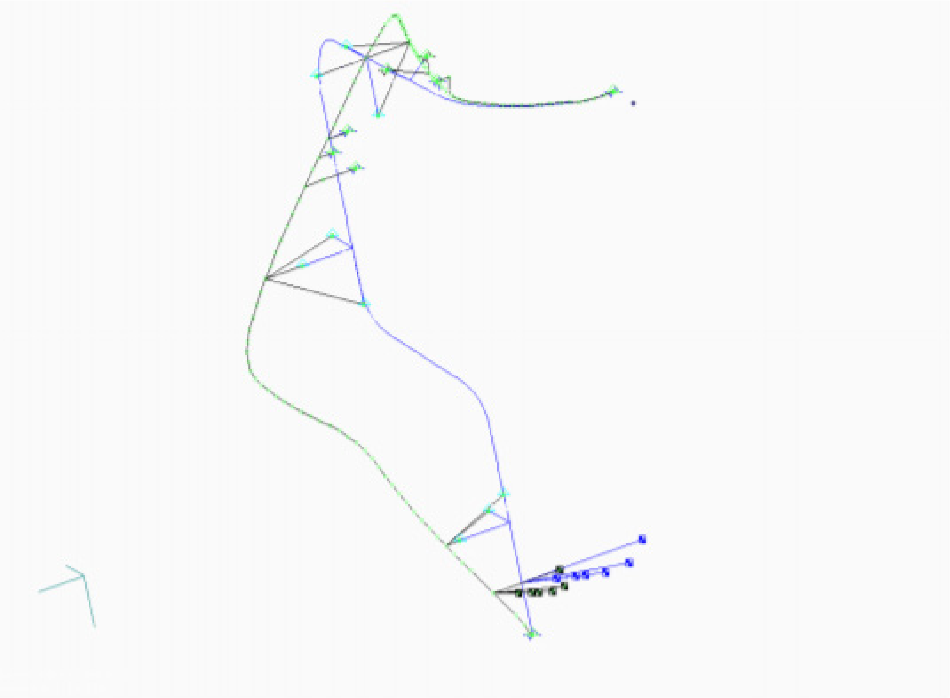


Figure 44: System 315 steam line no. 2 first bending mode

A total of six dampers of type VES-5/V40/H40 was to be mounted on the condensate lines. The condensate lines were to be fitted with:

- Two pairs of VES-5/V40/H40 mounted in the ceiling in room 7.59.
- Two pairs of VES-5/V40/H40 mounted in room 7.59 as high up as practical on the vertical span.
- Two pairs of VES-5/V40/H40 mounted on the floor in room 7.59 in between the middle of the horizontal span and support U967

Figure 45 below illustrates the FEM modelling of the condensate lines in the first bending mode after installation of viscous dampers.

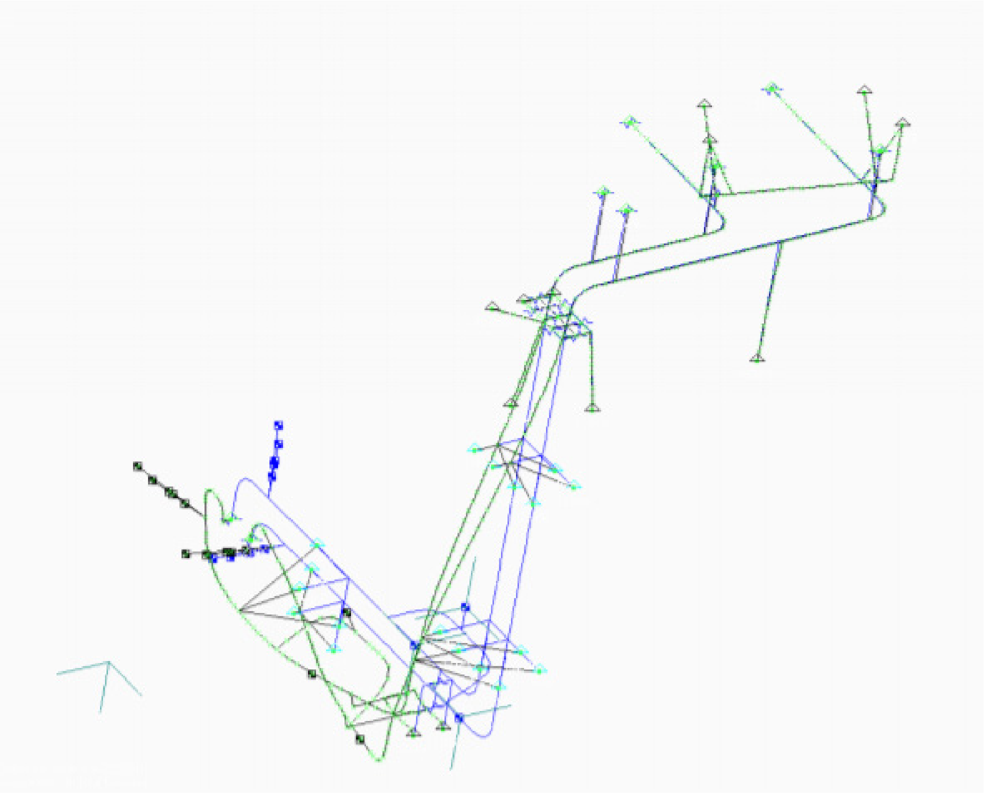


Figure 45: System 315 condenser lines first bending mode

It was concluded that, in addition to increasing the damping, the viscous dampers would have a stiffness contribution, and a contribution to the modal mass for each mode. The frequency shift was deemed to be of little importance, and the added damping to govern the vibration response.

For the following design of the dampers, a thermic analysis of the damper fixtures was done using FEM software to be able to predict the needed design temperature of the dampers. Temperatures of both the pipes and the room in question were measured and a FEM analysis of heat transfer through the clamp to the damper fluid. The result of this analysis was then used as input for the choice of damper fluid with regards to temperature for each part of the piping systems.

In 2007 during outage a follow up study was made of the piping eigenfrequencies and damping after installation of the dampers. Impact testing of the pipes showed that damping was increased by 200% on the steam lines and by 70% on the condenser lines. Figure 46 to Figure 49 and Table 2 to Table 5 below shows the measured results on steam lines 1 and 2 as well as condenser line 1 and 2. Figure 51 in section 4.4.5 shows an installation example of these dampers.

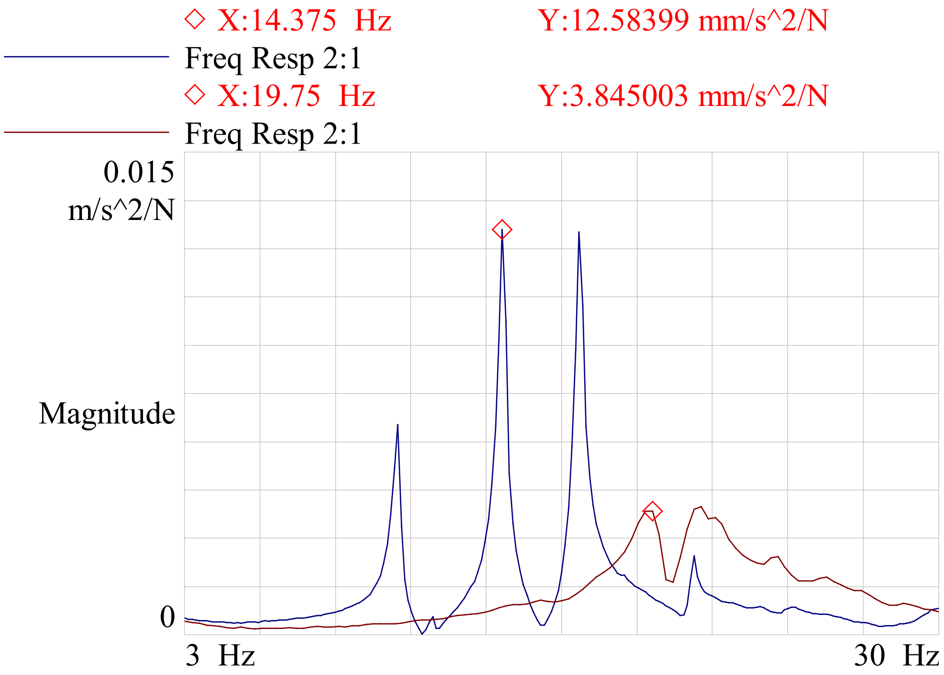


Figure 46: Measured point accelerance on steam line 1 before (blue curve) and after damper installation (brown curve)

Table 2 Comparison of measurements before and after installation of dampers at steam line 1, O1

	Frequency [Hz]	Accelerance [mm/s²/N]	Damping [%]
Before	14,4	12,6	0,9
After	19,8	3,8	2,1

The highest accelerance magnitude value was diminished from 12,6 to 3,8 mm/s²/N. This means a 70% decrease. For the same excitation the damped system vibrates only 30% of what the undamped system would do. However, this is for room temperatures. For the correct temperature damping was predicted to increase.

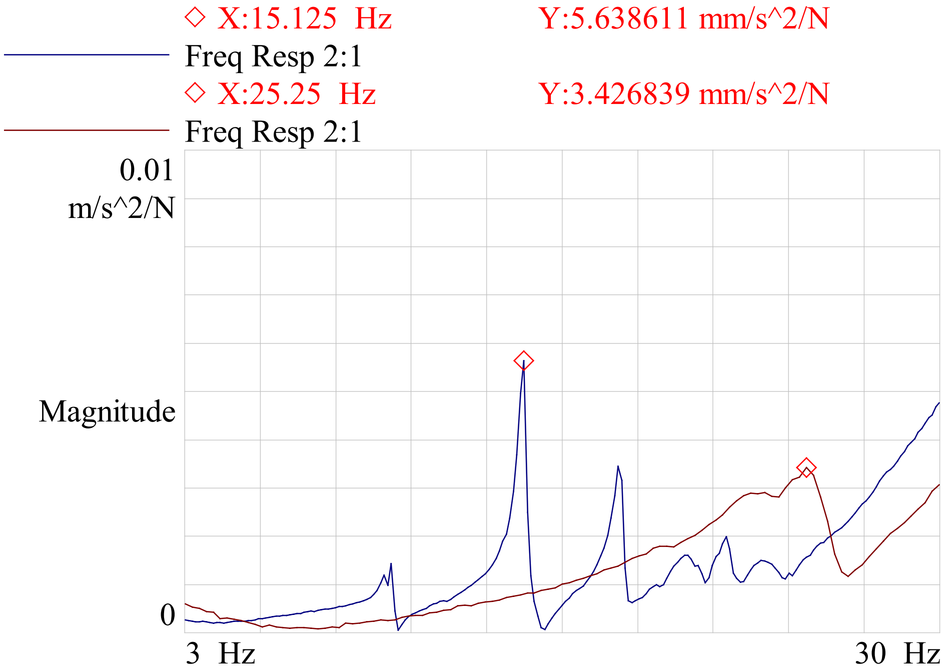


Figure 47: Point accelerance before (blue curve) and after damper installation (brown curve) at steam line 2

Table 3: Results steamline 2

	Frequency [Hz]	Accelerance [mm/s²/N]	Damping [%]
Before	15,1	5,6	0,8
After	25,3	3,4	3,0

The highest accelerance magnitude value decreased from 5,6 till 3,4 mm/s2/N. That is a reduction of 39% which means for the same excitation the damped system vibration is just 61% of the undamped system and at a higher frequency.

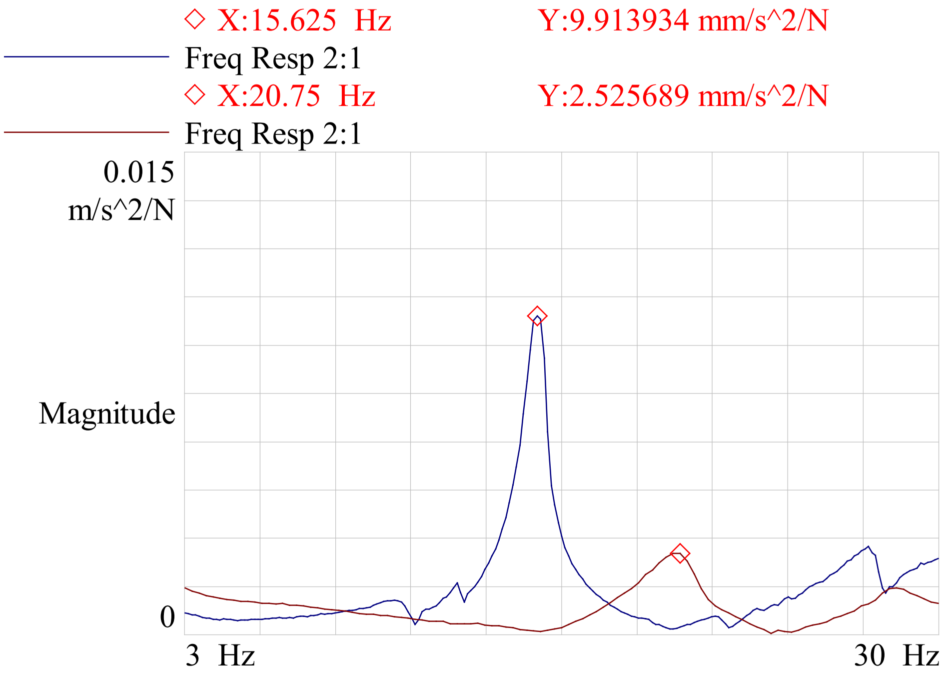


Figure 48: Point accelerance before damper installation (blue curve) and after damper installation (brown curve) on condenser line 1

Table 4: Comparison of measured results before and after damper installation on condenser line 1

	Frequency [Hz]	Accelerance [mm/s²/N]	Damping [%]
Before	15,6	9,9	2,7
After	20,8	2,5	4,5

The highest measured accelerance magnitude decreased from 9,9 to 2,5 mm/s2/N, which means a reduction of 75%. This means that the damped system only vibrates 25% of the undamped system for the same excitation level and at a higher frequency.

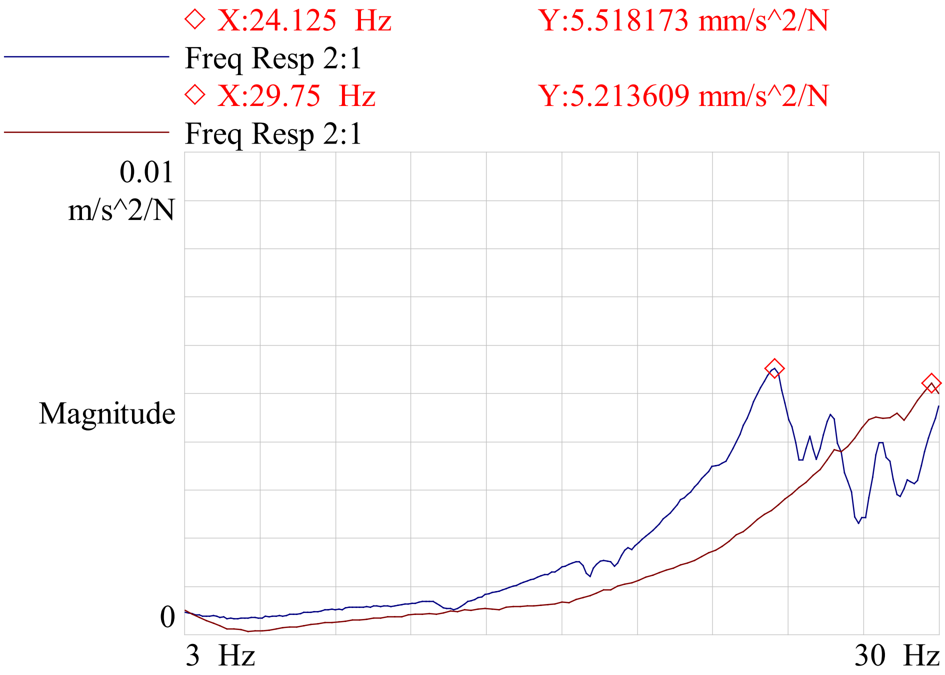


Figure 49 Point accelerance before (blue curve) and after damper (brown curve) on condenser line 2

Table 5 Measured results before and after damper installation on condenser line 2

	Frequency [Hz]	Accelerance [mm/s²/N]	Damping [%]
Before	24,1	5,5	2,2
After	29,8	5,2	3,8

The highest measured accelerance magnitude decreased from 5,5 to 5,2 mm/s2/N, which means a decrease of 5%. This means that the damped system only vibrates 95% of the undamped system for the same excitation level and at a higher frequency.

In average the damping increased with about 200% (factor 3) for the steam lines and 70% for the condenser lines.

In the O3 turbine feedwater system 463, its main job is to transport, pressurize and preheat the water from the feedwater tank to the reactor feedwater system, issues with high vibrations preceded a decision to install some new dampers (3x3) downstream of the flow valves. Viscodampers of type Gerb VES-50/V40/H40.

In an investigation 2012 the stress loads were calculated using for example the software PIPESTRESS were also the dampers might be added, however only at three different stiffness cases of the viscodampers and not all frequencies since each stiffness case is a separate run in PIPESTRESS.

In Figure 50 and example of a PIPSTRESS model can be seen.

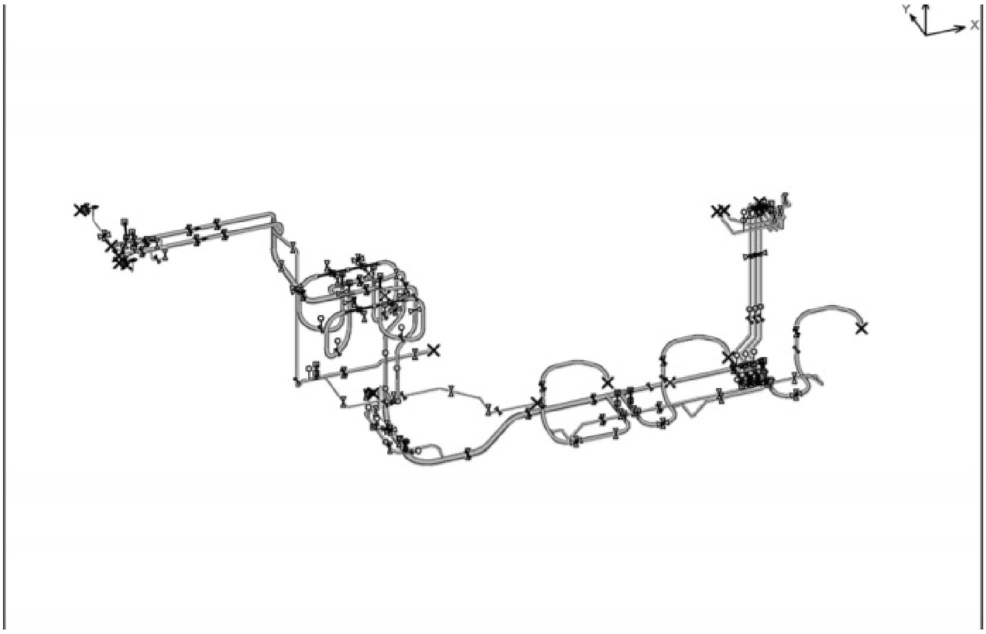


Figure 50 example of model of a pipe system in the software PIPESTRESS.

4.4.4 Design of dampers

Damper design is usually done by measurements and troubleshooting of the problem at hand to identify design frequencies, amplitudes, positions, temperature etc. Damper solutions are chosen and designed in collaboration between OKG mechanical design engineers and suppliers.

The approach is usually to measure the vibrations and investigate the problem with regards to frequency area, root cause, amplitudes etc.

For modeling of pipelines usually a software called Pipe-Stress is used however in this software it is difficult do model viscous dampers and for this FEM software's are better to use.

One of the most complicated issues when designing and installing dampers are to find a good approximation between damping effect and actual space/positioning possible to install a damper. There is sometimes a lack of space for installation where one would prefer the damper an also it should not be hindering of other measures, maintenance need or outage work etc.

Temperature is also important to consider not only in the design phase but also in the installation phase. O3 has relatively even temperature over time but a big variation between 'offline' and 'online' mode. That is OKG specialists does usually not do anything with the dampers in offline mode since positioning of piping, pumps etc. change when plant is up and running. E.g. two dampers had to be misaligned in cold conditions and then adjusted back in hot condition due to large movements in the pumps, up to 1.5 centimeters.

Usually a slow warm up of the plant works well for the dampers with regards to alignment etc.

OKG design their own brackets, pipe clamps and attachments for the viscodampers and do not use the standard ones supplied by Gerb.

An example of OKG design of dampers, is well documented for the pipe systems 315 in O1. Before installing viscous dampers on pipe system 315 in O1 several investigations were made to optimize the design of the dampers, for instance extensive measurements and root cause analysis of the vibration issue, FEM modelling of piping and damping design. Also, thermic analysis of the damper brackets and temperature measurements to choose the correct design temperature for the dampers as well as modal impact testing before and after the installation.

4.4.5 Installation examples

Installation example of dampers in Oskarshamn 1, system 315.

Figure 51 Viscous dampers mounted on condenser lines 1 and 2.

The Gerb dampers in Oskarhamn NPP are mainly installed for vertical damping according to the NPP specialists.

4.4.6 Maintenance

Regarding maintenance, viscodampers are considered a sub-system to the brackets holding them/the pipes. There has not yet been any proper maintenance program/routine for dampers on O3 but is under development, however on O1 and O2 there was fixed vibration monitoring to the control room as well as a maintenance and visual inspection routine. Vibration levels were monitored to check that no significant change in levels occurred and during visual inspection the fluid was checked for any changes.

Visual inspection frequency varies but during each outage approx., 20% are inspected. The inspection often results with following vibration measurements.

The Lisega dampers have replacement parts/complete dampers in storage. However, it has been noticed that the ones in storage are ageing equally as when in use and are put in rotation schedule were the dampers are changed every 5th or 10th year and then sent for functionality control to the supplier.

When it comes to ageing of the viscodampers there is no documented limitation. However, approx. 20 years has been discussed and at some time mentioned by the supplier Gerb. Nowadays a visual inspection and assessment of their status is done every year and so far, there has been no noted ageing or wear and tear of the damper protection sleeve. According to the supplier the dampers should be maintenance free.

4.4.7 Experiences and lessons learned

According to documentation found, first contact with viscodampers was in 1988 when Gerb presented their new type of damper, a viscoelastic damper that they developed with the quality to accept slow movements and to prevent fast movements such as vibration and shocks. The damping fluid was then presented as a petroleum-based product, but they were very secretive about the fluid in general. A number of approx. 32 dampers were decided to be installed and tested on the O3 steam lines.

In 1990 an investigation was made of the damper temperature dependency on the steam lines in Oskarshamn 3 at full effect. The conclusion was that a change of the damping fluid to a fluid better suited temperature wise should not significantly affect the vibration level in the steam lines in question, but rather an addition of new dampers would be needed.

More experience of the viscodampers was made from the investigation of vibration issue on system 315 steam lines and condenser lines. Vibrations were known early on and the root cause as well. A solution with dampers was chosen however the issue could be solved by redesigning the system completely to avoid the design flaw that causes the vibrations however this would have been very expensive and most likely other issues that the dampers also takes care of would have still been present.

One of the lessons learned by OKG specialists is that if there are signs of ageing, more dampers can be needed to lower their wear of the plant. Some places currently have high vibrations and transients and therefore it would be surprising if more damping will be added to the plant. Most issues are known, and ‘old’ issues and new issues does not occur that often. Although fast shutdown and fast partial shutdown of the plant creates transients in the piping systems that might cause new problems to occur.

When it comes to ageing, there is now documentation regarding the viscodampers, however twenty years longevity has been mentioned in a meeting with Gerb some years back.

Regarding damper maintenance, a yearly review is made, and the dampers are then investigated and handled case by case. Supplier documentation claims the dampers to be maintenance free and there has been no trouble with ageing or wear on the protective sleeves on the OKG dampers so far.

Gerb did an inspection of all the dampers on system 462, 463 and the reactor in 2012. Two dampers were considered to be under dimensioned and recommended to be changed and a couple were working in temperatures slightly higher than the design temperatures. One damper had a broken position indicator however this did not affect the damping. Another one had broken welding. Except these comments, all dampers looked fine and the corrosion protection was undamaged, all but two sleeves were in order.

There was, at another occasion, an issue of the fixture of the dampers to the feed water pipes. These are 600mm piping with large 20kg clamps and bolts were breaking and the clamps were misaligned. During the outage 2018 it was designed that these needed to be renovated and restored to match the original drawings. That is straight installation and no misalignment. After this restoration the dampers work as designed/expected and no issues has been reported. The dampers had no damage to them.

OKG specialists concluded that after 35 years of running and being subjected to vibration it can be expected that clamps might move little by little, until they reach a point where they are not working properly. This kind of restoration of damper installation might be necessary every 15 years or so.

After this OKG specialists are very vigilant making sure that system and dampers maintain their positioning when any maintenance is made e.g. changing of valves etc.

For example, the HC pumps that have dampers in three directions was optimized after they were installed at an angle instead. The measurements showed an improvement of the dampers effect when measuring with displacement sensors.

Regarding radiation a calculation received from supplier Gerb show that the dampers should not age in radioactive environment and no such ageing effects has been seen yet at the OKG dampers.

There was a case where two dampers were installed to a horizontal pipe attached by clamps. The clamps were able to rotate around the pipe and that resulted in that one damper shaft was in the bottom and one was in the top of the fluid. When this was adjusted the dampers self-healed and were working properly again. It is quite possible that the clamp moved due to vibrations in the pipe.

Regarding the fluid material composition OKG has not, like the other NPPs received any information from the supplier chemical composition lists are all outdated and has been classified since the early 80s.

In around 2006 a viscodamper of type Gerb VES-40 was replaced in O3 system 421 due to ageing of the fluid.

2018 damages on a double damper clamp as found on 462 system. The clamp cracked and measurements showed high frequency vibrations on the piping that would not be present if the damper functioned properly. The vibrations were found already in 1985 and Gerb inspected the dampers around approximately 2013 and concluded that the dampers were under dimensioned, however further investigation 2018 concluded that the damper design was correct. An identical damper was ordered and a new installation clamp that was more robust was designed. Also, bad welding was minimized.

OKG has not changed the fluid of the dampers since the cost for a new damper is estimated to be of the same level as changing the fluid. The discussions about changing fluid is based on a general recommendation from Gerb that the lifespan of the fluid is not guaranteed longer than 20 years however this recommendation is not documented but originated from a meeting with Gerb many years ago.

4.5 RESULT FROM INTERVIEW WITH TVO

4.5.1 About the NPP

The TVO nuclear power plant units, Olkiluoto 1 and Olkiluoto 2 (OL1 and OL2), are identical. Both have a boiling water reactor with a current net output of 860 MW.

The OL1 unit was first connected to the national grid in September 1978, and the OL2 unit in February 1980.

TVO is currently building a third power plant unit, Olkiluoto 3 (OL3). With the electrical output of approximately 1,600 MWe, OL3 will almost double the production capacity of the Olkiluoto power plant.

OL3 is a power plant unit with a Pressurized Water Reactor (PWR). The type of the unit is known as a European Pressurized Water Reactor (EPR).

Olkiluoto 3 EPR was ordered as a turnkey delivery from a consortium (plant supplier) formed by AREVA GmbH, AREVA NP SAS, and Siemens AG. The commercial electricity production of the plant unit was originally supposed to commence at the end of April 2009. Regular production at the plant unit will begin in 2021 or 2023.

4.5.2 Type of dampers installed

At OL1 and OL2 nuclear power plants TVO has both hydraulic dampers and viscous dampers. The hydraulic dampers are mainly manufactured by Lisega and viscous dampers are Gerb's VES type dampers. The dampers are mainly installed on turbine system´s piping but the complete list of dampers installed in operating plants isn't currently available.

OL3 also has a 'broadband' mass tuned damper of the type REKI. It is installed on containment heat removal system on a JMQ pump. It is still too early to say anything about output

4.5.3 Background to different pipe mitigation countermeasures

Olkiluoto NPPs are equipped with only one turbine each. This makes it difficult if one generator would for example break and it takes one year for replacement part.

For OL1 & 2 generator vibrations are increasing and exceeding limits year after year for every start-up.

OL3 reactor type EPR with probably the highest power in the world of turbine and generator have fixed points of measured torsional vibrations and strain gauges to monitor the vibrations and to identify the torsional modes for start-up.

TVO, VTT and Siemens has put in extra strain gauges for this purpose as well as 'last blades deflection' sensors. A visual sensor that can see rotor angle position and follow blade angle position.

For the start of OL3, start-up will be done in steps in thermal power under approx. 8 months with increase/decrease of thermal power and tripping tests etc.

OL3 experiences excessive vibrations on the surge line. The pipe from the bottom of the pressuriser to hot leg 3 now have two viscodampers of type Gerb installed. As well as weight supports with spring hangers.

The vibration issue is temperature dependant and the highest vibration measured was 68,6mm/s rms at f=5.3Hz. Vibration level is not steady, it fluctuates and varies a lot in level as well as in frequency. Highest vibration in pipe direction but also in all directions. The global acoustic natural frequencies based on temp of primary loop water, at max temp is close to the f= 5,6hz. Pressuriser level of water has impact on the vibration levels. Root cause is not known, and pumps are not mechanically possible to induce these frequencies. The damper installed are viscous dampers GERB VES-50/V40/H120 with 2*60kg bitumen (Note: Fluid not specified in GERB datasheet). There was a big risk investigation done regarding potential leakage of the bitumen or fluid to the suction point. The solution was to put an inhibitor 'net' to prevent leakages.

In containment heat removal system on OL3. A JMQ pump has a limit that it should be able to run 2 years continuously without break. With vibration levels at approx. 11mm/s and 5-6mm/s horizontally with several frequency peaks this was not possible.

Several steps of mitigation were tested

- 1st mitigation test was change of orifice and it had some effect. Then a flow straightener was tested. It also some effect but not enough. A bigger flow straightener, length of 1.4meters had some effect as well.
- Suction and discharge plug change. That is, small bore ends that 'plugs' the branch of the main pipe. This had effect and is still in use.
- Fixed mass damper was then tested. It had some effect but later on it didn't have effect anymore.
- Bearing bracket support. Fixed plate over the motor drive side. Plate fixed to motor and to the floor. Had significant effect on the horizontal vibrations. Not in use anymore since the plate started to bend due to thermal expansion etc.
- Last a REKI mass damper was tested.

REKI dampers are basically wire dampers with additional masses, see Figure 52. It was fine-tuned five times to find the configuration that worked best. Mainly by changing the masses added. One of the pumps now has 31 kg in vertical direction and 12 kg in one side for damping in the transversal direction. The damper was installed in 2019 and it works fine. However, it was noticed that the damping effect was reduced due to oil leakage on the motor that affected the friction damping of the wires.

4.5.4 Design of dampers

Thermal expansion is a critical parameter.
Regarding design temperature it is nowadays based on CFD simulations and measurements. Before it was mainly based on experience. It is possible that GERB has done some kind of calculation for the first couple of dampers, but it is not known to the TVO vibration specialists.

If a damper would be designed today. First step would be to try some new support. Second to try to identify and fix the source of the vibration problem and third would be to design a damper. When a damper is chosen as a counter measure there has already been some measurements done and there is therefore quite some knowledge regarding the vibration issue and the piping that can be used as input to FEM modelling and then the correct dampers chosen (TVO).

Dynamic analysis is made, stiffness calculations. Use Finnish F-Pipe + German company Sigma (ror2) program that has GERB damping catalogue in the model. For OL3 AREVA Ansys was most probably used.
Damper position is chosen usually on pipe analysis model in combination with measurements.

Major complexities for installation are heat and radiation as well as paperwork needed. A lot of paperwork is needed to put a damper inside the containment. Capture of the fluid, or as TVO has learned ‘bitumen’, capture is critical. In OL3 there is a 'collector net' installed in case the fluid (bitumen) leaks.

The stress analysis that needs to be done is also a big task that takes time. If you add some spring or damping somewhere on the critical safety class 1 piping you have to redo the stress analysis of the entire line. The amount of work depends on what safety class it is.

There is no specific bookkeeping of dampers lifecycle. Dampers are listed in a excel list of damper type, installation year and modification etc.

In TVO Ol3 there has not been those kinds of cases yet for were viscodampers are designed. However, TVO specialists would in most part rely on measurements like Modal impact testing to design dampers.

4.5.5 Installation examples

Below can be seen an installation example of a mass tuned damper on a pump on the OL3 heat removal system. It is a REKI damper that was installed due to its possibility to dampen a broader band frequency range since the pump's vibration spectra consisted of several frequency peaks that needed damping.

To achieve the best result, the damper is tuned adding or removing mass. It also works in all directions for this case. However, it needs to be protected against oil spill since the damping effect then is diminished.

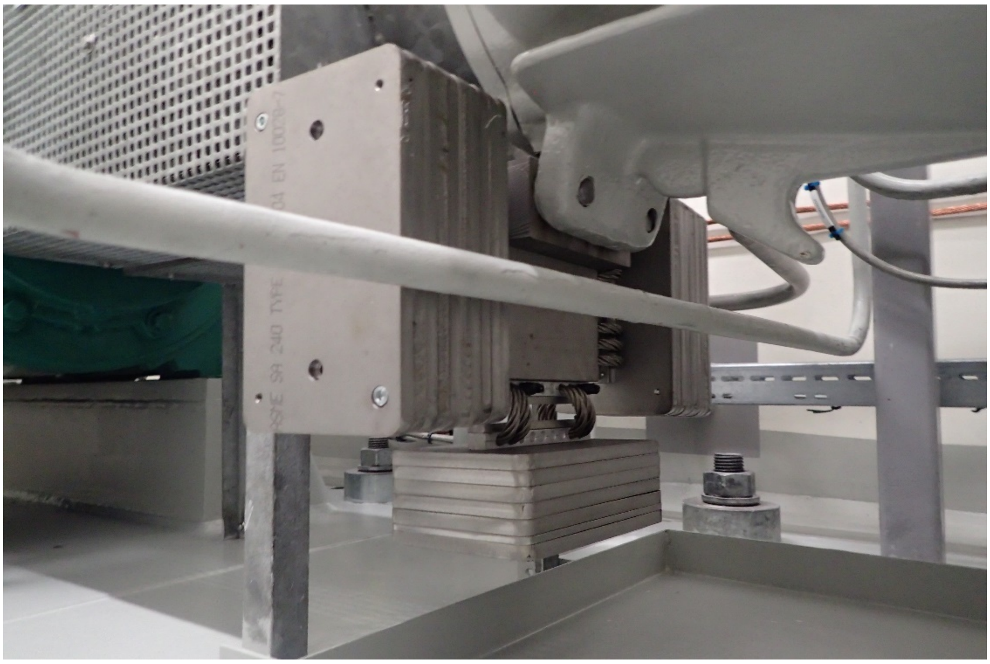


Figure 52 Example of a REKI damper installation in OL3.

4.5.6 Maintenance

The dampers are annually inspected by TVO's specialist or contractor during outages and maintained as required.

4.5.7 Experiences and lessons learned

Designing and choosing dampers is not 'everyday job' and is handled case by case and is usually the last solution.

First step would be trying to use 'normal' and 'catalogue' supports such as spring hangers, Lisega products etc.

Viscous dampers are usually the final solution if nothing else works and each vibration problem is handled case by case.

For higher vibrations TVO usually use as stiff supports as possible however thermal loading is the dimensioning factor. The piping needs to be able to change or move due to thermal loading.

Regarding the installed viscodampers most are still functioning at original position and purpose. Some 'older' viscodampers are still functioning in OL1 and OL2 but most of them are since 2012/2013.

When it comes to ageing of the dampers. There has not been any information received from GERB. However, TVO specialists has noticed that in some places there has been aging and fluid has been refilled for one damper that had an alignment change. A couple has been completely changed due to that the surface of fluid was harder and had some kind of ageing. They were changed to the same kind of fluid or changed to new dampers with same specification.

It is estimated that it is the same amount of work to change the complete damper as it is to change the fluid. To take the fluid out of the pot you can heat it and pour it out or freeze it and take it out as a block.

Regarding radiation sensitivity, it is not known to TVO at what extent the viscodampers are sensitive to radiation if at all. A GERB datasheet, seen many years back, has shown some kind of limitation for radiation but that it can withstand radiation dose and that the fluid is of some type of bitumen like compound. There is no supplier documentation for the silicone fluid. Negative with bitumen is its large dependence of temperature. Silicone fluid is less sensitive to temperature but has no paper or certification for radiation etc.

The largest complexities for installation of dampers are heat and radiation also paperwork is heavy. A lot of paperwork is needed to put dampers inside the containment at TVO. Also capture of the damper fluid in case of breakage of the damper protective sleeve is critical. In OL3 there is a 'collector net' installed in case the damper fluid leaks.

The stress analysis is also a big task affected by installation of dampers. If you add some spring or damping somewhere on the critical safety class 1 piping you must redo the stress analysis of the entire line. The amount of work depends on what safety class it is. However, it is quite time consuming.

In TVO there is no bookkeeping of dampers lifecycle. However, there is an excel list of damper type and installation year and modification etc. to keep track of damper types and status.

TVO vibration specialist also has experience of other types of dampers not usually used in NPP sector but are used a lot in other industry areas such as process industry e.g. paper machines. To compare the requirements in these two sectors, for a paper machine 2mm/s is too much and at a power plant 8-10mm/s is often approved (TVO specialist experience).

4.6 RESULT FROM INTERVIEW WITH FORTUM

4.6.1 About the NPP

The Loviisa power plant was the first nuclear power plant in Finland. The power plant has two units: unit 1 started operating in February 1977, and unit 2 in November 1980. Construction began in 1971 and 1972. The units are VVER-440 type pressurized water reactors. Power capacity (net) of 507 MW each.

The Loviisa power plant was a multicultural project, in which West and East co-operated in the field of nuclear technology for the first time. The degree of domestic origin was approximately 50%. The reactor, turbine, generator and other main components are from the former Soviet Union. Safety systems, control systems and automation systems are of Western origin. The steel containment and its related ice condensers were manufactured using Westinghouse licenses.

4.6.2 Type of dampers installed

Loviisa NPP has several types of dampers installed. Except for viscous dampers of type GERB they have elastic hangers and snubbers as well.

Experience of 25-30 years with dampers. As well with dampers inside containment. --> radiation levels.

A total number of 95 viscous dampers are installed at Loviisa NPP (approx. 45 dampers per plant): 71 dampers at main steam lines of which 8 are inside the reactor containment and 24 dampers at main feedwater lines. Among 95 dampers 48 were VRD, 8 VES and 39 VD type. Only VES inside containment (total of 8) because they conform to the requirements with TÜV certificate.

On turbine there are one or two mass tuned dampers. They are an inhouse design from end of 90's to early 00's installed on the turbine bearing pillars.

Loviisa NPP also have some snubbers installed but not that many.

4.6.3 Background to different pipe mitigation countermeasures

After capacity increase high vibrations appeared on the main steam line and feed-water lines. Excessive piping vibration occurred as the result of an increasing of working media flow in piping due to 10% upgrading of the Unit 1 and Unit 2 reactors power capacity. Piping flow induced vibration in several cases has been significantly higher codes’ recommended thresholds levels and NPPs best operational practice.

Several attempts to decrease the vibrations, such as redesigning of piping support system, strengthening supports, installation of elastic supports etc. since these measures did not provide positive effect and shifting in some cases, systems vibration frequency and not affecting the vibration levels as well as increase of vibration and noise transferring to environmental structures.

An optimum minimal number and location of VES and VD high viscous dampers was determined and then installed at the lines. An essential vibration reduction of the examined systems was achieved. See installation example section 4.6.5.

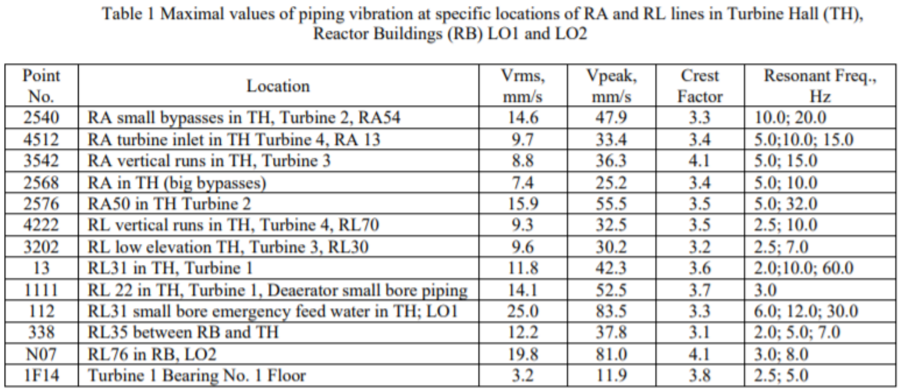


Table 1 Maximal values of piping vibration at specific locations of RA and RL lines in Turbine Hall (TH), Reactor Buildings (RB) LO1 and LO2

Point No.	Location	Vrms, mm/s	Vpeak, mm/s	Crest Factor	Resonant Freq., Hz
2540	RA small bypasses in TH, Turbine 2, RA54	14.6	47.9	3.3	10.0; 20.0
4512	RA turbine inlet in TH Turbine 4, RA 13	9.7	33.4	3.4	5.0;10.0; 15.0
3542	RA vertical runs in TH, Turbine 3	8.8	36.3	4.1	5.0; 15.0
2568	RA in TH (big bypasses)	7.4	25.2	3.4	5.0; 10.0
2576	RA50 in TH Turbine 2	15.9	55.5	3.5	5.0; 32.0
4222	RL vertical runs in TH, Turbine 4, RL70	9.3	32.5	3.5	2.5; 10.0
3202	RL low elevation TH, Turbine 3, RL30	9.6	30.2	3.2	2.5; 7.0
13	RL31 in TH, Turbine 1	11.8	42.3	3.6	2.0;10.0; 60.0
1111	RL 22 in TH, Turbine 1, Deaerator small bore piping	14.1	52.5	3.7	3.0
112	RL31 small bore emergency feed water in TH; LO1	25.0	83.5	3.3	6.0; 12.0; 30.0
338	RL35 between RB and TH	12.2	37.8	3.1	2.0; 5.0; 7.0
N07	RL76 in RB, LO2	19.8	81.0	4.1	3.0; 8.0
1F14	Turbine 1 Bearing No. 1 Floor	3.2	11.9	3.8	2.5; 5.0

Figure 53 Table showing maximal values of piping vibration for the RA and RL lines at LO1 and LO2.

The following thresholds for piping vibration at Loviisa NPP have been approved (Based on all available documentation and a good nuclear plant's operational practice):

RMS vibrovelocity < 7.5 mm/s

Peak vibrovelocity < 20mm/s

The criterion on RMS piping vibration was recognized as the primary limit and peak value as the secondary one.

Extensive analysis showed that the root cause of vibration was connected with, that after upgrading of the Loviisa NPP power in the same proportion the mass flow (and thus its velocity) of feed water and steam in piping was increased.

Resulting in pressure drop, vortex and turbulence at all piping pressure restrictions, liquid or mixed phase flow excitation, pressure surges and hydraulic hammers became more powerful and frequencies of pressure unstable pulsations increased.

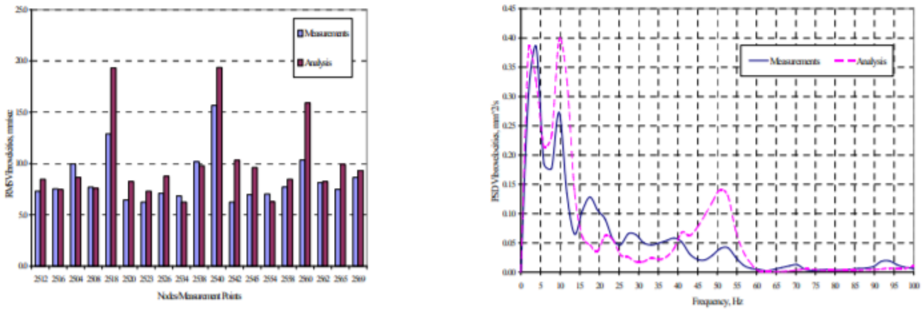
Strouhal vortex frequency could tune on one or several acoustic piping resonances creating self-excited vibration system inside piping with unbalanced forces in piping elbows. In case of coincidence of acoustic frequencies with mechanical natural frequencies of piping a powerful common acoustic-mechanical resonance of piping system could exist.

At Loviisa, for piping vibration analysis and resolving of vibration matter the following analytical procedure has been developed and approved:

- generation of finite-element model of piping
- solving of eigenvalue problem to define the natural frequencies and mode shapes
- modal time-history analysis of piping system
- post-processing of results in time domain: defining of RMS and Peak values of vibration velocities, creation of PSD Spectra for selected points.

The input vibration excitation is usually generated by using analysis results (piping natural frequencies and mode shapes) and experimental results obtained in piping vibration measurements. This is realized in the dPIPE piping software.

The Figure 54 below illustrates this procedure.



a) vibration distribution along the piping

b) PSD spectra in the control point

Figure 54 Experimental results and predicted (analysis in dPipe) results of piping vibration

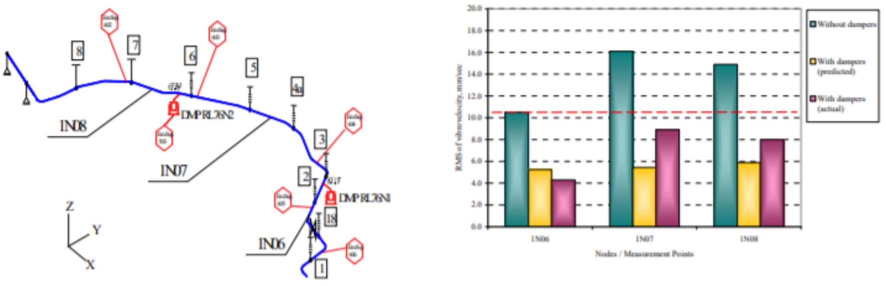
Due to negative experience using piping support see Figure 55, viscous dampers were decided for this problem.

a) wear of the rod hanger

b) fatigue collapse of elastic vibration support

Figure 55 Example of piping supports degradation due to vibration.

Figure 56 below demonstrates the preliminary analysis results of piping feedwater system in containment subjected to flow induced excitation without and with high viscous dampers.



(a) (b)

Fig. 7 Layout of the feedwater RL76 piping in the containment LO2 with dampers location (a) and analytically predicted and actual influence of dampers on the piping vibration (b).

Figure 56 Layout of the feedwater piping and damper locations and the predicted and actual influence of dampers on the piping vibrations.

In result of dynamic analysis and cost analysis an optimal number of 95 dampers was installed. 71 dampers at main steam lines and 24 dampers at main feedwater lines. Among these 95 dampers 48 were VRD, 8 VES and 39 VD type.

Results and efficiency of the installed dampers can be seen in Figure 57 and in Table 6 and Table 7 below.

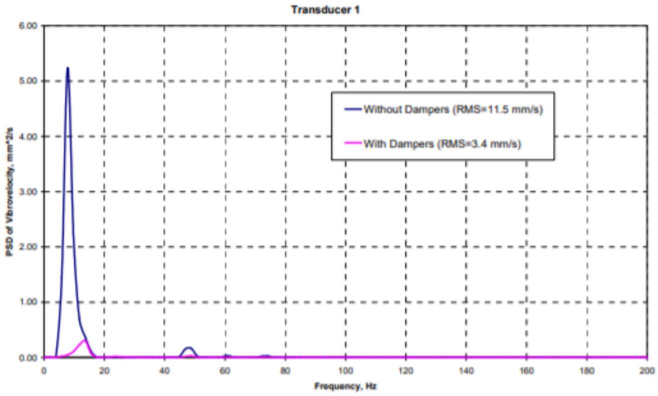


Figure 57 Typical results of damper influence. Example, PSD spectra of RA10 piping vibration before and after damper installation

Table 6 Values of final piping vibration and dampers efficiency.

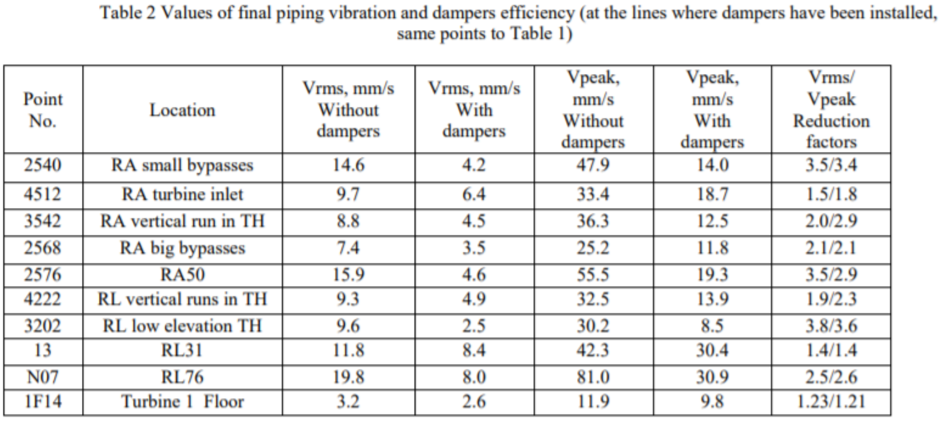


Table 2 Values of final piping vibration and dampers efficiency (at the lines where dampers have been installed, same points to Table 1)

Point No.	Location	Vrms, mm/s Without dampers	Vrms, mm/s With dampers	Vpeak, mm/s Without dampers	Vpeak, mm/s With dampers	Vrms/ Vpeak Reduction factors
2540	RA small bypasses	14.6	4.2	47.9	14.0	3.5/3.4
4512	RA turbine inlet	9.7	6.4	33.4	18.7	1.5/1.8
3542	RA vertical run in TH	8.8	4.5	36.3	12.5	2.0/2.9
2568	RA big bypasses	7.4	3.5	25.2	11.8	2.1/2.1
2576	RA50	15.9	4.6	55.5	19.3	3.5/2.9
4222	RL vertical runs in TH	9.3	4.9	32.5	13.9	1.9/2.3
3202	RL low elevation TH	9.6	2.5	30.2	8.5	3.8/3.6
13	RL31	11.8	8.4	42.3	30.4	1.4/1.4
N07	RL76	19.8	8.0	81.0	30.9	2.5/2.6
1F14	Turbine 1 Floor	3.2	2.6	11.9	9.8	1.23/1.21

Table 7 General influence of damper installation on vibration on Loviisa RA and RL piping compared to approved thresholds vibration criteria.

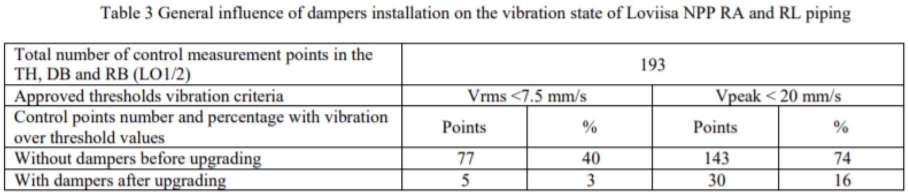


Table 3 General influence of dampers installation on the vibration state of Loviisa NPP RA and RL piping

Total number of control measurement points in the TH, DB and RB (LO1/2)	193			
Approved thresholds vibration criteria	Vrms <7.5 mm/s		Vpeak < 20 mm/s	
Control points number and percentage with vibration over threshold values	Points	%	Points	%
Without dampers before upgrading	77	40	143	74
With dampers after upgrading	5	3	30	16

4.6.4 Design of dampers

When designing viscous dampers thermal expansion is a critical parameter. Regarding the viscodampers the design temperature is included in the naming if the damper which makes it easier to choose and also easier to follow up if the chosen design is correct after for example a capacity increase or something that might affect the temperature or vibrations were the dampers are installed.

Regarding design temperature it is nowadays based on CFD simulations and measurements whilst before it was more based on experience.

The earliest installations were designed by the supplier, Gerb. If they have done some kind of calculation for the early installations, it is not known.

For the new dampers there is an insulation pad between pipe and piston. Rough estimate was that it might reduce the fluid temp 5-10 degrees.

If designing dampers today the 1st step would be to try some new support. The 2nd step would be to try to fix the source of the vibration and the 3rd step to design and install a damper. Regarding damper design Fortum would initially start with some in-house engineering and then discuss further with the supplier. They might also consider outsourcing it if there is a bigger scope.

Dynamic analysis is made, stiffness calculations. Use Finnish F-Pipe + German company Sigma (ror2) program that has GERB damping catalogue in the model.

When choosing damper position impact testing is done on some dampers but not all. Most are based on pipe analysis models and vibration measurements.

Most of the pipe viscodampers were designed and installed at same time over a 3-year period. Fortum does not have a typical known number of dampers per pipe segment since it is dependent on what analysis of piping and vibration issue show the need for but typically 1 or 2 per segment are installed.

The mountings/fixtures for the viscous dampers are outside engineered and partly inhouse manufactured. Ready products usually don't fulfil all the requirements for safety class needed.

The damper is normally mounted aligned. Loviisa specialists has only seen one case of misalignment probably due to aging of fluid and sliding of clamp over time.

There is no direct 'rule of thumb' for designing of damper support, anchor positions etc.

4.6.5 Installation examples

Dampers have been installed in three ways:

a) damper’s piston attached to the piping, housing to the rigid structure, see Figure 58, Figure 59 and Figure 60

b) housing at the piping, piston to the rigid structure, see Figure 62

c) piston to one piping, housing to another piping using different dynamic properties of the lines with dampening of two lines by one damper as illustrated in Figure 61.

Figure 58: VES damper installed in Reactor Building LO2 at RL76. Damper’s piston at the piping and housing fixed to the RB wall.

Figure 59: Three dampers installed in the Turbine hall

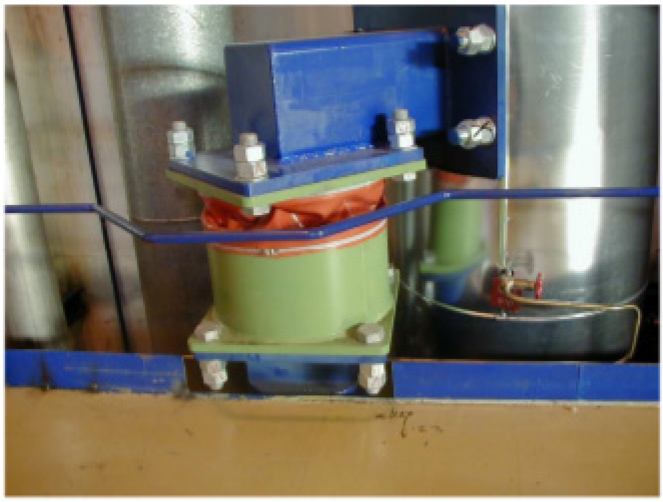


Figure 60: VD damper installed at the RA11 in Turbine Hall with damper piston at the piping and the housing at the TH floor.

Figure 61: VD damper installed between to RA lines with different dynamic properties.

Figure 62: A VRD damper installed at RA10 line in Turbine Hall with the housing at the piping and the piston attached to the wall using a horizontal bracket.

4.6.6 Maintenance

Dampers are controlled during outage when a visual inspection is made, not specifically for the dampers however there are instructions to check all hanger rods visually and some spring hangers are measured for position, spring load etc. New routine for the viscodampers is under development.

Previously GERB had Russian partner company to install the dampers and to check them a couple of years after installation.

In Loviisa there is currently no bookkeeping of dampers lifecycle. However, there is an excel list of damper type and installation year and modification etc. to keep track of damper types and status.

When installed: Yearly inspection of pipe wall thickness and then insulation is removed and then the dampers are inspected, not systematically instructed but are now working on updating these instructions to clearly include the dampers.

Example from walk down 2018 it was found that one damper tightening band was loose, and the protection sleeve was open. The fluid was okay, and it is now repaired.

Dampers do not have their own 'identity' in drawings and follow up system and are 'attached' to the pipe supports identification numbers.

4.6.7 Experiences and lessons learned

When designing installation of the dampers, for higher vibrations usually as stiff supports as possible is used but thermal loading is dimensioning of that. The piping needs to be able to change/move due to thermal loading.

Experience made from YA primary coolant loop installation. Fire insulation fabric and custom-made outer sealing. First some problems occurred with fluid choice for operation temperature. Temperatures were measured after plant shut down. Fluid was to stiff. And then changed fluid to lower temperature.

Installations inside containment. Types VES 20/40/80, 4 in each plant. One was moved to other location due to modal optimisation. On main feedwater lines cover sheets are installed to protect against pipe break (water jet). Accident scenarios would be for instance if steam or water leakage blows the damper fluid (bitumen) out of the damper that is a problem for containment security. The cover sheets might affect the temperature of the damper.

Fortum has now (before 2020) replaced 4 or 5 of these viscodampers after approx. 15 years of installation. Because it was discovered that the surface of the fluid was hard and a bit cracked and some dust was present. Investigation together with the supplier GERB showed that it was due to temperature and not radiation. Also, there was some small misalignment of the dampers.

After this experience, some sort of insulation (5mm thick) are installed on these dampers to reduce temperature transference from the pipe to the damper fluid. This insulation sheet is a GERB product.

Besides these examples most dampers are still functioning at original position and purpose.

The damper type and fluid are also unknown by Fortum. However, it has been mentioned that it is some type of bitumen compound and GERB have their own mixture of bitumen.

Summary by Fortum specialists working with viscodampers, is that installing viscous dampers is not an 'everyday job' and is handled case by case and is usually the last solution when everything else fails.

A mentioned, Fortum has GERB experience since 2000. approx. 20 years and has noticed that in some places there has been aging of the viscodampers.

Fortum has refilled fluid for one damper that had an alignment change and a couple has been completely changed due to surface of fluid was harder and had some kind of ageing. Although changed to the same kind of fluid or changed to new dampers with same specification. It is considered to be the same amount of work required to change complete damper as to change fluid. To take the fluid out of the pot you can heat it and pour it out or freeze it and take it out as a block.

GERB datasheet, seen at some point by Fortum specialists, has shown some kind of limitation for radiation but that it can withstand a radiation dose. The Russian company that has been involved in the earliest installations might have done a study of this, however there are no documentation for the silicone fluid. Negative with bitumen is its large dependence of temperature. Silicone fluid is less sensitive to temperature but has no paper or certification for radiation etc.

The largest complexities for installation of dampers are heat and radiation as well as paperwork. A lot of paperwork is needed to put dampers inside the containment. Also capture of the damper fluid in case of breakage of the damper is critical. Loviisa has a protective casing seal of the fluid in damper to prevent leakage.

Fortum specialists have noticed that GERB dampers are preferably installed under f=50 Hz and must have some level of displacement in order to achieve the best results.

In sister plants in Poland, it has been observed that GERB dampers are also used for seismic load.

Problems above f=50 Hz are handled case by case. First use measurements to identify the issue, then if needed FEM analysis. After that Fortum specialists would try to change support first, change stiffness of support.

5 Vibration dampers capabilities

Damping is a way to increase lifetime/reduce risk in the case of resonant response.

As a dynamic restraint Pipework viscoelastic damper work in a softer manner than snubbers and stoppers (strouts) providing essential additional damping to the system. A viscoelastic damper does not take up any static loading and have then limited effect on influencing the pipe system (increase or decrease its system resonances). It just operates dynamically at the tuned dampers resonance frequency by adding damping to the tuned eigenfrequency. Additionally, it will allow for slow movements (for instance due to thermal effects).

Excitations are critical if they contain frequencies that are close to natural frequencies of the piping system (resonance effects).

By adding them to the pipe system there will be:

- Increase of damping = Increase of energy dissipation
- Reduction of resonance amplification
- Reduction of shock response
- Faster decay of shock excited vibrations

One of essential advantages of using a viscoelastic damper technology is a very low maintenance operational cost times less to associated with the snubber technology.

Viscoelastic dampers are used to solve very different pipe vibration problems originate from both operational and shock like forces. Also, they can be used in combination with a steel spring to add damping to machines foundations and buildings.

5.1 VIBRATION DAMPERS FOR OPERATIONAL VIBRATIONS IN PIPES

Modal system damping of piping systems is usually assumed to be 2 - 5 % of critical damping depending on different guidelines. Viscodampers will provide in their location’s additional velocity proportional damping. This will lead to an increased system damping, if type, size, and location of the pipework dampers are properly selected. Viscodampers will, therefore, not only respond in emergency cases, but will also reduce operational vibrations.

Even if the load limits are exceeded, the pipework damper will return to normal operation again after a brief regeneration period. Replacement of the Viscoliquid is not necessary.

5.2 VIBRATION DAMPERS FOR DYNAMIC TRANSIENT PIPE VIBRATIONS

These can be induced e.g. by a forge hammer. In this case, the damping device needs to absorb a significant amount of energy in a very short time, so that the system comes to rest as quickly as possible allowing the start of the next operation of the hammer with minimum recovery time.

Visco-/Viscoelastic dampers respond without clearance, time delay, or minimal response deflection. The damper piston is always in contact with the Viscoliquid so that the pipework damper responds as a support without clearance, time delay, or minimal deflection. Damping resistance is always proportional to the relative velocity between the damper piston and housing. Visco-/Viscoelastic damper reacts without delay, reaction begins already in the initial phase of the shock parallel to the increasing shock velocity. This leads to a smooth reaction of the piping system. The pipework damper develops its energy dissipating properties already at a time where snubbers, for example, don't yet react see Figure 63.

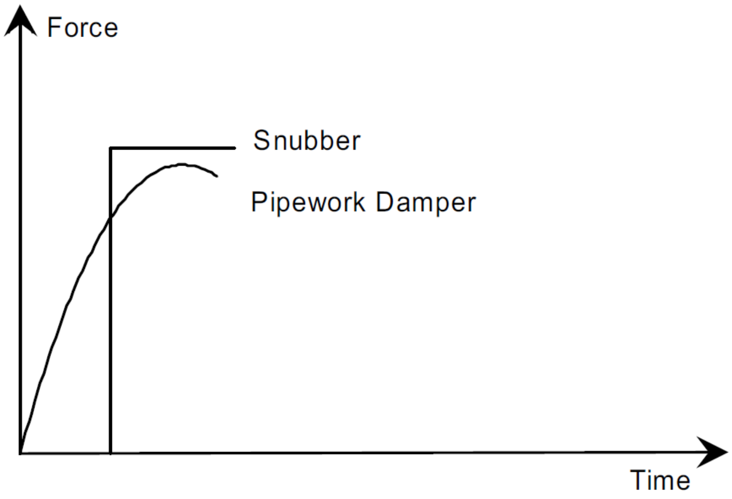


Figure 63: Time/Force Reaction Diagram of Snubbers and Visco/ViscoElastic Dampers

5.3 VIBRATION DAMPERS FOR MACHINE AND BUILDING VIBRATIONS

Pure viscodampers cannot carry any static load which often make them unsuitable to be used for machine- and building vibration. However, if they are used in combination with a spring package, they can often be an excellent choice.

6 Design of dampers

There are a lot of different damper solution available but in this report, there is a main focus put on visco/viscoelastic damping and mass tuned damper since these are preferable for use as pipe vibration dampers. The design procedure of these dampers is described below.

6.1 STANDARD COMMERCIAL DAMPERS

Viscodampers and mass tuned dampers can be quoted and delivered by supplier simply by informing them on following specification. They will then recommend which standard element to use.

Mass Tuned Dampers:

The modal mass for relevant modes of the pipe in question and a statement about the expected displacements under full load conditions. The modal mass for the modes can be determined by an impact test or a FE-simulation.

Viscodampers:

The resulting relative displacements (+/- microns) for relevant load conditions in vertical and horizontal direction. Preferably also the required damping resistance (kNs/m), see Equation 7. The input parameters modal mass and stiffness are determined with an impact test. The damping ration is the design critical damping. Furthermore, the operating temperature range of the viscodamper is needed. Based on this the supplier can customize elements and perform work shop tests. The results of these tests are the dimensions of the devices and the frequency dependency of the damping elements. The data can be used for further analysis and for design of the pipe supports.

$$\mathbf{d=2\zeta\sqrt{m * k}} \quad \left[\frac{\mathbf{Ns}}{\mathbf{m}}\right] \qquad \textbf{Equation 7}$$

d: damping resistance [Ns/m]
ζ: damping ratio, fraction of critical damping [%]
m: modal mass [kg]
k: dynamic stiffness [N/m]

6.2 REQUIREMENTS

Designed-in damping using viscoelastic materials can be a feasible option. However, the idea of using these materials as load bearing elements is tarnished by the fact that the structural strength may suffer adversely. It is probably due to this limitation, that there is hardly any application research reviewed that would endorse the idea of using these materials in such configurations. To make this approach feasible, the design configuration has to ensure high structural damping while maintaining stiffness of the fixture to a optimum level.

Such a damping design is not just the selection of a high loss material for the frequency range of interest, it is an integrated structural and materials design process. To achieve high damping, maximum strain energy must be directed into the viscoelastic material and this energy must be dissipated. To maintain an appropriate level of structural static strength, design of the damping treatment must be well thought out. This needs intensive efforts in investigating the stiffness of the parent structure, inherent damping, modes of interest, mode shapes and required loss factor of the VEMs.

A damping design process can be shown by a flow chart as shown in Figure 64

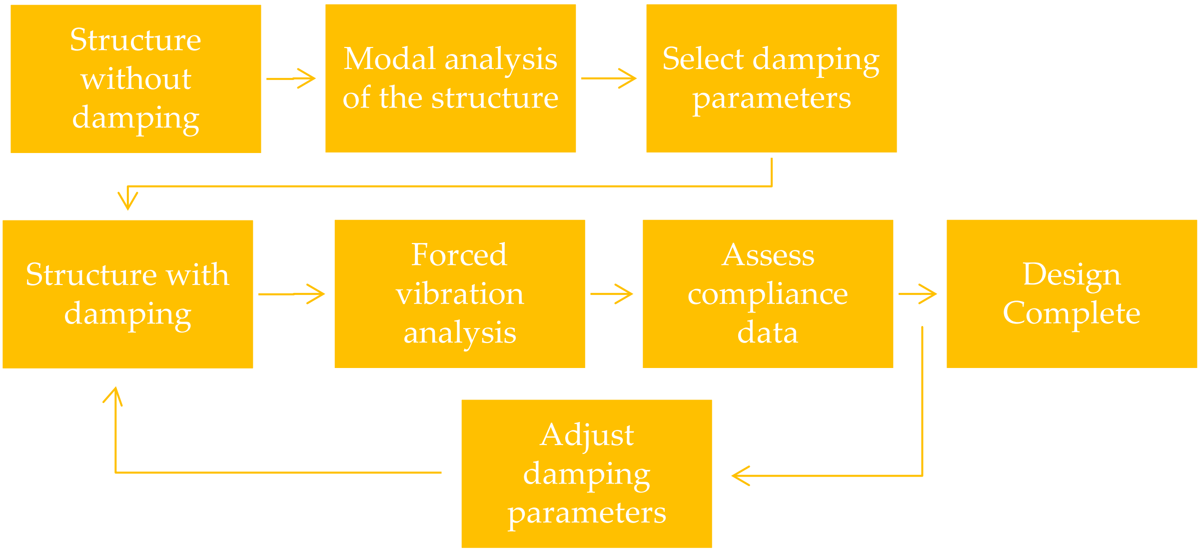


Figure 64: Basic flow chart for damping design process

6.3 SELECTION OF DAMPING MATERIAL OF DAMPERS

The use of viscoelastic materials to reduce resonant vibration amplitudes in structures depends to a great deal on knowing the environment of the application and how the viscoelastic material properties behave in such environments. Most viscoelastic materials have damping properties that vary greatly with certain environmental factors. Of these, temperature, frequency, time, and strain amplitude are the most important. However, for most practical applications, other environmental factors should also be considered to determine their effects on the survivability of the material and the stability of its properties. Such factors could include resistance to oil, aging, heat, cold, radiation, etc.

Figure 65 [Faribaldi L, Ohah H.N, 1996] shows a combined graph for loss factor and shear modules of viscoelastic materials as function of temperature and frequency.

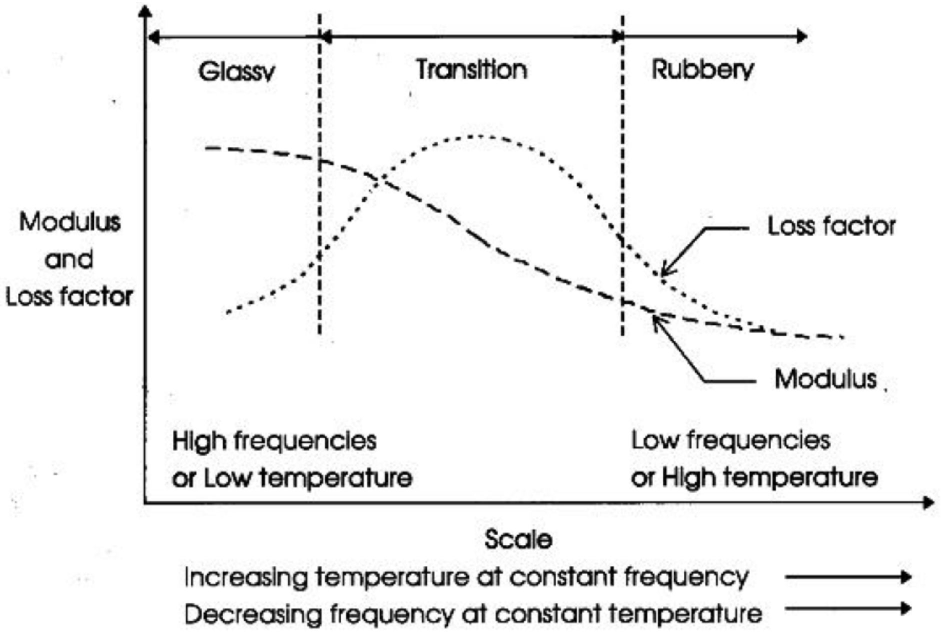


Figure 65: Properties of typical viscoelastic material

At low frequencies and/or high temperatures, the material is soft and mobile enough for the strain to follow an applied stress without appreciable phase shift so that the damping is small; the material is said to be in its “rubbery” state. At high frequencies and/or low temperatures, the material is stiff, immobile, may tend to be brittle, is relatively undamped, and behaves somewhat like glass; it is said to be in “glassy state”.

At intermediate frequencies and temperatures, the modulus takes on intermediate values and the loss factor is highest; the material is said to be in its “transition” state and the damping capacity of the material is highest in this state.

The above-mentioned material behavior may be explained on the basis of the interactions of the long-chain molecules that constitute polymeric materials.

At low temperatures, the molecules are relatively inactive. They remain “locked together” resulting in high stiffness and because they move little relative to each other, there is little molecular friction to produce damping. At high temperatures, the molecules become active, they move easily relatively to each other, resulting in low stiffness. And because they interact little, there is again little energy dissipation from intermolecular friction with no significant damping again. At intermediate temperature, where the molecules have intermediate relative motion and interaction, the stiffness also takes on an intermediate value and the loss factor is greatest.

A similar discussion applies to the effect of frequency on the material properties, with the inertia of the molecules leading to their decreasing mobility and interaction with increasing frequency.

For a vibration damper to be effective it must be tuned near the frequencies of maximum energy dissipation illustrated in Figure 65. This tuning effect has a profound influence on the choice of VEM used in the damper. If the VEM damper was to be operated within the transition temperature range, where the loss factor is high and the modulus changes rapidly with temperature, then the internal heating of the damper due to energy dissipation would cause the resonant frequency to change and the damper p detune itself. Therefore, VEMs for tuned dampers should generally be used in the rubbery region, as shown in Figure 65, where small changes in temperature do not have a large effect on the stiffness. Therefore, most practical VEMs have a maximum loss factor in the rubbery region, from 0.1 to 0.2.

6.3.1 Effect of temperature

Temperature is usually considered to be the single most important environment affecting the properties of damping materials. This effect is illustrated in Figure 66, where four distinct regions for a given damping material can be observed.

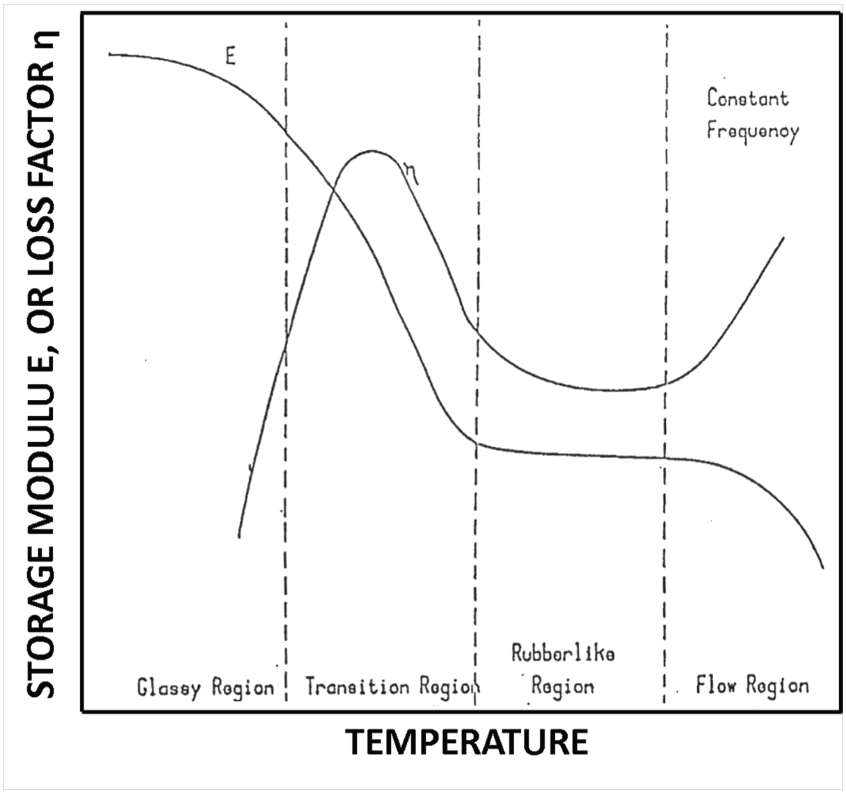


Figure 66: Variation of the Storage Modulus and Loss Factor with Temperature in four different regions Glassy-, Transition-, Rubberlike- and Flow Regions

The first region is the so-called glassy region, where the material takes on its maximum values for the storage modulus while having extremely low values for the loss factor. The modulus in the glassy region changes slowly with temperature while the loss factor increases significantly with increasing temperature.

The second region is characterized by having a modulus that decreases rapidly with increasing temperature while the loss factor takes on its maximum value.

The third region is the rubbery one, where both the modulus and the loss factor take on somewhat low values and slowly vary with temperature.

The fourth region is typical of materials such as vitreous enamels and thermoplastics. In this region the material continues to soften with increasing temperature as it melts, while the loss factor takes on a very high value. Although the fourth region is important for complete understanding of the behavior of materials, it is of little use in the design of damped system because of its instability and other unwanted physical properties.

Although the behavior illustrated in Figure 66 is typical of all rubber-like materials, different materials have different specific properties, characterized mainly by the various levels of the storage modulus and loss factor within each temperature region and the location of each region with respect to temperature, which usually varies from material to material. Typical values of the storage modulus could be as high as 10^8 kPa in the glassy region, and as low as 10 kPa in the rubbery region. The width of the transition region could vary anywhere from T=20 ˚C for an unfilled viscoelastic material to as high as T=200 ˚C or T=300 ˚C for a vitreous enamel. The width of the rubbery region could vary anywhere from T=50 ˚C or T=300 ˚C, as for may silicone materials. The loss factor in the glassy region is usually below 10^{-2}or 10^{-3}, while it could reach values as high as 1 or 2 in the transition region. Typical loss factor values in the rubbery region are usually between 0.1 to 0.5 for most materials, depending on their composition.

If the application requires materials with properties that do not change significantly either as function of temperature or frequency (6.3.2), then one must use them within the rubbery region only. Such situations are often encountered in tuned dampers. Those devices are designed for a specific resonant frequency and therefore, if the temperature changes and the rubber material have temperature dependent properties, then their performance will be greatly affected.

One of the easiest ways of broadening the temperature range over which damping can be achieved by unconstrained-layer damping treatments is by selecting materials with different properties. These optimum properties must occur at two different temperatures. For instance, if the temperature range for which the treatment has to operate is from T=-45 ˚C to T=65 ˚C, it might be necessary to select one material that has its optimum value around T=-18 ˚C and another material that has its optimum value at approximately T=38 ˚C. It will then be possible to place one material layer on each side of the structure, so their performances are combined to give wide temperature coverage.

Other attempts have been made to combine the effects of multiple materials in one viscoelastic material. To do this, it is necessary to combine materials that are chemically incompatible. For example, nitrile-butadiene rubber, polyvinyl acetate, and polystyrene are three materials which are not chemically compatible. These materials, if mixed by a mechanical mill before curing, can produce one macroscopically homogeneous material having three sets of properties in three temperature ranges. The reason for this is that the nitrile-butadiene rubber has its optimum damping below room temperature, the polyvinyl acetate has its optimum damping at approximately T=65 ˚C, and polystyrene has its optimum damping at approximately T=150 ˚C. Therefore, by combining these three materials, it is expected that three transition regions with temperature will occur, and high damping can be achieved around each of those temperatures. Figure 67 illustrates the performance of such a blend with temperature. Three distinct peaks exist where each of the materials goes through its transition region. Although the performance of such a treatment is very broad, the peak loss factor is not very high at any single temperature. This is the trade-off that must be made when resorting to multiple materials.

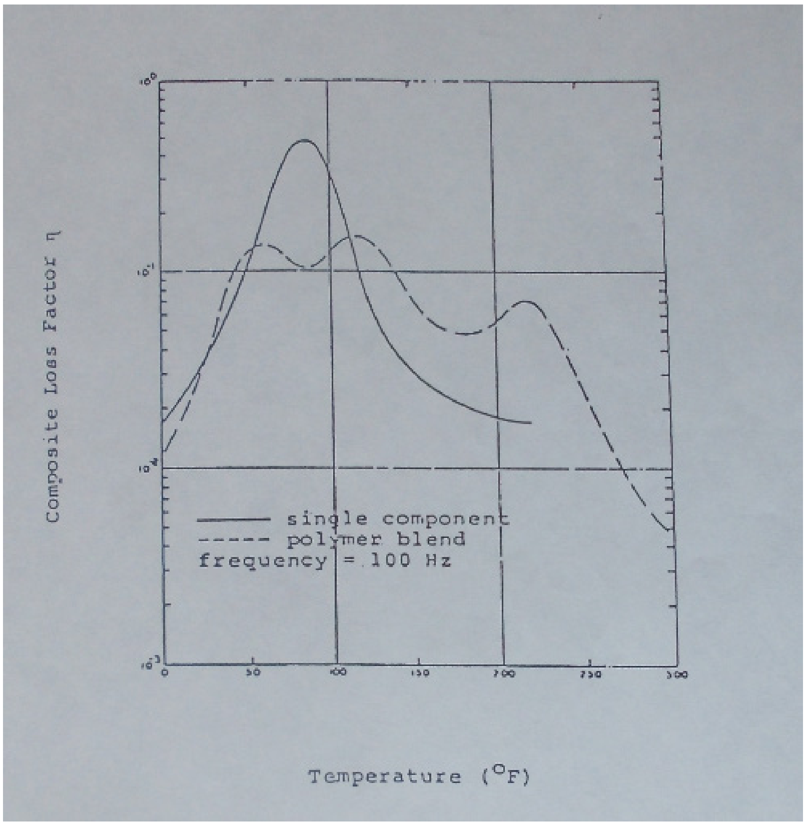


Figure 67: Effects of Polymer Blends on the performance of the unconstrained- layer damping treatment.

Different viscous liquids for standard viscodampers, are available with very low, limited, and high temperature dependency. Liquid with low temperature dependency is of low viscosity and will, therefore, lead typically to bigger dampers and more complicated systems.

A major criterion in the selection of viscodampers of high temperature dependency is the so-called operating temperature, which is the maximum temperature inside the viscous liquid during continuous operation of the plant. It is typically much lower than the temperature inside the piping and depends in a major way on the ambient temperature.

The viscous liquid will be adapted to the operating temperature and can be selected for temperature dependent viscous liquid in the temperature range between T=20 °C and T=80 °C in steps of T=10 °C.

Viscous liquid with limited temperature dependency can be used in the temperature range between T=-10 °C and T=40 °C.

Standard pipework dampers will allow heat expansion of ± 40 mm in all directions, but special dampers have been developed, permitting horizontal direction deflections up to ± 120 mm. Other combinations of vertical and horizontal heat expansion will need a special design, which is usually possible.

In case of high heat expansion, the operating temperature in the temperature dependent liquid should not be more than 20 °C above the start-up temperature, as otherwise very high loads in the connecting structure must be expected during start-up. In case of high expansion velocities and high temperatures in the pipe, the connecting structure between piping and pipework damper should be designed in a way that as little heat as possible is transmitted from the pipe into the damper.

6.3.2 Effect of frequency

The effect of frequency on the damping properties of a rubber-like material is illustrated in Figure 68 for a number of different temperatures. These temperatures are selected to illustrate the effects of frequency on the damping properties in the glassy, transition and rubbery regions. One of the effects which frequency has on the damping properties is the fact that the modulus always increases with increasing frequency. However, as illustrated in Figure 68, this increase is rather small in both the glassy (temperature T_{-1} and T_{-2}) and rubbery regions (temperatures T_1 and T_2), while it takes on its greatest rate of change in the transition region (temperature T_0).

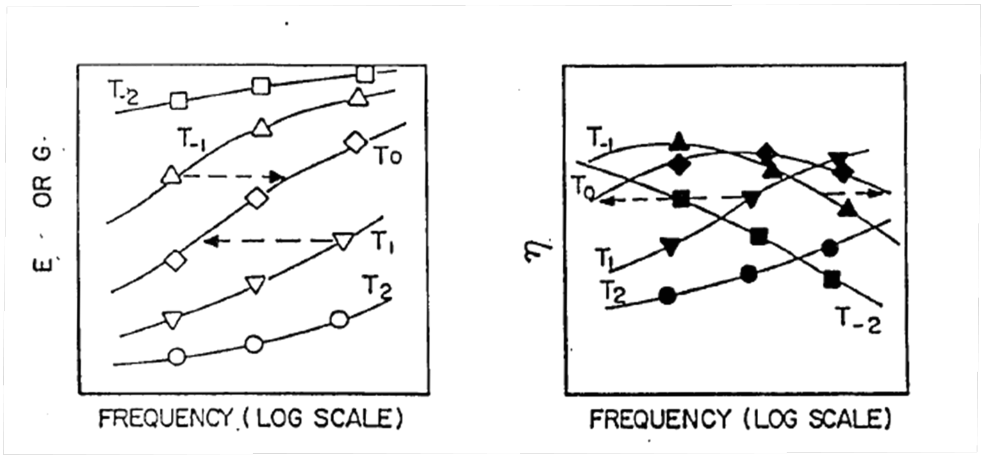


Figure 68: Variation of the Complex Storage Modulus (to the left) and Loss factor (to the right) with frequency in the glassy- (temperature T_{-1} and T_{-2}), rubbery- (temperatures T_1 and T_2), transition region (temperature T_0).

As far as the loss factor is concerned, it can be seen, in Figure 69 that it increases with increasing frequency in the rubbery region, (temperatures T_1 and T_2), while it takes on its maximum value in the transition region (temperature T_0) where it is almost flat, and then it decreases with the increasing frequency in the glassy region (temperature T_{-1} and T_{-2}).

The variation of the material properties illustrated above is typical of those materials with high damping capabilities over a frequency range of about two or three decades. If a considerably larger frequency range is considered, such as ten decades or more, then the variation of the damping properties with frequency at fixed temperature is expected to take the shape illustrated in Figure 69.

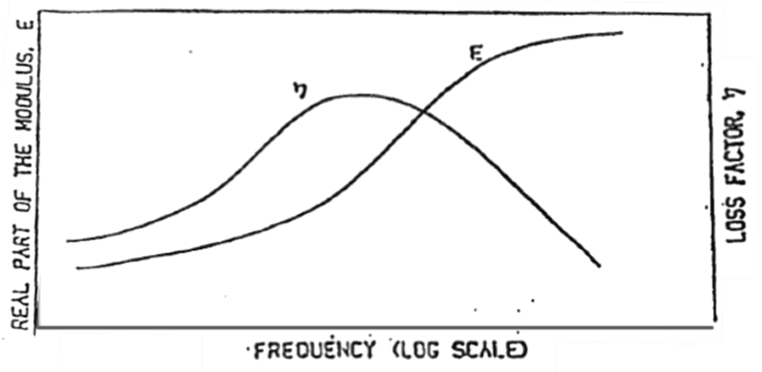


Figure 69: Variation of the Real Part of the Modulus and Loss Factor with frequency

A close examination of Figure 69 reveals that it is qualitatively the inverse of the temperature, but to a lesser degree i.e. it takes several decades of frequency to reflect the same change of behavior with a few degrees of temperature. Such a phenomenon is probably one of the most important aspects of viscoelastic materials. This behavior provides the basis for the temperature-frequency superposition principle which is used to transform material properties from the frequency domain to the temperature domain and vice-versa.

6.3.3 Effects of cyclic dynamic strain

The effects of the dynamic strain amplitude on the damping properties of materials are very difficult to measure. This is because high strain amplitudes usually result in high energy dissipation in the material, which causes the temperature of the material to rise rapidly, so that the two effects of temperature and strain amplitude become combined.

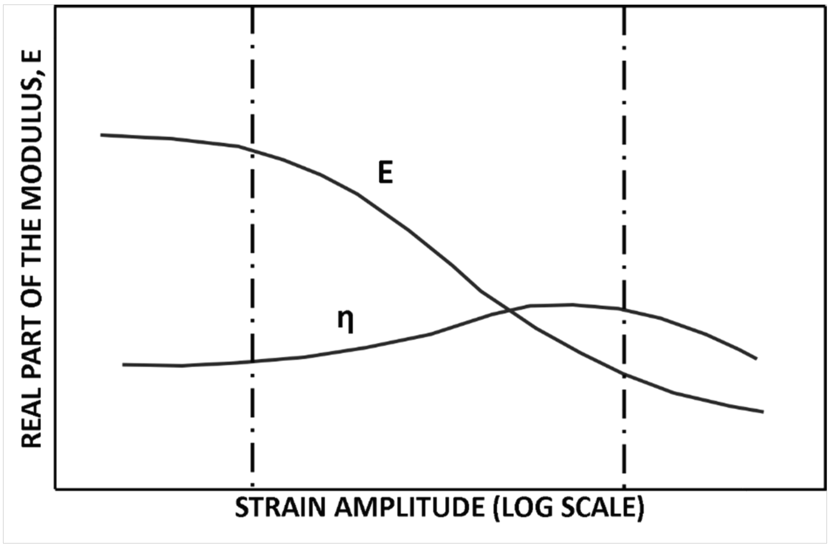


Figure 70: Variation of the Real Part of the Modulus and Loss Factor with Strain Amplitude

Since damping is usually best achieved when the damping material is subjected to large cyclic deformations, the location of the damping material on the vibrating structure is important. Therefore, a knowledge of the vibrational mode shapes of interest is necessary to determine the location where the maximum bending stresses occur. Unfortunately, for most cases, it is not practical to do this, because damping is usually required for many modes covering a wide frequency range.

6.3.4 Effects of time

It has been mentioned before that viscoelastic materials behave differently than elastic materials. One significant difference is the fact that when a load is applied to a viscoelastic material and then removed, the material recovers only some of its strain energy and dissipates the remainder into heat. This recovery varies not only with time but also with the environment, such as temperature.

Effects of time are measured in terms of relaxation or creep. A relaxation test consists of applying a fixed displacement to a material and then measuring the resulting force as a function of time. Conversely, a creep test consists of applying a fixed force to the material and then measuring the resulting deformation as function of time.

6.3.5 Effects of radiation

Among the two main suppliers of viscodampers GERB and Vicoda so is it only GERB which review permissible radiation dose for one their viscodamper type VES.

Metallic parts	10^7 J/kg
Non-metallic parts	10^5 J/kg
Viscofluid	10^5 J/kg

None of the members in the NPP have detected problems with their viscodampers which can be traced to radiation effect.

6.3.6 Effects of fire

Visco-fluid and visco-elastic materials should be kept away from all sources of ignition, fire, heat and sparks.

Decomposition products are carbon oxides (CO, CO2). The fluid will depolymerize at temperatures above 250 °C. Flash point is above 170 °C.

The damping effect will be reduced when decomposition takes place.

Rapid depolymerization can occur during a fire which may lead to production of flammable vapors.

If welding is done near the pipework dampers, the dampers and especially the sleeves must be protected from being damaged.

The sleeves prevent foreign substances from getting into the liquid. Visco-fluid retains its properties for decades as long as no contaminants (e.g. water, mineral oil, other liquids etc.) get into the liquid.

6.3.7 Effects of load range

Since damping is usually best achieved when the damping material is subjected to large cyclic deformation, the location of the damping device on the vibrating pipe is important. Therefore, a knowledge of the vibrational mode shapes of interest is necessary to determine the location where the maximum bending stresses occur.

The effect of the dynamic strain amplitude on the damping properties of materials are very difficult to measure. This is because high strain amplitudes usually result in high energy dissipation in the material, which causes the temperature of the material to rise rapidly, so that the two effects of temperature and strain amplitude become combined. This is especially true if one tries to measure the effects of the dynamic strain in the transition region of materials, see Figure 65 in chapter 6.3, where their damping is extremely high. However, in the rubbery region where the modulus and the loss factor vary more slowly with temperature, the effect of temperature becomes secondary to that of dynamic strain amplitude. Therefore, most work on the effects of dynamic strain amplitude on the damping properties has been limited to the rubbery region.

6.4 INSTALLATION OF VISCO DAMPERS

Viscodampers must stand upright during transport, storage and installation. If not handled properly, it could happen that

a) the highly viscous damping liquid leaks out,

b) the protective sleeve and

c) the protective paint cover is damaged.

Any damage must be properly repaired.

Small gaps between top plate of the viscodamper and the pipework system or substructure (up to max. 5 mm) during installation can be closed by pulling up the top part of the pipework damper. Wider gaps must be closed with steel shims.

Make sure that the expected heat expansion of the pipe during operation is taken into account and that the clamping system is not allowed to become loose.

6.4.1 Alignment

Depending on number of designed SDOF direction of the viscodamper the alignment influences the damping capability. Let's say that the viscodamper is designed only for vertical damping and not for damping in the horizontal direction. By experience, an angle of up to 5 degrees should not significantly change the behavior of the viscodamper. A bigger angle would actually increase the damping resistance, since the shear area increases, but would also create a bigger moment on the piston.

However, if the damping device is misaligned and it is designed for multiple SDOF directions this will influence the damping resistance to be unevenly distributed. Depending on misalignment direction, shear area from the piston can increase or decrease with an uneven damping performance.

An example of reduction of damping capability in vertical direction due to a misalignment problem is shown in Figure 71 and Figure 72. The result shows that the floor vibration response reached 0.60 mm/s rms with a correct aligned damper but a vibration level as high as 0.85 mm/s rms with a with a vertical misalignment about 7-9 degrees. Comparison tests was made at fixed pump speed 960 rpm (16.0 Hz). This verifies that alignment above 5 degrees should be taken care of. Note that the verification was not done at the tuned damper frequency at 16.1 Hz where optimum damping occurs. As a result, a higher deviation between aligned and misaligned condition is to be expected if the fixed pump speed has shifted to the tuned frequency 966 rpm (f=16.1 Hz).

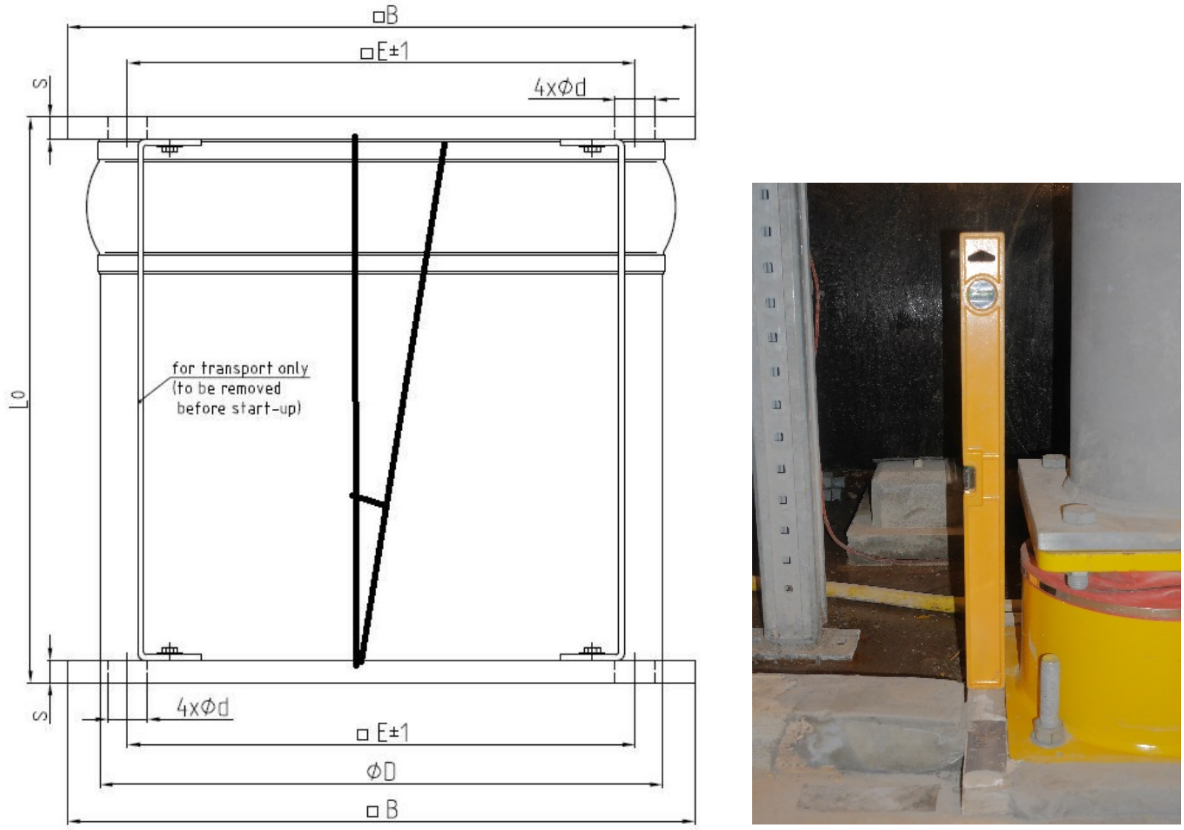


Figure 71 Viscodamper with vertical misalignment to approximately 7-9 degrees.

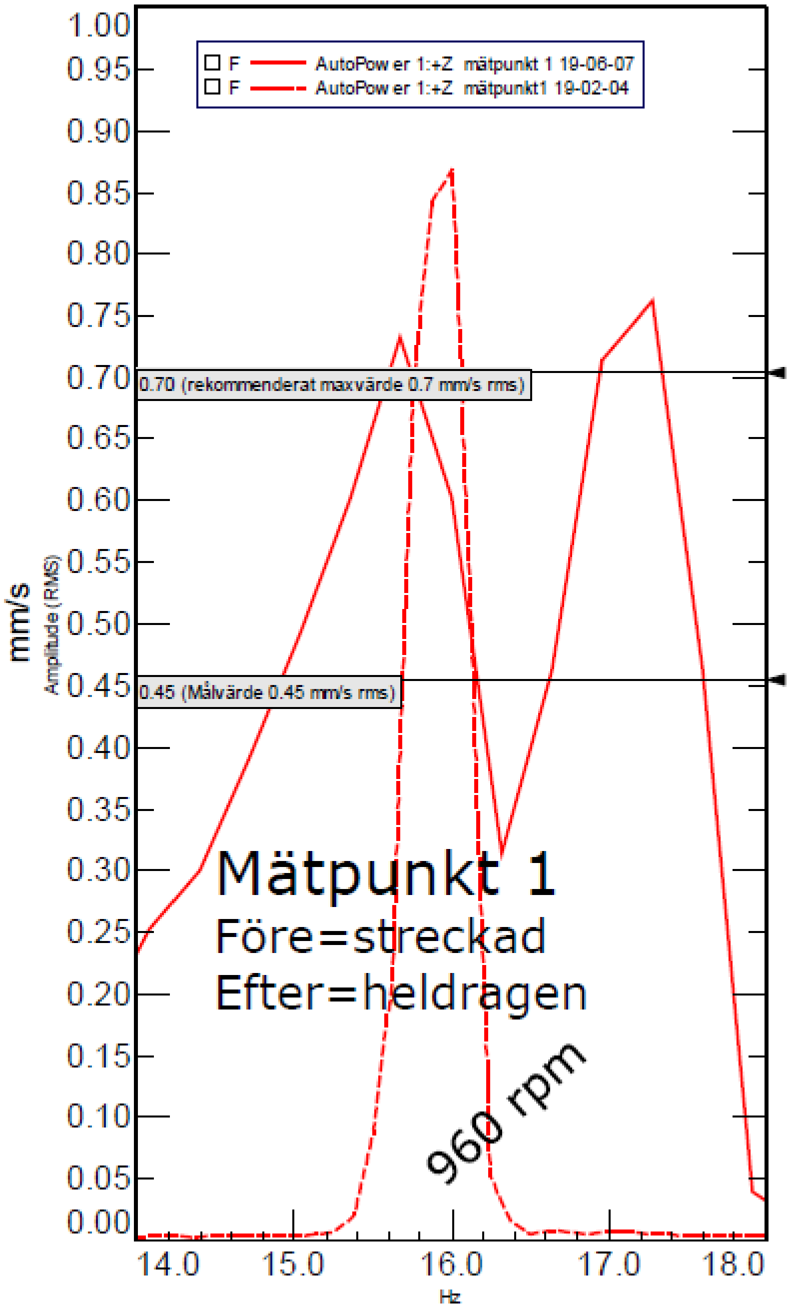


Figure 72: Vibration response on a damped machine floor with GERB damper tuned to f=16.1 Hz. Runup of pump between 840 -1080 rpm (=14.0-18.0 Hz) with a correct aligned viscodamper. The second dotted curve shows the floor vibration response at fixed rpm 960 rpm (=16.0 Hz) when damper is misaligned approximately 7-9 degrees.

When you have hot pipes, you have to take into account the temperature effect when aligning the piston in the viscodamper. During cold conditions the viscodamper often needs to be mounted misaligned but when system is preheated the dampers will get erected in an aligned position.

The viscous fluid will also get influenced by heating and therefore the fluid properties needs to be selected for the added external heating during operational conditions. A viscofluid will get stiffer when heat is added, and the tuned frequency may increase. It's a recommendation to verify the viscofluid temperature during the operation and check datasheet for verification of effective temperature. Efterklang® has performed verification temperature tests of GERB viscodampers with good results to follow the supplied data sheets see 6.6.

A viscoelastic damper link requires to be mounted with correct alignment, i.e. make sure that the connecting nuts on upper and lower part of the link have not been welded in an aligned way. A misalignment will lead to a reduced shearing area and then a reduction of damping as shown in Figure 73.

Figure 73: Misalignment of a damper link which gives reduced damping performance.

6.4.2 Damper installation to a structure

To achieve optimal damping of a shearing damper device like GERB viscodamper, the anchor mounting position of the damper must be dynamically rigid so that a relative movement is allow for shearing can take place in the damper.

A rule of thumb is that the mounting anchor position needs to be at least 10 times stiffer than the upper moving part.

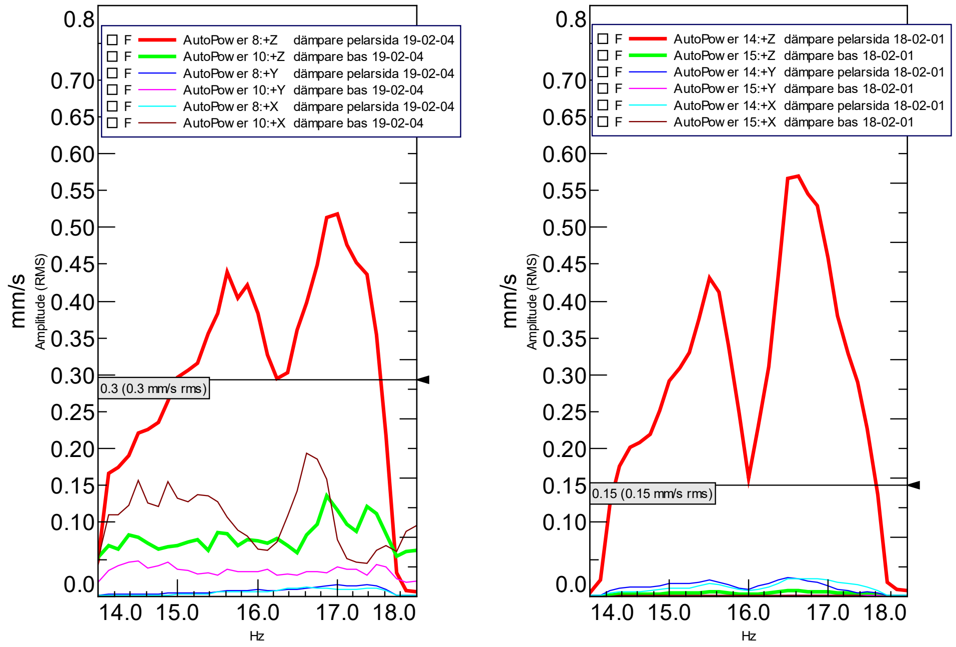


Figure 74: Same damper device but with two different dynamic anchoring positions. Picture to left shows a vibration level of 0.3 mm/s rms @ f=16.1 Hz with damper. Picture to right shows a vibration level of 0.15 mm/s rms @ f=16.1 Hz with same damper.

In Figure 74 there is an example of different performance of damper capability tuned to f=16.1 Hz when the mounting anchor position is a factor of at least 10 times more flexible between the two cases (left and right picture in Figure 76.

Halved damping capacity at tuned damper frequency f=16.1 Hz is achieved when the anchor base position is 10 times more flexible at f=16.1 Hz.

The base for the damper (measuring point 10/15 in Figure 74) is at least 10 times more mobile in all three directions x-, y-, z-point between the two cases.

When vibration levels are predicted for damping countermeasures there is always a recommendation during the design phase to verify with an impact test the dynamic stiffness of the mounting base structure. The dynamic stiffness ratio between the moving and fixed position of the viscodamper should always be at least of a factor 10 to achieve an optimum damping performance.

6.5 LABORATORY TESTS

Laboratory tests are preferable if dampers need to be checked for low cycle fatigue i.e. slow temperature variations, control of supplier’s data sheets, temperature effect and how they will degrade with age etc.

Also, for product development test rigs are to prefer.

The test rig should be able to measure displacement and force when the test sample is tested under different operational excitation profiles, like random and stepped sine profile or low frequency triangular waves. It’s a recommendation that the test rig conforms to a standard. An example of standard for resilient materials is ISO10846-2.

ISO 10846-2:2008 specifies a method for determining the dynamic transfer stiffness for translations of resilient supports, under specified preload.

The dynamic stiffness can be directly registered from the force cell which register acting force, F, in the top part of the damper and the displacement, d, from the displacement sensor in the lower part.

By knowing dynamic displacement and force, two often occurring damping measures from damper supplier can be determined and compared to initial conditions and changed conditions due to temperature, fatigue cycles etc. These are the dynamic stiffness [N/m] and damping resistant [Ns/m]. Damping resistant, is the mechanical impedance which can be calculated by a first derivative of the dynamic stiffness.

Damping resistant = Re {F/v} [Ns/m] Equation 8

Dynamic stiffness= Re {F/d} [N/m] Equation 9

A life cycle test of a damper link for slow fatigue cycle test in a test rig can be set up in following sequence:

A triangular saw tooth wave with frequency f=0.1 Hz is cycled with repeatable cycles 100, 3600, 5400 and 10 000 cycles with a displacement of 1 mm. The damper link was mounted in the servo-hydraulic test rig as can be seen in Figure 75. Dynamic stiffness measurement was taken after each discrete numbers of cycles was reached.

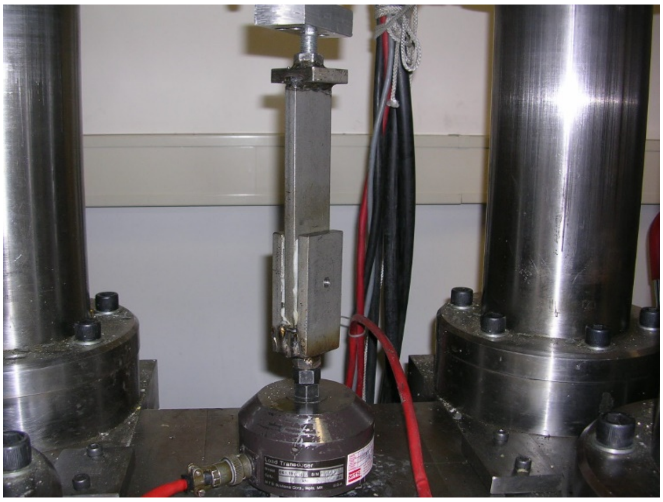


Figure 75: Damper link installed in a servo-hydraulic test rig which belongs to Efterklang®. Test rig conforms to ISO10846-2. Picture shows initial damper link status for 0 cycles.

By visual inspection there is no major difference of the damper link from initial 0 cycles and 10 000 cycles test, see Figure 76.

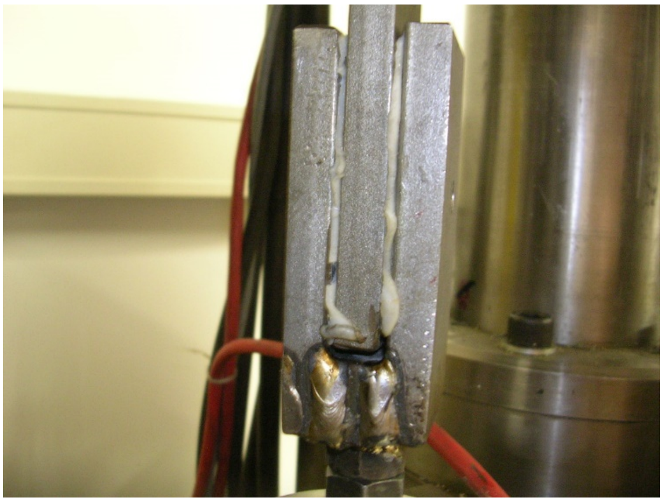


Figure 76: Damper link after 10 000 cycles

Visual inspection is a first quality test for fatigue influence but needs to be verified by test, see dynamic stiffness results after different cycle numbers in Figure 79.

Next, the damper link was broken, see Figure 77, and repaired, see Figure 78, by fitting the pieces together again. No glue is needed since viscoelastic polymer is often self-adhesive. This is preferable since the glue needs to be selected carefully when thin shearing areas requires thinner glue layer and with a glue which is relative stiff so the shearing takes place in the polymer and not in the softer glue layer, see 3.3.1.

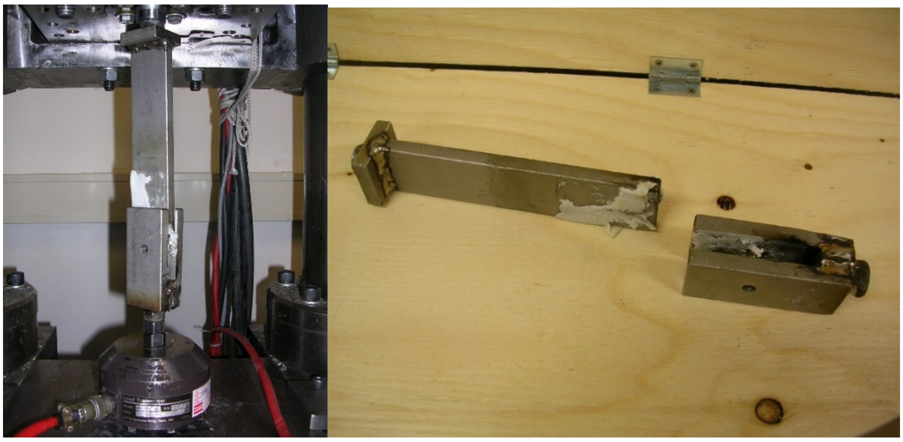


Figure 77: The viscoelastic shear layer was torn apart i.e. a broken damper link.

Figure 78: Broken and repaired damper link. The viscoelastic polymer is self-adhesive.

By a visual inspection from Figure 78 there is not difficult to predict that the damping performance must have been changed from initial condition. There are many more questions about how these viscoelastic materials which are usually made up by long polymer chains are dynamical changed depending on which loading they are interfering.

New questions, like what will happened when a broken and repaired damper link will undergo additional cycles and rest for 24 hours before new event of cycles occurs.

This cannot any longer be judge by visual inspection and you don’t know before you have verified it by controlled rig test. Result from the above described tests can be read i99 6.6.

6.5.1 Laboratory tests performed for the standard viscodampers

The viscoelastic dampers and damping parameters from VICODA are tested and monitored by their in-house test lab as well as independent test laboratories based on Safety Standard KTA 3205.3 issued by the German Nuclear Safety Standards Commission (KTA).

GERB viscodampers type VES are performance tested by German TÜV for use as a standard part in nuclear power plants and fulfills KTA Safety Standard 3205.3.

According to KTA Safety Standard 3205.3 all assemblies shall be tested with reference to their:

- Structural design
- Structural strength
- Weld details
- Material
- Function

The vibration test according to the KTA Safety Standard 3205.3 including 2 x 10^6 load cycles at a frequency of 15 Hz and an amplitude of 0.1 mm is covered by the fatigue test carried out including 2 x 10^6 load cycles at a frequency of 11 Hz and 10 % nominal load.

6.6 VERIFICATION MEASUREMENTS OF DAMPERS

From the first test with the cycled damper link described in 6.5 shows that the damper-link maintain its dynamic performance up to 3600 cycles, see Figure 79, in frequency range f=2-100 Hz. However, after 5 400 cycles there is a significant drop in dynamic stiffness but seems to repair itself after 10 000 cycles especially above 40 Hz.

The second test where the damper link was broken and repaired still shows a very good damping performance up to 5000 cycles for frequencies above 10 Hz.

The broken, repaired and 24 h rested damper link confirms that the damper link is self-repairing, se Figure 80.

Both result of the two tests shows that viscoelastic polymer is robust material which does not show low cycle fatigue and is self-repairing.

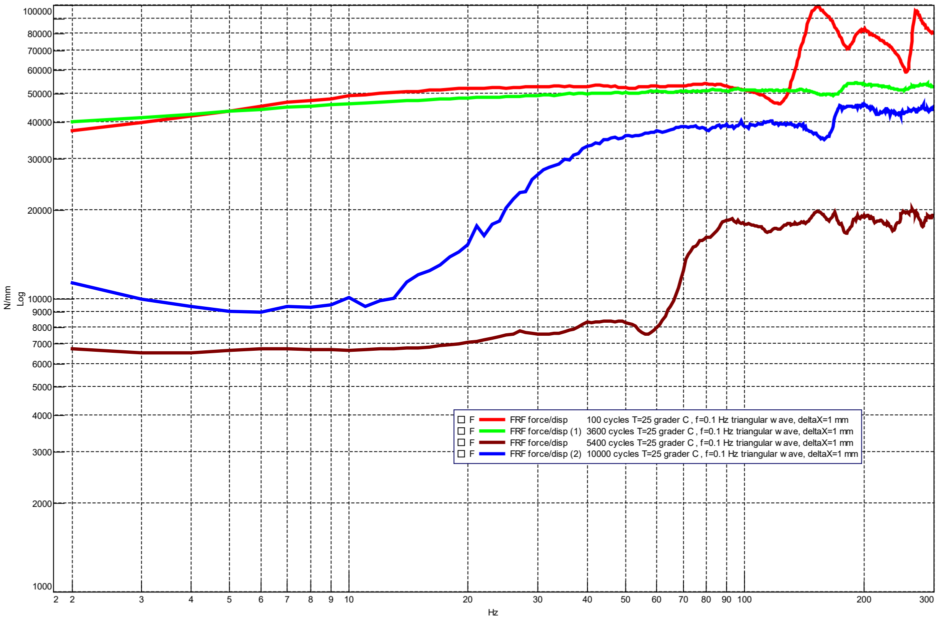


Figure 79: Dynamic stiffness result for low cycle fatigue tests at f=0.1 Hz triangular wave excitation after 100 cycles, 3600 cycles, 5400 cycles and 10 000 cycles.

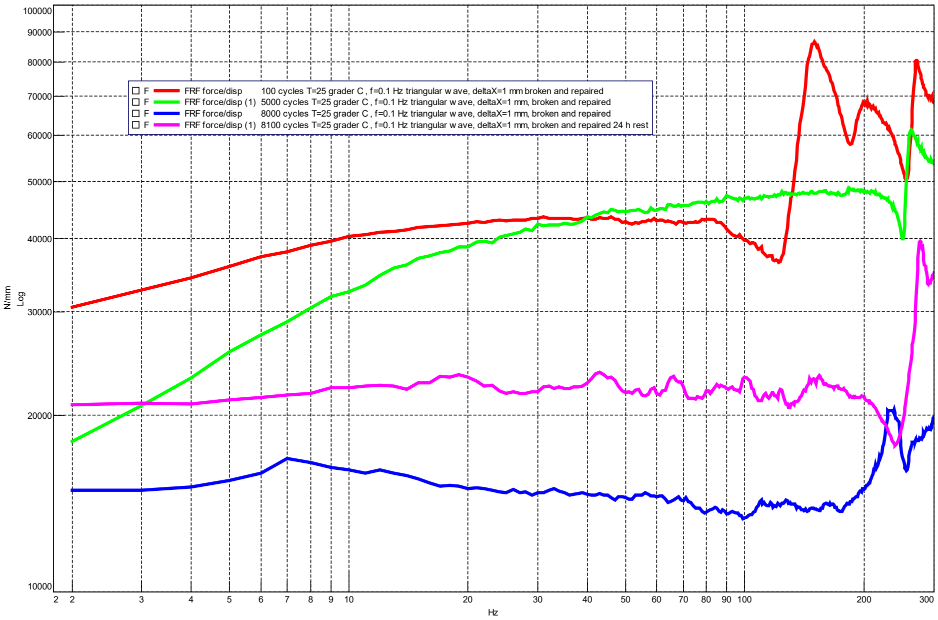


Figure 80: Dynamic stiffness result for low cycle fatigue tests at f=0.1 Hz triangular wave excitation after broken and repaired damper link. Curves show result after: 100 cycles, 5000 cycles, 8000 cycles and 8100 cycles (material has been under rest in 24 h)

Test on how the viscodamper dynamic damping resistance varies with temperature and frequency can also be checked and verified with test rig measurements. The tested article is described in Figure 81

Figure 81: Test rig verification of a VES-5/V40/H40 GERB damper. Damping resistant and dynamic stiffness are measured at different temperature during a stepped sine test. Test rig belongs to Efterklang® (part of AFRY)

The following measurement parameters were used in the data collection:

- Excitation with stepped sine signal 2 - 30 Hz
- Constant vibration velocity 5 mm/s RMS
- Frequency resolution 2 Hz

The results between the measured damping resistance and suppliers datasheet agreed very well, both evaluated in Temperature as in Frequency, as can be seen in Figure 82 and Figure 83.

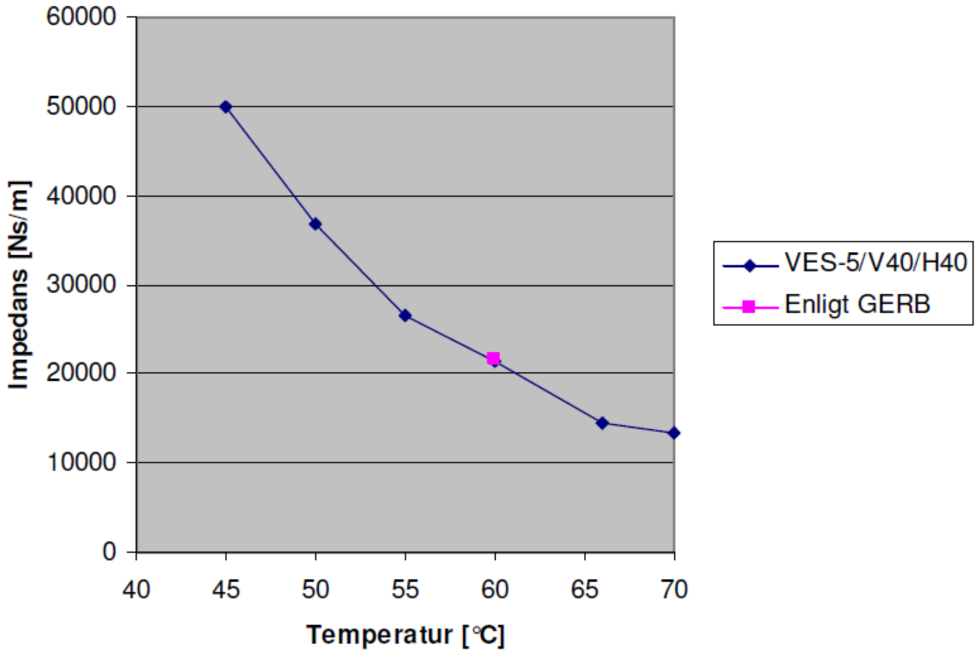


Figure 82: Measured damping resistance at f=10 Hz as function of temperature with tabulated supplier value at T=60 ˚C for damper VES-5/V40/H40.

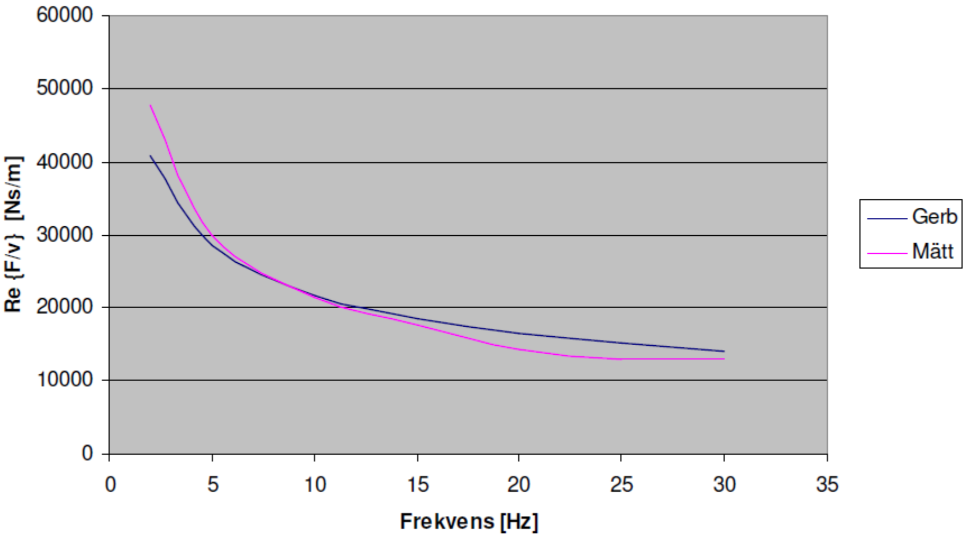


Figure 83: Measured damping resistance at T=60˚C as function of frequency with supplier curve

The reason to check the damper at T=60˚C was that the damper was to be direct mounted at a varying steam pipe at OKG according to a Figure 84.

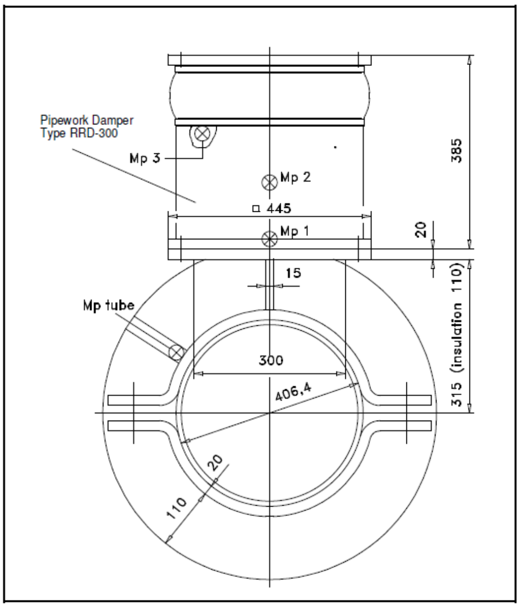


Figure 84: Mp=Temperature position on pipe, MP1=Temperature position on bottom plate, MP2=Temperature position for the damper housing and MP3=Temperature position for the viscofluid

The temperature decrease from a varying steam pipe to the dampers viscofluid is shown in Table 8, for a direct mounting to a steam pipe.

MP: Steam pipe T [˚C]	MP1: Dampers bottom plate T [˚C]	MP2: Damper housing T [˚C]	MP3: Viscofluid T [˚C]
144	47	39	36
125	50	41	38
150	55	42	38
175	64	45	41
210	70	52	45
225	75	55	45
250	81	59	49
300	102	77	62

Table 8: Temperature decrease between a hot steam pipe and the actual temperature decreases between the bottom plate, damper housing and finally the viscofluid.

The measurements show that the temperature drops rapidly from the steam pipe T=300 °C to be estimated to T=62 °C for viscous fluid.

For heating, a standard stove plate was placed directly under the lower mounting plate of the damper in the test rig.

The temperature of the viscofluid may have varied during the tests, due to the low heat conductivity of the viscoelastic mass. Possibly most of the viscosity mass has been warmer than the monitored, since the temperature sensor was stuck only a few millimeters in the viscofluid mass.

6.7 MAINTENANCE ISSUES OF DIFFERENT DAMPERS

Environmental conditions in combination with long holding times may deteriorate the viscofluid/VEM properties affecting the modulus and loss factor.

Long-term exposure of natural rubber to sunlight or oxygen induces ageing which increases molecular cross linking in the material and results in an increase in dynamic modulus and a decrease in the loss factor. Ageing also results with steady holding of the material at elevated temperatures for a long time. Some materials lose plasticizer content by evaporation due to long held high temperatures while others can ´out gas´ under long periods of low pressure or vacuum. Some are deteriorated by exposure to oil while others are sensitive to moisture. In short, environmental conditions affect dynamic properties of VEMs in one way or the other, therefore, must be given due consideration when selecting a material for a particular damping treatment.

6.7.1 Standard viscodampers

However, both suppliers recommend visual control should be an integral part of regular plant inspection and maintenance and is recommended once a year.

Following parameters should be checked:

- Is the viscodamper still properly fixed ?
- Is the damper piston still within its permissible vertical and horizontal limits, see Figure 85?

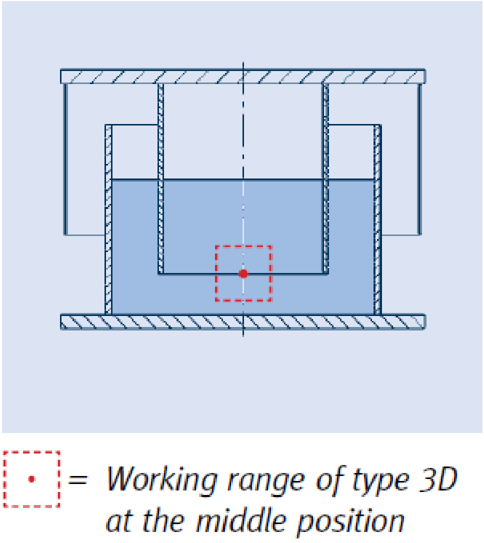


Figure 85: Viscodamper with permissible vertical and horizontal limits

If the piston is beyond permissible limits or if it appears it may go beyond these limits, loosen the connecting bolts between the upper and lower parts of the viscodamper and pipework itself. Move the entire pipework damper until the piston is again in a central or otherwise permissible position. Tighten the connecting bolts again.

- Are the sleeves still properly secured?
- Are the clamps sufficiently tensioned?
- Are there tears or holes in the sleeves?

Any damaged sleeves must be replaced. Remove the damper and check the visco-liquid. If the damping medium is contaminated, contact the supplier. As long as the sleeves are intact, the pipework dampers should not be damaged.

6.7.2 Snubbers

The maintenance of these dampers is controlled by the SSM regulations. There it is stated that the dampers are to be functionality checked every ten years. In Forsmark this means that the damper is removed from its position and is replaced with a new damper or renovated. For example, each year Forsmark replaces approximately 50 hydraulic dampers and the ones that are removed are thereafter sent to the manufacturer for a function test, tensile test, as a ''as found'' test. The damper is then renovated and sent back to Forsmark to be used as a replacement part for the next year outage. Besides this functionality check there are continuous visual inspections done were one looks for oil leakage, unnormal wear and tear in connection points etc.

There is also, in the SSM regulations, written that when a new damper is installed it has to be checked for functionality after 3 years. Life Cycle Costs of different dampers.

6.8 LIFE CYCLE OF DIFFERENT DAMPERS

6.8.1 Standard Viscodampers

Viscodampers are by experience from all the NPPs very robust if properly designed and installed.

GERB viscodampers are expected to require no maintenance at least for a period of 40 years, because of their simple design and the lack of mechanical wear and tear parts. The visco-liquid is resistant to aging for the same period. The expectation for Vicoda viscodampers are the same, even though the supplier does not promise any life span. As a result, when installed and mounted their cost is very limited.

Their price to buy are approximately 35 000 SEK (2017) per each for their standard element on the shelf. If the standard viscodamper need to be verified or tuned to a special frequency, additional load etc. the supplier recommends an extra verification rig test. This test brings an additional cost of approx. 30 000 SEK (2017).

However, the main cost is the engineering cost in the design phase for Testing/FE-simulation to determine the damping resistance, operating temperature, load conditions etc.

6.8.2 Snubbers

Snubbers are shock absorbers which is not certified as standard product at the NPPs which then requires maintenance and periodic verification function tests in test rig, see Forsmark maintenance chapter 4.3.6.

According to GERB the life cycle cost is double in price compared to standard visco-dampers.

6.8.3 Mass Tuned Dampers

Mass tuned dampers are expected to also have low life cycle costs since they are maintenance- and wear-free if correctly designed and installed.

The engineering cost in the design phase is the main cost to the life cycle cost.

7 Problem solving with the DIAM-matrices

The DIAM (Detection Investigation Analysis Mitigation) matrix tool was developed by Paul Smeekes and Mikko Merikoski. A systematic approach was developed to simplify the process of solving and understanding pipe vibrations. The matrix tool guides the user through the process and recommends following actions. Based on the investigation findings the matrices suggest useful analysis methods and possible mitigation methods for the vibration problem.

The Vibration Identification starts with Detections and continues with Investigations and Analysis Methods.

If one or even more Vibration Phenomena have been identified, the procedure continues with the Vibration Mitigation A flow chart has been developed to control the flow of information between the matrices M1 to M4. Probability numbers are used in these matrices in order to identify the Vibration Phenomena in the described Identification steps followed by the selection of a suited Mitigation strategy.

In this project an additional matrix, to be implemented in DIAM matrix tool, when damping is selected as mitigation method. This matrix is to be used for identification of damper type and possible damper problems to take into account when designing and installing dampers in NPP pipe systems.

The matrix, see Table 9 or Appendix B, is based on the type of dampers discussed in this report, its requirements, problems and maintenance need.

- Viscous damper
- Viscoelastic damper
- Mass tuned damper
- Magnetic damper
- Hydraulic damper
- Regular pipe damper (i.e. spring)
- Mechanical damper
- Friction damper
- Yielding damper

And the corresponding properties of

- Vibration sources
    - × Steady-State random vibration
    - × Steady-State periodic vibration
    - × Dynamic-Transient vibration
- Response type
    - × Resonance
    - × Forced
- Prerequisites
    - × low frequency <50Hz / high freq >50Hz
    - × low displ <2mm / high displ. 2-40mm
    - × low temp / high temp
    - × radiation
    - × Static Load / Dynamic Load
    - × Single direction vibration / Multidirection vibration
    - × requires anchor point
- Damper Functions
    - × Velocity
    - × Acceleration
    - × Shearing
    - × SDOF
    - × Magnetic
    - × Friction
    - × Yielding
- Damper problems
    - × ageing
    - × thermal sensitivity
    - × Contamination sensitivity, eg oil
    - × leakage or loss of medium
    - × radiation sensitivity
    - × installation alignment sensitivity
    - × NPP classification NA
    - × Wear and tear
- Maintenance
    - × Visual inspection
    - × Functionality test

Table 9 Damper types and properties for DIAM matrix implementation. For close up see Appendix B

	Vibration sources			Response type		Prerequisites												Damper Functions							Damper problems								Mainteneance	
	Steady-State random vibration	Steady-State periodic vibration	Dynamic-Transient vibration	Resonance	Forced	low frequency <50Hz	high freq >50Hz	low displ <2mm	high displ. 2-40mm	low temp	high temp	radiation	Static Load	Dynamic Load	Single direction vibration	Multidirection vibration	requires anchor point	Velocity	Acceleration	Shearing	SDOF	Magnetic	Friction	Yielding	ageing	thermal sensitivity	Contamination sensitivity, eg oil	leakage or loss of medium	radiation sensitivity	installation alignment	NPP classification NA	Wear and tear	Visual inspection	Functionality test (SSM regulated)
Damper type																																		
Viscous damper	1	1	1	1	0	1	0	0	1	1	1	*NV	0	1	1	1	1	0	0	1	0	0	0	0	*NV	1	1	1	*NV	1	0	1	1	0
Viscoelastic damper	1	1	1	1	0	1	1	1	0	1	1	*NV	1	1	1	1	1	0	0	1	0	0	0	0	*NV	1	1	1	*NV	1	1	1	1	1
Mass tuned damper	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	0	?	0	*NV	1	1	0	*NV	0	1	1	1	1
Magnetic damper	1	1	1	1	0	1	1	1	0	1	1	*NV	0	1	1	0	0	0	0	0	0	1	0	0	*NV	0	1	0	*NV	0	1	1	1	1
Hydraulic damper	0	0	1	0	1	1	0	0	1	1	1	1*	1	1	1	0	1	1	1	0	0	0	0	0	1	0	0	1	0	1	0	1	1	1
Regular pipe damper (eg	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	1	0	0	0	1	0	0	0	0	1	1	1	1	0
Mechanical damper	0	0	1	0	1	1	1	0	1	1	1	1	1	1	1	0	1	1	1	0	0	0	0	0	1	0	0	0	0	1	1	1	1	1
Friction damper	1	1	1	1	1	1	0	1	0	1	1	1	1	1	1	1	1	0	0	0	0	0	1	0	*NV	1	1	0	0	0	1	0	1	1
Yielding damper	*NV	*NV	*NV	*NV	*NV	*NV	*NV	*NV	*NV	*NV	*NV	*NV	*NV	*NV	*NV	*NV	*NV	*NV	*NV	*NV	*NV	*NV	*NV	*NV	*NV	*NV	*NV	*NV	*NV	*NV	*NV	*NV	*NV	*NV
	(*NV= Not Verifierd)																																	

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

Appendix A: Questionnaire

Questionnaire

Survey of vibration dampers – Analysis and mitigation.
Project KKU52440

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2019-12-11

Sammanfattning

Frågorna i detta dokument är främst relaterad till vibrationsdämpare för rör men också andra strukturella objekt såsom maskiner och byggnad.

Mottagare av detta dokument är medlemmar i referensgruppen i projektet

KKU52440

Summary

The questions in this document are mainly related to vibration dampers for piping but also vibration dampers to other structural objects are included.

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

List of content

1 Background to different pipe mitigation countermeasures

There are different types of dynamic restraints that are specially designed to absorb sudden increase in load from the pipe and transfer into the structure and to dampen any opposing oscillation between the pipe and the structure. These restraints are not intended to carry the weight of pipe work and should not impede the function of the supports which also conforms to vibration dampers.

Examples on different conventual devices are “rigid studs, “mechanical or hydraulic snubber” etc.

Examples on different vibration dampers are “tuned mass dampers”, “viscoelastic dampers” etc.

a) Describe the specific examples when your site has selected a vibration damper counter measure instead of the conventual restraints and vice versa? Specify selection criterion.

b) What kind of experience do you have to vibrations dampers with regards to pipe excitation types? Examples of pipe excitation types can be “pressure shocks from valve operation”, “water hammer”, “fluid disturbances”, “mechanical vibrations transmitted from pumps or other equipment” etc.

c) When do you find vibration dampers most suitable for solving pipe vibration?

d) Lessons learned. Did your measures work as expected? Do you have any examples on outcomes that was not expected/predicted? Please describe how.

2 Damper types with fluids

There are visco- and visco-elastic dampers of different types that mitigates the pipe vibrations or dampers to other structures.

a) What kind of vibration dampers does your site have?

b) Where do you have them installed? (pipes, building, machines)

c) For how long time have they been installed?

d) What loads are they designed for?

e) Which temperature ranges are they designed for?

f) What frequency ranges are they designed for?

g) What is your site's designed maximum stroke length (thermal + operational)?

h) How often do you verify that your dampers are OK? That they are/are still doing their job.

i) Lessons learned. Did your measures work as expected? Do you have any examples on outcomes that was not expected/predicted? Please describe how.

3 Fluid type damper degeneracy

Structural applications require a fluid that is fire-resistant, nontoxic, thermally stable and that will not degrade with age.

a) Do you have any on-site procedure/s to check the dampers for degeneracy, wrt. irradiation, temperature effect etc.?
    a. If a method is available, please describe the method?
    b. Which observations have your site made for degradation of dampers?

b) How may Joules per kg in terms of radiation are the fluid in the dampers designed for?

c) What flame point must the fluid fulfil?

d) Do your installed dampers fulfil any kind of certificate specifically for using them in a nuclear power plant? Ex. German Technical Authority (TUV), German Nuclear Engineering Committee (KTA)?
    a. If not. Do you have an inhouse developed routine for testing the dampers?

e) Have you made any replacements of dampers due to malfunctioning after the first installation?

4 Vibration dampers mass tuned dampers, MTD

a) Do you have any MTD installed?

b) Where do you have them installed? (pipes, building, machines)

c) For what period of time have they been installed?

d) What loads are they designed for?

e) What frequency range are they designed for?

f) How often do you verify that your dampers are OK, still working as expected?

g) Lessons learned. Did your measures work as expected? Do you have any examples on outcomes that was not expected/predicted? Please describe how.

5 Design of dampers

a) What pipe systems do you find it most complicated to install pipe dampers to? Why? Please describe

b) How long is your NPP life cycle for a vibration damper?

c) Which vibration damper suppliers have you engaged and in what way?

d) Who usually designs the damper for your NPP?

e) What kind of vibration measurement results do you have as input to design a damper? Please describe in detail.

f) Do you carry out FEM/CFD analysis in order to design a damper? If yes, please describe.

g) How much added damping have you achieved in your different projects?

   a. Specify Damper type, Pipe type, Design Temperature with the archived added damping.

   b. If you succeeded to achieve damping in another direction than the main design direction, what was the outcome? Please describe.

h) Try to specify what problem areas you have encountered in the design process of a vibration damper?

i) Is it difficult to find a rigid base to attach a relative motion damper to?

   a. Are there any rule of thumbs you use for defining the base as rigid? If yes, please describe in detail.

   b. Do you have any workarounds to solve the problem if the base is not rigid enough?

6 Installations of damper

a) Please give some examples of pipe damper holders for both hot- / cold pipe for different kinds of dampers in vertical direction?

b) Please give some examples of pipe damper holders for both hot- / cold pipe for different kinds of dampers in horizontal direction?

c) Do you have any experience of damper holders which are used for all three excitation directions? If yes, please describe.

d) How do you make sure, during installation, that no alignment offset between stiff and movable part of damper occur in damper due to, for instance temperature effects?

e) Lessons learned. Did your measures work as expected? Do you have any examples on outcomes that was not expected/predicted? Please describe how.

7 In-situ and laboratory measurements of dampers

a) When a damper is designed, do you verify the function of the damper in a laboratory? If yes:

   a. Why do you perform complementary tests of dampers? Is some information often missing from the supplier for the selected damper?

   b. What parameters have been checked (temperature, radiation, low cycle fatigue etc)?

   c. Do you use internal or external laboratory and how is the facility equipped, for instance access to climate chamber?

   d. Do you perform accelerated life cycle tests on dampers for Life Cycle Analysis? If yes, please describe.

   e. What kind of verification measurements do you carry out to check that the damper is OK and that expected functionality is achieved and maintained over time?

   f. How was the agreement between laboratory tests and supplier data sheets for the selected damper?

b) Have you carried out in-situ measurements, to check dampers sensibility to unexpected changes of loads of equipment and/or increased flow? How were the tests planned and how were the safety, risk and validation handled?

c) Lessons learned. Did your measures work as expected? Do you have any examples on outcomes that was not expected/predicted? Please describe how.

SURVEY OF VIBRATION DAMPERS

Knowledge and practical experience on vibration dampers at the Nordic nuclear power plants has been collected here.

The main focus is vibration dampers suitable for piping applications, where both transient and steady state vibration are common problems that may be mitigated using vibration dampers.

Comparison of different types of dampers and their functions and capabilities including their advantages and disadvantages are highlighted, but also design and maintenance issues using vibration dampers to follow the special requirements at the nuclear power plants are described.

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