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PROTECTION OF PIPING SYSTEMS AGAINST OPERATIONAL VIBRATION AND SEISMIC EXCITATION BY MEANS OF VISCOELASTIC FLUID DAMPERS

F. Barutzki(1), I. Tamura(2) , M. Kuramasu(3), S. Kaneko(4)

(1) Technical Director, GERB Schwingungsisolierungen GmbH & Co.KG, frank.barutzki@gerb.de
(2) Manager, The Chugoku Electric Power Co., Inc., 350593@pnet.energia.co.jp
(3) Assistant Manager, The Chugoku Electric Power Co., Inc., 188918@pnet.energia.co.jp
(4) Engineering Section Manager, GERB Vibration Control Systems Japan, Inc., shuhei.kaneko@gerb.co.jp

Abstract

Pipe vibrations are often a major cause for failure of piping systems. They can lead to leakage, fatigue fractures and sudden breakdowns of pipes, pipe support systems and other attached components. The excitation mechanisms are manifold. Oscillations can occur due to operational reasons by fluid flow phenomena, connected machinery, but also by system failures, rapid shutdowns or earthquakes. Particular strong vibrations occur when natural frequencies of a piping system are excited and resonance-like amplifications of the movements develop.

After the Fukushima earthquake power plant operators in Japan had to significantly increase the safety of plant equipment and piping systems. This article describes the use of viscoelastic fluid dampers to protect piping against vibrations during normal operations as well as upset conditions like water hammer or earthquakes.

By selectively increasing the damping of a system, structures with low dynamic responsiveness are established, which are difficult to excite. A reduction of the occurring vibrations leads to a reduction of stresses and load cycles in the pipes and attached equipment and to an increase of safety and service life.

General characteristics and the complex stiffness behavior of these vibration dampers are explained using rheological models. Procedures for the proper selection of these dynamic piping restraints and for determining optimal installation locations will be introduced. Calculation examples show the effects and benefits of these elements, which are widely used in conventional and nuclear power plants as well as in chemical and offshore facilities worldwide. The validity of modeling and the performance of these viscoelastic dampers have been confirmed by shaking table tests on an actual piping system with and without dampers.

For the use in nuclear facilities with extremely high safety requirements certified dampers are available and manufactured in accordance to strict quality control measures.

Keywords: pipe vibration; seismic protection; viscoelastic damper

1. Introduction

Operational experience often shows that reliability and life expectancy of piping systems in power and chemical plants largely depend on their dynamic characteristics and behavior. Dynamic loads can be caused by internal and external excitations during normal and upset operations as well as emergency situations.

Normal operation:
- Pressure surges from closing and opening of valves or switching of pumps
- Two-face flow with slug forces
- Vortex shedding in valves, tees, orifices
- Pressure pulsation due to machine operation (e.g. piston compressor)
- Vibrations of directly or indirectly connected machines

Upset operations:
- Machine faults
- Quick closing operations of valves and resulting water hammers
- Blowing-off of safety device

Emergency situations:
- Earthquake
- Plane crash
- Explosion (blast)
- Pipe breakage

Usually unacceptable pipe motions during normal operations only occur when an excitation frequency, e. g. the operating frequency of a connected pump or compressor, matches a natural frequency of the piping system. In this case even small excitation forces cause larger motions due to resonance effects, not only close to the excitation source, but also at greater distances. Especially critical are situations were acoustical and mechanical natural frequencies are close and the vibration phenomena amplify each other.

Usual piping systems (low damping, flexible structure) are characterized by closely spaced natural frequencies, which may be easily activated by one of the broadband excitation frequencies. Therefore, attempts to decrease operational vibrations by adding or changing standard supports (bearings, anchors) and restraints (bracers, guides) or by adding mass are usually not very successful since they only slightly shift the natural frequencies. Removing the excitation source is often not possible, or at the least, very costly. The addition of damping to the piping system is in many cases the better measure to decrease operational vibrations.

Operational vibrations often show only small displacements and stresses. Yet they can lead, on a long-term basis, to pipe fatigue and increased vibration crack corrosion. Alternating stresses that are well below the static yield point of the pipe material can lead to micro slips, which cause submicroscopic cracks near the top surface. Due to crack propagation and unification, technical cracks may develop with a large stress peak at their tip. And finally, under continuously alternating loads, fatigue fractures may appear. As a result, operational vibrations are often the cause of pipe damage. Material fatigue increases with vibration velocity and number of load cycles. Vibration amplitude and frequency are determinant factors causing pipe damage.

For emergency situations (e.g. earthquakes) actual pipe motions, stresses and loads on support elements must be evaluated and checked. Large displacements, high stresses and improper loads are critical and must be reduced to acceptable levels to prevent damage of pipes and supporting systems. This can be done using appropriate restraints, e.g. viscoelastic fluid dampers.

2. Evaluation of Pipework Vibrations

The evaluation of operational vibrations in piping systems depends on the type of plant and operation and governing regulations. Unfortunately there is lack of internationally accepted and consistent criteria. Based on the particular standard, displacement or velocity amplitudes are assessed depending on vibration frequency. Peak- or RMS-values are sometimes used as acceptable vibration limits. The following diagram, Fig. 1, of the German VDI guideline 3842 [1] shows assessment values for operational vibrations based on vibration measurements that were taken and evaluated for 25 years in petrochemical facilities.

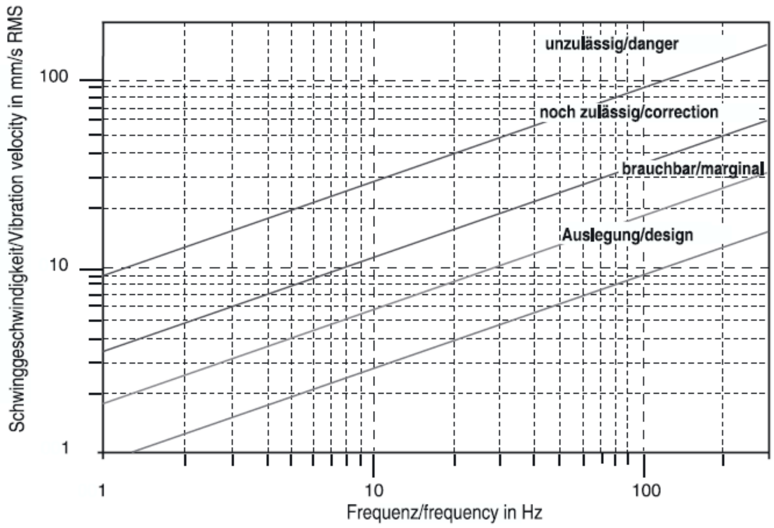


Fig. 1 – Vibration limits acc. to VDI 3842

The guideline proposes that the pipe sections with unacceptably high vibrations must be analyzed dynamically with the goal of reducing the vibrations to acceptable values. An attempt should be made to improve the source of vibrations.

3. Dynamic Restraints for Piping Systems

Several types of dynamic restraints are used in power and chemical plants:

- Mechanical and hydraulic snubbers
- Elastic-plastic absorbers or stoppers
- Axial shock absorbers
- High viscous fluid dampers

Basically dynamic restraints should provide the following features:

- High damping capacity for any dynamic excitation (seismic, shock, vibration)
- Negligible forces under thermal expansion
- No delay under dynamic loads
- Long service life
- Easy inspection and maintenance
- Overload ability without losing functionality

Without compromising the usefulness of other elements - only viscous fluid dampers fulfill all of the above mentioned criteria. Although snubbers are widely used, there are a number of shortcomings. For example, they are not suitable for damping of operational vibrations.

4. Viscous Fluid Dampers as Pipework Dampers

A pipework damper consists of a damper housing, containing a highly viscous damping fluid, and a damper piston, which is immersed in the damping fluid. The piston can move in all directions, short of contact with the damper housing. Therefore, the damper is effective in all six degrees of freedom. The damping forces result from shearing and displacing of the damping fluid. They are approximately proportional to the relative velocity v between damper piston and damper housing. The frequency dependent proportionality factor is called damping resistance c, Eq. (1) [2].

$$F \approx c \cdot v \approx c(f) \cdot v \tag{1}$$

In order to assure proper function of the damper (see Fig. 2 for a cross section), one damper component, either the piston or the damper housing, must be rigidly fixed. For practical applications, this means that a sufficiently stiff support structure is required. Then, the absolute velocity of the moving part can be used for the design calculations.

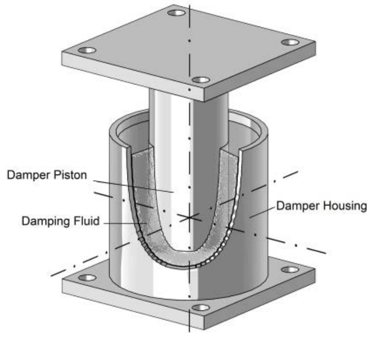


Fig. 2 – Basic design of pipework dampers

Ideal viscoelastic dampers have a frequency-independent damping resistance. When harmonically loaded the phase angle between damper force and displacement would be 90°. In reality, depending on the frequency of the motion viscoelastic dampers have phase angles below 90° as the damper force always consists of both a viscous and an elastic component. In general, the damping resistance decreases when the frequency increases. In case of sinusoidal motions a hysteresis loop can be drawn showing the force over displacement relationship. The area of the hysteresis loop is a measure for the work of the damper and corresponds to the dissipated energy per load cycle, Fig. 3.

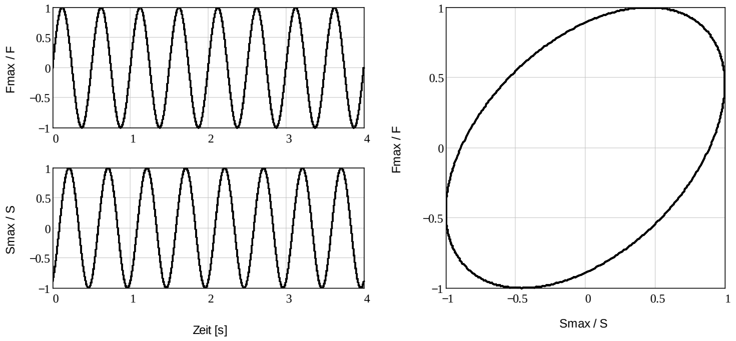


Fig. 3 – Hysteresis loop and dissipated energy

The achievable damping effect depends on the damping medium, the internal damper design, and the damper loading. Due to the velocity proportional behavior of the damper static loads are not supported and slow movements, like thermal expansions, cause only minor resistance forces. As a result viscoelastic dampers have no impact on the static behavior of the piping system. This makes them ideal components for retrofits as all other components can remain without the need for additional static analysis.

The viscoelastic qualities of a fluid damper can be described with rheological models, which are formed from the combination of ideal spring and damper elements, Fig. 4. The Voigt-Kelvin-Model is well known and often used for the description of vibration systems - for example for the elastic support of machinery or in TMDs. When describing basic damper behavior, the generalized Maxwell-Model suits well, since it has ideal relaxation qualities. It is able to describe the viscoelastic qualities of the damper for harmonic excitations, as well as for sudden shock-type loads over a large frequency range.

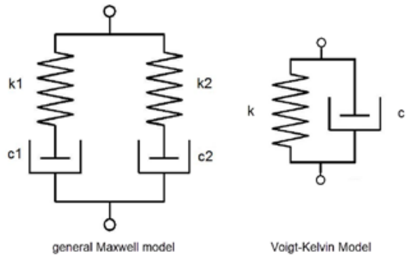


Fig. 4 – Rheological models

Different parameters are used to select dampers for specific applications. These parameters are determined experimentally for each pipework damper:

- Vertical and horizontal damping resistance [kNs/m]
- Vertical and horizontal equivalent stiffness [kN/mm]
- Nominal load [kN]
- Permissible vertical and horizontal displacements [mm]

Damping resistance and equivalent stiffness are determined experimentally over a large frequency range from the dynamic amplitudes of force and displacement. Fig. 5 shows a comparison of the measured equivalent stiffness and the damping resistance of an aptitude-tested damper with the calculated values of an adapted and optimized 4-parameter Maxwell-Model.

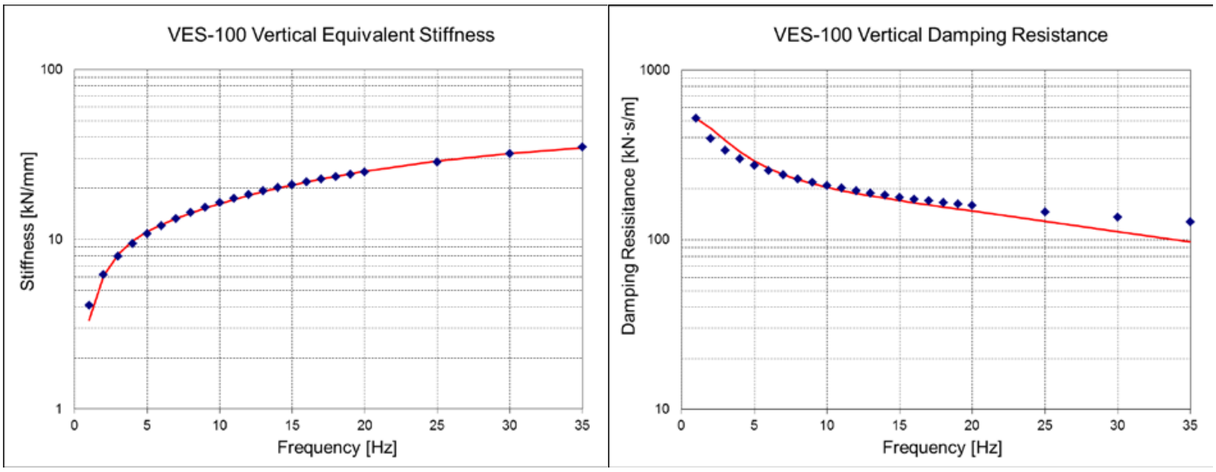


Fig. 5 – Comparison of measured and calculated stiffness and damping curves

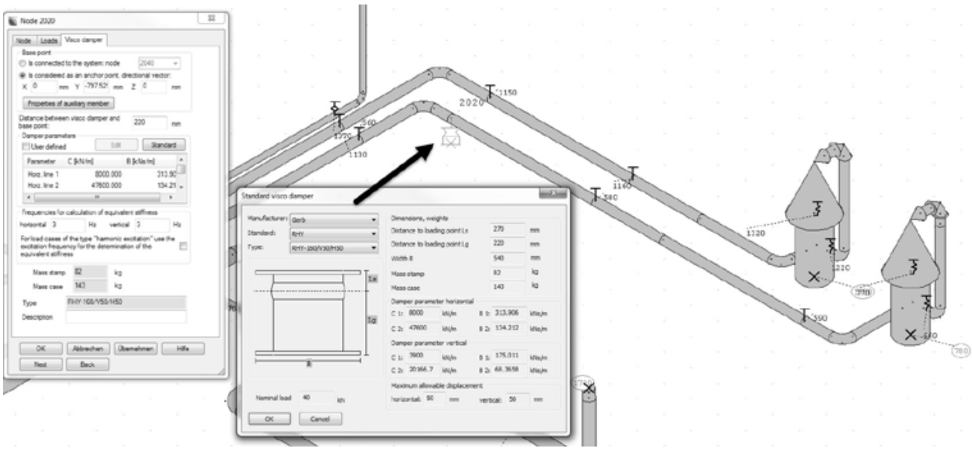
The complex stiffness of a 4-parameter Maxwell model is given by Eq. (2)[2]:

$$\underline{K} = \sum k_i \left\{ \frac{(\omega/\omega_i)^2}{1+(\omega/\omega_i)^2} + j \cdot \frac{(\omega/\omega_i)}{1+(\omega/\omega_i)^2} \right\} \quad with \quad \omega_i = \frac{k_i}{c_i} \tag{2}$$

where ω_i is the natural angular frequency, k_i is the stiffness and c_i is the damping resistance of the particular Maxwell element.

Today Maxwell models can be used in several modern piping analysis and general FEM programs, e.g. ‘dPipe’, ‘ROHR2’ or ‘ANSYS’ to take the frequency dependent, energy dissipating characteristics of viscoelastic fluid dampers into account and to calculate the dampened behavior of complex piping systems. These programs also allow considering the maximum allowable damper forces and permissible travels.

Fig. 6 shows a typical representation of a chemical plant in ROHR2 including a damper installation.



Base point
○ Is connected to the system: node 2040
● Is considered as an anchor point, directional vector:
X 0 mm Y -797.52 mm Z 0 mm
Distance between visco damper and base point: 220 mm
Damper parameters
☐ User defined

Parameter	C [kN/m]	B [kNs/m]
Horiz. line 1	8000.000	313.90
Horiz. line 2	47600.000	134.21

Frequencies for calculation of equivalent stiffness
horizontal 3 Hz vertical 3 Hz
For load cases of the type "harmonic excitation" use the excitation frequency for the determination of the equivalent stiffness ☐
Mass stamp 82 kg
Mass case 143 kg
Type RHY 100/V50/H50
Description

Manufacturer: Gerb
Standard: RHY
Type: RHY-100/V50/H50
Dimensions, weights
Distance to loading point Ls 270 mm
Distance to loading point Lg 220 mm
Width B 540 mm
Mass stamp 82 kg
Mass case 143 kg
Damper parameter horizontal
C 1: 8000 kN/m B 1: 313.906 kNs/m
C 2: 47600 kN/m B 2: 134.212 kNs/m
Damper parameter vertical
C 1: 3900 kN/m B 1: 175.011 kNs/m
C 2: 20166.7 kN/m B 2: 68.3658 kNs/m
Maximum allowable displacement
horizontal: 50 mm vertical: 50 mm
Nominal load 40 kN

Fig. 6 – Representation of viscoelastic dampers in Rohr2

5. Procedure for the Reduction of Operational Vibrations

A possible procedure scheme for the reduction of operational vibrations is depicted in Fig. 7. The structural analysis is carried out using a piping analysis program. Piping model and excitation should be based on actual plant data and performed vibration measurements. The excitation time histories should be defined conservatively and adjusted using measured vibration time histories. When measured and calculated vibration behaviors sufficiently coincide the existing piping support system can be optimized. Viscoelastic dampers are selected and mounting locations are defined based on modal shapes and on-site installation conditions.

The goal of the damper selection and placement is to increase and optimize the system damping in such a way that the crucial vibration modes receive the maximal possible modal damping. Due to the increased damping and energy dissipation these modes are significantly reduced, deflections are unable to build up, and resonance effects are softened.

By installing several dampers, damping can be selectively inserted into the piping structure at the most efficient positions. Several critical modes can be effectively dampened and resonance effects are eliminated. This practice reduces fatigue of the piping, and therefore, increases the service life of the piping and all connected pipe components. In addition the safety against upset situation and emergencies are also increased by these measures.

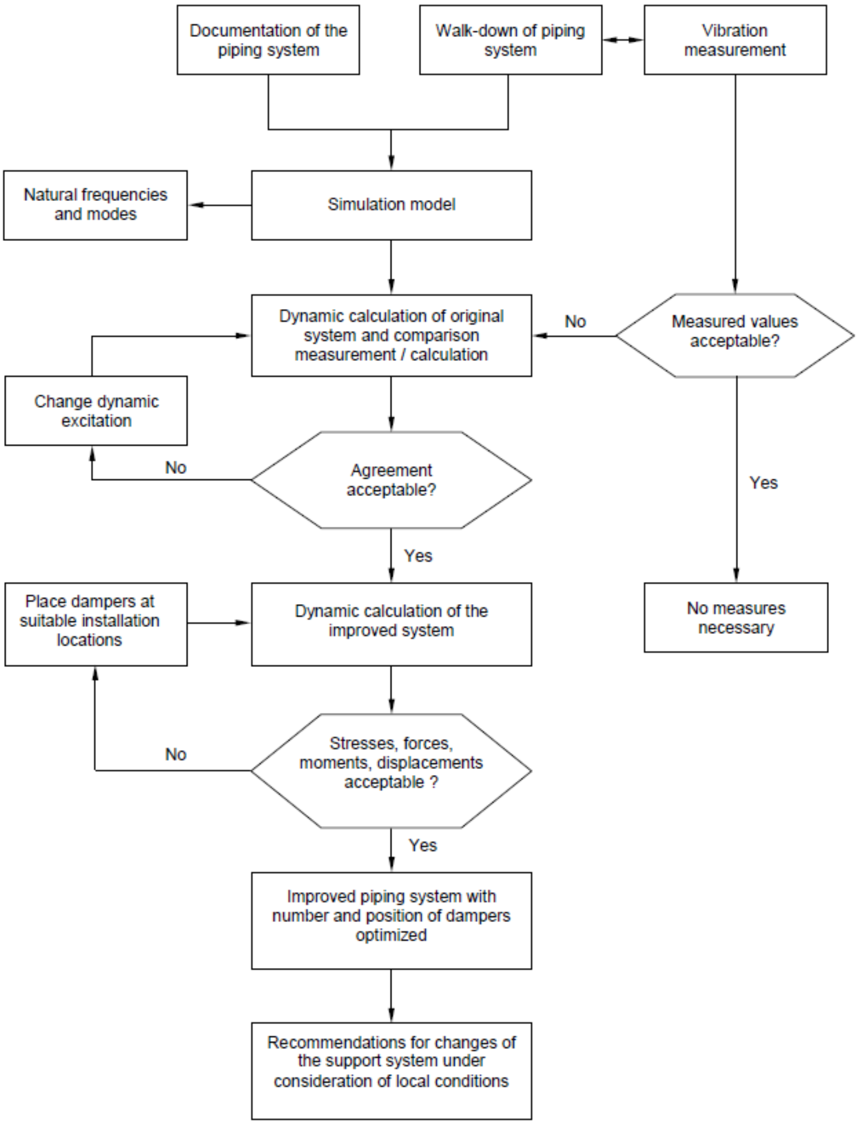


Fig. 7 – Workflow for reduction of operational vibrations (for an existing plant)

This practice must be complemented by site inspections to find compromises between the calculated optimal mounting points and the installation options feasible on site. The use of viscous fluid dampers to reduce operational vibrations was applied with great success on feed water lines at the NPP PAKS in Hungary, Fig. 8. These lines experienced strong vibrations during normal operations. The actual situation of the piping system and the existing layout drawings were the basis of the piping analysis model. A limited number of vibration measurements on several locations determined magnitude and frequency content of the occurring vibrations. These data were then used to calibrate the synthetic excitation for the subsequent analysis. The occurring vibrations were rated according to ASME and PNAE.

Fig. 9 shows the results of the procedure by comparing the occurring deflections with and without dampers. The implemented damping could significantly reduce vibrations and subsequently lower stress and moment values in the pipe and branch connections.

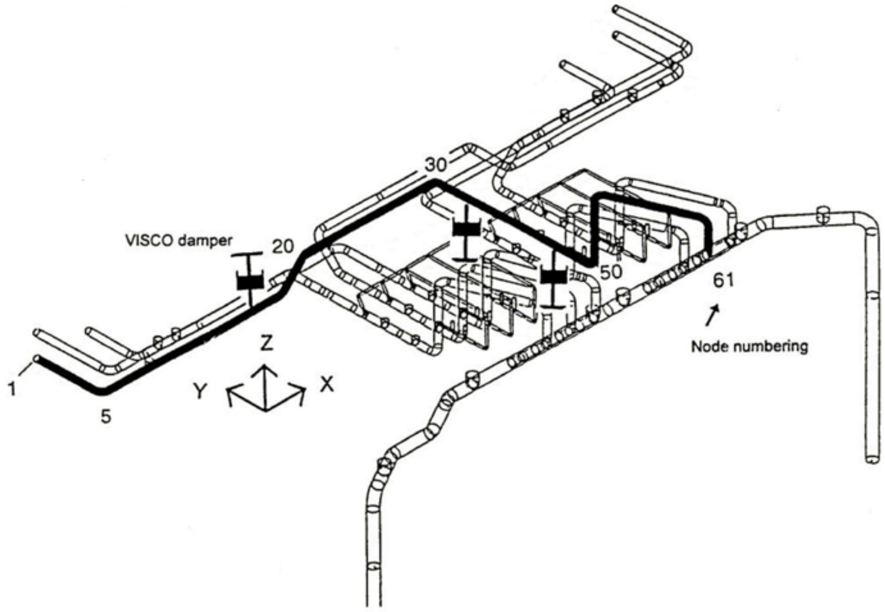


Fig. 8 – NPP PAKS, Hungary, feed-water piping system

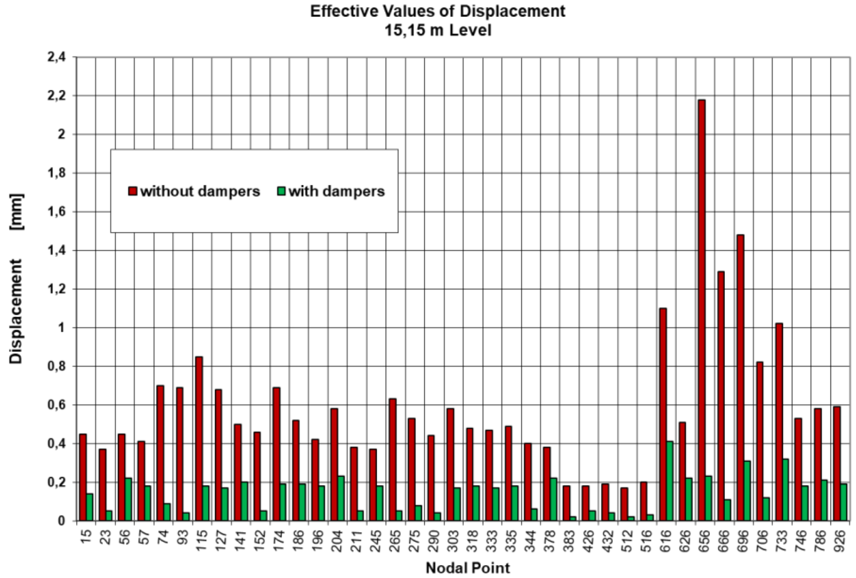


Fig. 9 – Reduction of displacements, NPP Paks, Hungary

Fig. 10 compares the MAX-Norm of two transfer functions (without dampers / with dampers). The significant low dampened natural frequencies and resonances amplifications of the original system are effectively suppressed by the implementation of damping. Such a system is dynamically good-natured and very difficult to excite not only by operational vibrations but also by emergency situations like earthquakes.

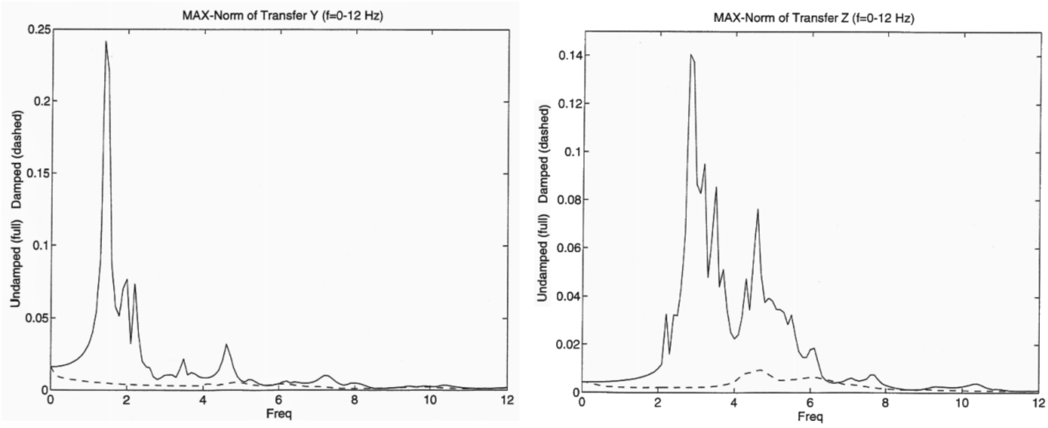


Fig. 10 – MAX-Norm of Transfer functions (—) original system, (- - -) system with dampers

Fig. 11 shows possible installation configurations how viscoelastic dampers can be attached to a piping system and support.

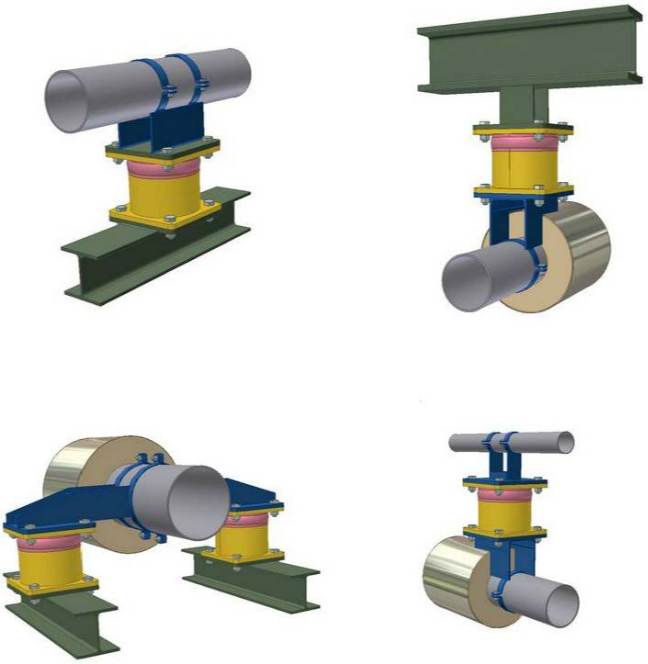


Fig. 11 – Possible installation configurations for pipework dampers

6. Procedure for the Reduction of Vibrations caused by Emergency Situations

The procedures for the reduction of vibrations caused by emergency situations like earthquakes follow a similar approach as used for operational vibrations. However, additional criteria must be fulfilled that depend on customer requirements and local regulations and can affect the damper selection and installation, e.g.:

- Maximum displacements
- Seismic criteria
- Loading of dynamic restraints like snubbers
- Loading of supports

Following the Kashiwazaki-Kariwa earthquake and the Fukushima events, the Japanese Nuclear Authorities developed new safety standards for nuclear power plants with significantly increased seismic requirements. Chugoku Electric Power Company has been planning and implementing a number of safety improvements for their Shimane Nuclear Power Plant with the goal to achieve highest nuclear safety. Amongst these improvements viscoelastic dampers will be installed on main steam lines to improve seismic safety and to meet the new requirements.

Intense testing activities and analyses were performed to ensure that a maximum of conservatism was applied to all stages of the project. At the heart of the project dynamic tests were performed at the Okumura Test Laboratory on a 3D shaking table with the goal to test viscoelastic dampers under most realistic conditions. Test signals have been defined considering the seismic conditions at the site of the Shimane power plant to fully qualify the dampers for the planned application. Finally, a design workflow for the selection of appropriate dampers incorporating developed design criteria was established and implemented for the subsequent analysis of crucial piping systems in the plant.

The high performance of viscoelastic dampers has been confirmed by the testing of a full scale piping model on the shaking table with severe seismic accelerations up to 20 m/s² in horizontal and 10 m/s² in vertical directions.

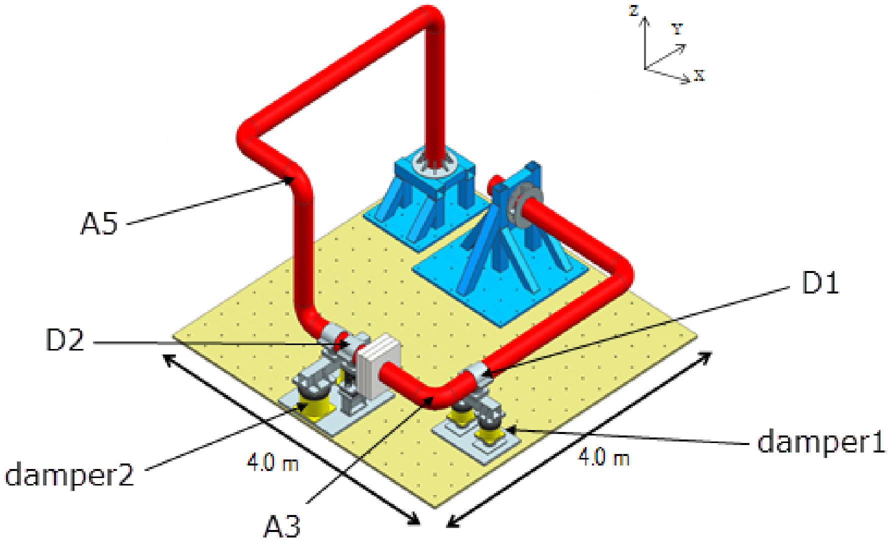


Fig. 12 – 3D shaking table arrangement

The transfer functions for accelerations at two distinct locations A3 and A5 were evaluated by means of an applied sinusoidal sweep excitation [3] for the system without and with viscoelastic dampers, Fig 13. It was found that the seismic response amplification of the system with dampers dropped down to a factor of 4.0 or 30 times less in comparison with the system without viscoelastic dampers. At the same time the main natural frequencies are shifted to higher values due the dynamic stiffness of the dampers. A direct comparison of the transfer functions in horizontal direction is given in Fig. 14.

The response accelerations of the piping without and protected by viscoelastic dampers under seismic wave excitation in X+Z-direction are compared in Fig. 15. In horizontal X-direction the amplification factors (response/input) at measurement points A3 and A5 for the piping without viscoelastic dampers are approximately 10. The same factor for the piping with viscoelastic dampers at the point A3 is close to 1.0 (means no amplification) and in the point A5 is around 2.0 (small amplification). That means that the response of the system with viscoelastic damper installations was reduced to 1/10 and 1/5, respectively.

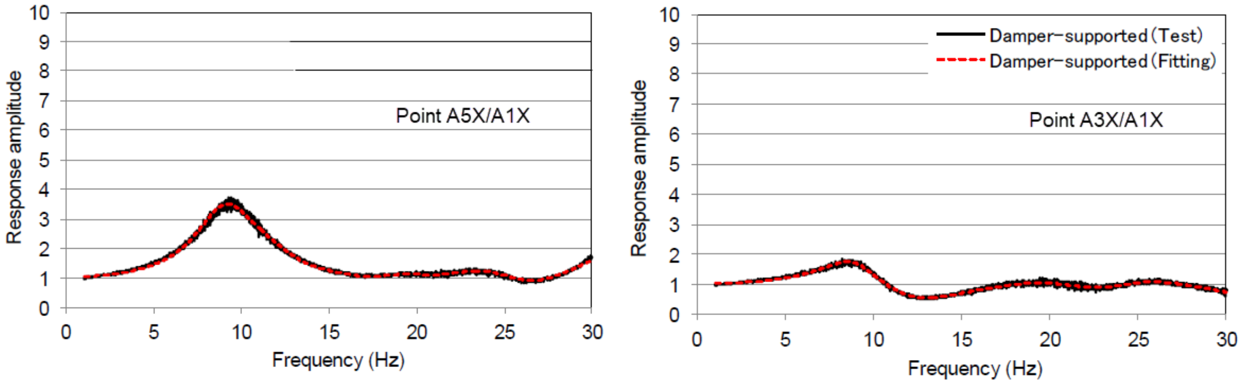


Fig. 13 – Response Amplitudes in horizontal X-direction with dampers (input acceleration 1.0 m/s²)

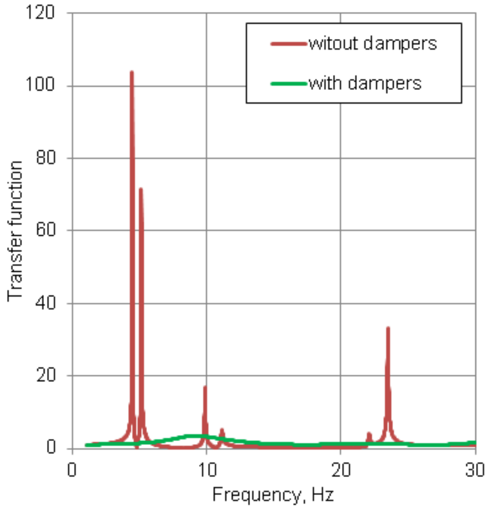
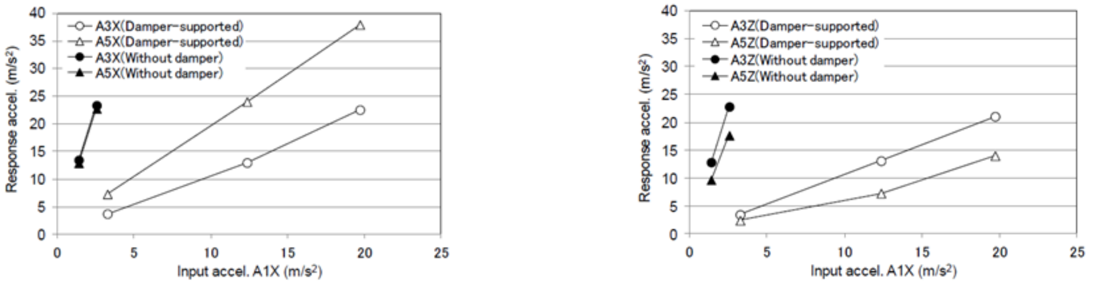


Fig. 14 – Transfer function in horizontal X-direction with / without dampers

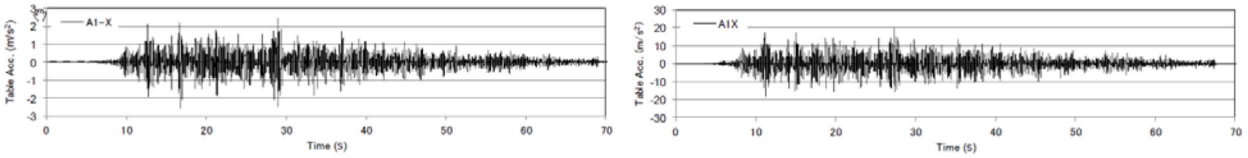
In vertical Z-direction the amplification factor at measurement points A3 and A5 was 10 without viscoelastic dampers. After installation of the viscoelastic dampers the amplification factor decreases to 1.0 at A3 and to 0.7 at A5 showing even a reduction effect. System responses were reduced to 1/10 and 7/100, respectively [4]. Corresponding time histories are shown in Fig. 16.



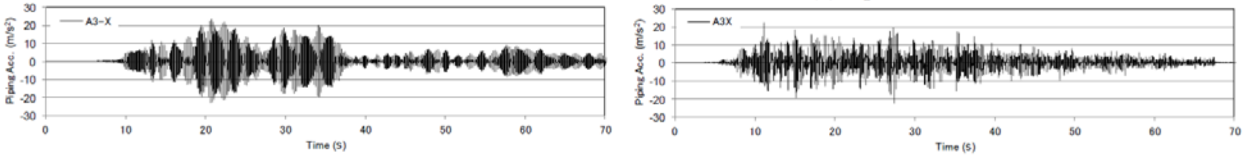
RESPONSE ACCELERATION IN X-DIRECTION UNDER INPUT ACCELERATION A1X (SEISMIC WAVE X+Z-DIRECTION SHAKING)

RESPONSE ACCELERATION IN Z-DIRECTION UNDER INPUT ACCELERATION A1X (SEISMIC WAVE X+Z-DIRECTION SHAKING)

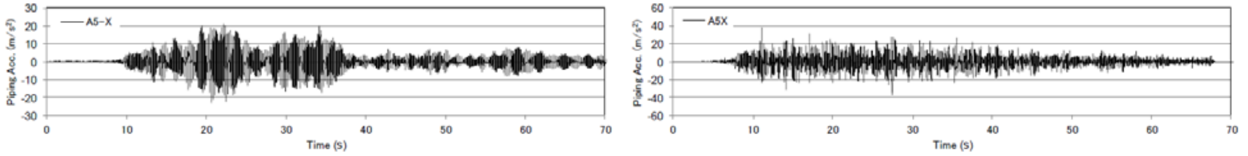
Fig. 15 – Response acceleration under seismic wave excitation



(1) Input acceleration A1X (1) Input acceleration A1X



(2) Piping acceleration A3X (2) Piping acceleration A3X



(3) Piping acceleration A5X (3) Piping acceleration A5X

Fig.16 – Acceleration time histories (left: without dampers, right: with dampers)

7. Conclusions

For decades, pipework dampers have been used successfully to protect piping systems and equipment against vibrations caused by normal operational, shocks, or earthquakes. They are able to provide selective damping, and can be integrated in the design of pipe support concepts in power and chemical plants.

Optimal results can be achieved when exact data of the operating conditions are available, and when proper support points are found. Measurements or piping calculations usually provide sufficient information for proper damper design and the selection of optimal damper locations.

Dampers can be considered during the design phase of a plant or subsequently in the event of unforeseen vibration problems. Their ability to be retrofitted into existing systems without impact on the static support situation make them ideal vibration remedial components.

Viscoelastic fluid dampers are very useful dynamic restraints not only for operational vibrations but also for emergency case excitations when hot piping cannot be rigidly fixed. The reduction of occurring accelerations, displacements and stresses are exceptional as it was demonstrated by the shaking table tests. It can be concluded that viscoelastic dampers can generally provide very high damping to the piping system and protection against severe earthquake motions. In general it is possible to incorporate customer or specific local demands and regulations into the design workflow to analyze piping systems with viscoelastic dampers.

8. References

[1] VDI-Gesellschaft (2004): Vibrations in Piping Systems, VDI 3842, Beuth-Verlag, pdf.

[2] Reinsch, K. H.; Barutzki, F.(1997): *Technical Report Pipework Dampers*, Rev. April 2018, pdf.

[3] Tamura, Kuramasu, Barutzki, Fischer, Kostarev, Berkovskiy, Vasiliev, Inoue, Okita, Namita (2016): *Dynamic Analysis of NPP piping systems and components with viscoelastic dampers subjected to severe Earthquake motions*, ASME 2016 PVP conference.

[4] Kostarev, Tamura, Kuramasu, Barutzki, Vasilev, Enomoto, Namita, Sato (2016): *Shaking Table Tests of a Piping System with viscoelastic dampers subjected to severe Earthquake motions*, ASME 2016 PVP conference.