Resolving of Steam and Feed-Water Piping Vibration Matter at Loviisa NPP

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ABSTRACT

The paper describes a piping operational vibration problem has been resolved at the Loviisa Nuclear Power Plant main steam (RA) and feed-water (RL) lines. Excessive piping vibration occurred as the result of an essential 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.

The project covers 3D vibration measurements and walkdowns of RA and RL lines with its support system, developing of dynamic finite element models of piping with vibration parameters close to obtained experimental data. In result vibration protective measures has been developed based on implementation of High Viscous Dampers Technology (HVD). An optimum minimal number and location of VES and VD high viscous dampers has been determined and then installed at the lines. Finally an essential vibration reduction of the examined systems has been achieved.

OBJECTIVES

Loviisa power plant is the first nuclear power plant in Finland. The power plant has two units. The first started its operation in February 1977 and the second in November 1980. The units are Russian designed VVER-440 type pressurized water reactors, turbines, generators and other main components. Safety systems, control systems and automation systems are of western origin. The steel containment and its related ice condensers were manufactured using Westinghouse licenses

The operation experience of the power plant has been very positive. Key figures measuring reliability and efficiency, load factors, are remarkably above the international average.

The present electric power capacity of Loviisa NPP is approximately 10 % larger than it was originally. The net electric power increase of each unit from 440 to 488 MWt is a result of the upgrading project that took place in 1997-2002. The primary and secondary systems water and steam pressure and temperature parameters remain the same. Primary circuit parameters are 123 bar with 300 ºC in the hot leg and 265 ºC in the cold leg. Feed water system has 90 bar and 180 ºC and parameters of live steam are 44 bar and 280 ºC. Thus power upgrading of the Units has been achieved by increasing of reactor, steam generator and other plant systems capacities in steam and feed water mass flow generation. It results in corresponding increasing of flow velocity in feed and steam piping with a negative consequence as an extensive vibration of the lines.

A number of attempts were carried out to decrease vibration prior turning to HVD technology. Redesigning of piping support system with its strengthening and installation of additional elastic supports in some cases has been arranged. All these measures did not provide positive effect shifting in some cases system's vibration frequency and not much influence on its vibration level. At the same time transferring of vibration to environmental structures has been increased.

PIPING VIBRATION CRITERION AND OPERATIONAL PRACTICE

NPP operational practice obviously shows correlation between piping operation reliability and service life limit from one side and level of piping operational vibration from another. High piping vibration in a number of cases results in through wall piping fatigue with an essential wear and even failure of piping supports. It have to be noted that vibrated piping achieves standard 106 cycles less than in one operation year meanwhile existing low cycle fatigue curves usually have cut off cycles number just at 106 and eliminates also negative environmental effects. An increasing concern of engineering society regarding high cycle piping vibration fatigue has been explained in trend to revise existing ASME fatigue curves extending cycle range up to 1011 together with considering of negative environmental effects. That could result, for example, in 1.8 times decreasing of endurance limit for a typical NPP carbon and low alloy steels: less than 50 MPa.

In addition to piping and supports fatigue problem a serious deterioration of plant conditions operation could take place due to environmental noise covering all the plant areas including control room. Plant's operational personnel threats also exist in working with highly vibrated distributing systems. However at the moment a recognized international practice in piping vibration limits does not exist yet in contrast with turbines and other rotating equipment. It is connected mainly with diversity of piping operational conditions, layouts, diameters and materials. Only a few national recommendations and guidelines were developed based on operational experience of safety related piping subjected to vibration loads.

ASME OMa S/G-2000 Standard Part 3 installs limits for piping vibrovelocities and vibrodisplacements based on a piping fatigue stress analysis according to ASME Code, [1]. ASME OM piping screening criterion is 12.7 mm/sec of peak vibrovelocity and seems to be very conservative piping vibration safety margin with guaranteed fatigue capacity independently on a piping layout and features. If vibration exceeds this level the Guide recommends to perform additional analysis or to improve piping oscillation state. ASME BPVC (NB-3622.3) recognizes inability to predict piping vibration on a design stage and thus indicates only that piping vibration has to be in limits that guarantee the safety operation [2].

In France a recommended threshold RMS vibration limit for NPP piping is defined as 12 mm/s [3]. These data correlates to a French standard in gas industry.

Russian Boiler Standard RD 10-249-98 recommended to control piping peak vibrovelocities according to the following criteria: less than 15.0 mm/s is excellent; 15.0-25.0 mm/s requires additional measurements and analysis to confirm safety; more than 25.0 mm/s recommends improving vibration state of the system, [4].

The most comprehensive European standard for piping vibration is VDI [5] that provides some screening criteria for piping vibrovelocities against frequency of vibration based on rearranged Wachel allowable, [6], fig 1. The vibrovelocities in the frequency range 3.0-30.0 Hz with corresponding values more than 6.0-20.0 mm/s RMS recognized as required corrections and 16-50 mm/s RMS as dangerous for piping safety.

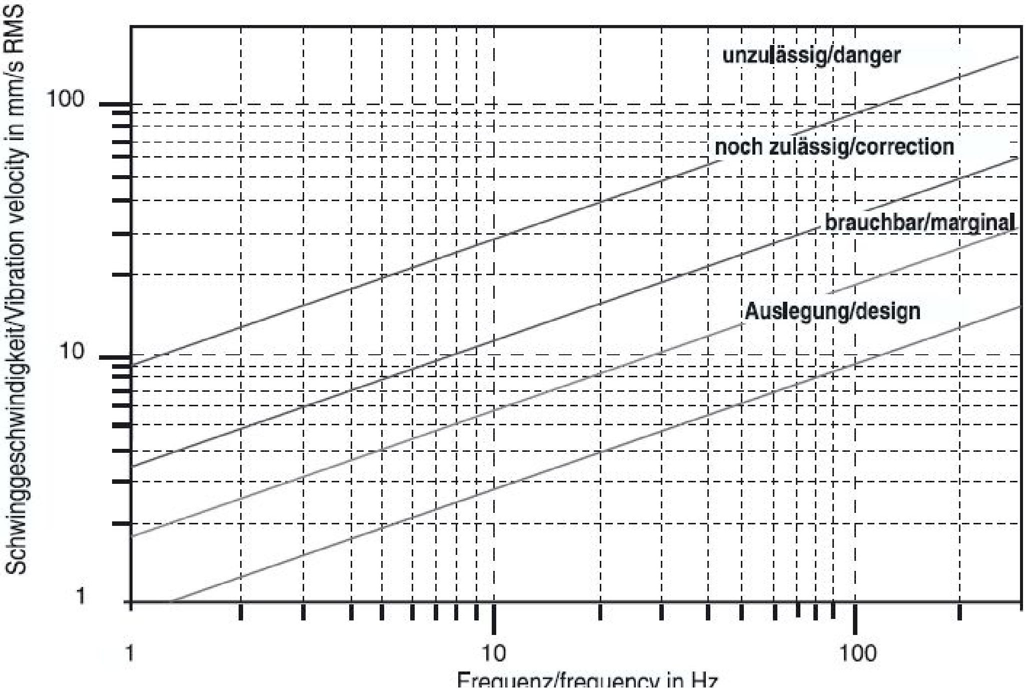


Fig 1 VDI limits for piping vibration

Based on all available documentation and a good nuclear plants' operational practice the following thresholds for piping vibration at Loviisa NPP have been approved:

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.

VIBRATION MEASUREMENTS AND WALKDOWN

Considering concerns connected with increased piping vibration comprehensive measurements have been carried out at all main steam and feed water piping at Loviisa NPP Unit 1 and Unit 2 in the common Turbines 1-4 Hall and in the Reactor Building containments' area. The total number of 3D measurement along piping, its supports and building structures has achieved several hundred points. At the same time an extensive program for piping walkdowns was performed in order to get information concerning actual piping and supports state. The length of observed lines was more than 40 km. The walkdown procedure allows significantly improve "as built" information and has shown, for example, essential degradation of piping supports due to vibration in a number of cases, fig. 2.

The vibration measurements were performed by several multi-channels Portable Signal Analyzers (PSA) based on laptop units manufactured by Mera Co., Russia. In some special cases instrumentation of CSI, USA and Bruel&Kjer, Denmark companies have been used.

The piezoelectric transducers were assembled at magnetic platforms for performing simultaneous 3D measurements in one or several points along piping to obtain actual relation of vibration along axes and on a case by case basis to define forced modes of piping vibration. The magnetic platforms in one's turn have been placed directly at piping in special openings in insulation, fig.3.

a) wear of the rod hanger b) fatigue collapse of elastic vibration support

Fig. 2 Example of piping supports degradation due to vibration:

(a) (b)

Fig.3 Transducers at the hot (a) and cold (b) piping

The main digital features of vibration measurements were as follows:

Frequency range	2.0-1000 Hz	Sampling frequency	2000 Hz
Hard disc time recording	60 sec	Low pass filter cut-off frequency	200 Hz.

For each measurement point maximum values of RMS ($V_{\max}^{RMS}$) and peak vibrovelocity ($V_{\max}^{Peak}$) were defined according to the following correlations:

$$V_{\max}^{RMS} = \max\begin{Bmatrix} V_{CS}^{RMS} \\ V_a^{RMS} \end{Bmatrix} \text{ and } V_{\max}^{Peak} = \max\{V_{1peak} V_{2peak} V_{3peak}\}$$

where:

Va = V_1 – piping axial RMS or peak velocity, Vcs - cross section RMS velocity: $Vcs = \sqrt{V_2^2 + V_3^2}$

$V_{1,2,3\ peak}$ - peak velocity along three axis

It was installed that in essential number of measurement points on the RA and RL lines the RMS and Peak vibration values of vibrovelocities exceed approved criteria of 7.5 mm/s RMS and 20 mm/s Peak vibration.

The most dynamically loaded zones of the RA and RL systems at Loviiisa NPP in terms of RMS and Peak vibrovelocities is shown in Table 1.

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 and Deaerator Building (DB)

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, 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 DB (big bypasses)	7.4	25.2	3.4	5.0; 10.0
2576	RA50, 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 DB, Turbine 1	11.8	42.3	3.6	2.0;10.0; 60.0
1111	RL 22 in DB, Turbine 1, Deaerator small bore piping	14.1	52.5	3.7	3.0
112	RL31 small bore emergency feed water in DB; 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

ROOT CAUSE OF VIBRATION

A general level of Loviisa main piping vibration should be recognized as moderately high 7.4-25.0 mm/s RMS with a primarily low frequency character 2.5-30 Hz and multi-harmonic and random nature: crest factor Vpeak/Vrms varies from 3.1 to 4.1.

The analysis has shown that the root cause of vibration is connected with the following phenomena. After upgrading of the Loviisa NPP power in the same proportion the mass flow of feed water and steam in piping has been increased and thus its velocities. Pressure drop, vortex and turbulence at all pressure restrictions in piping as tees, orifices, obstructions, valves, etc., liquid or mixed phase flow excitation, pressure surges and hydraulic hammers became more powerful and in addition frequencies of pressure unstable pulsations increased. The frequencies of the initial pressure pulsations in pressure restrictions are centered on a frequency which can be determined by the following equation:

$$F_s = S_n V/D,$$

where: Fs – Strouhal vortex frequency, Sn – Strouhal number, dimensionless (0.2 to 0.5); V –flow velocity in the pipe; D – characteristic diameter.

These vortex frequencies 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. The effect of possible overlapping of these three factors: initial vortex frequencies in piping restrictions, piping acoustic resonance frequencies and finally piping mechanical resonance frequencies is demonstrated in fig. 4.

In general existing of extensive and powerful piping acoustic vibration has probabilistic nature and depends on a number of uncertainties and undefined factors and could not be predicted reliably on a design stage that really happened at Loviisa NPP. Thus such a piping phenomenon becomes obvious on preoperational or operational stages only making this matter an intractable problem covered by the ASME OM standard, [1].

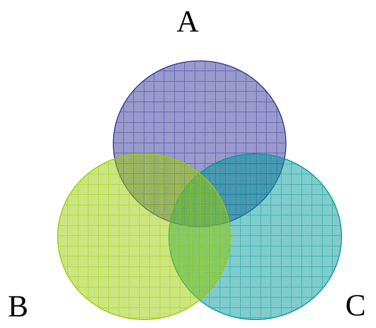


Fig. 4 Probabilistic interpretation of an extensive piping flow induced vibration:
A) Piping mechanical resonance frequencies;
B) Vortex frequencies in pressure restrictions;
C) Acoustic resonance frequencies of piping medium.

In a majority of cases due to a plant operational conditions and cost limitations it is not possible to influence directly on root source of vibration changing layout of piping or its elements creating pressure restrictions and vortex.

That is why a practical solution for resolving of piping vibration matter often consists of piping support system upgrading: tuning or changing parameters of existing system, adding new supports or using special devices.

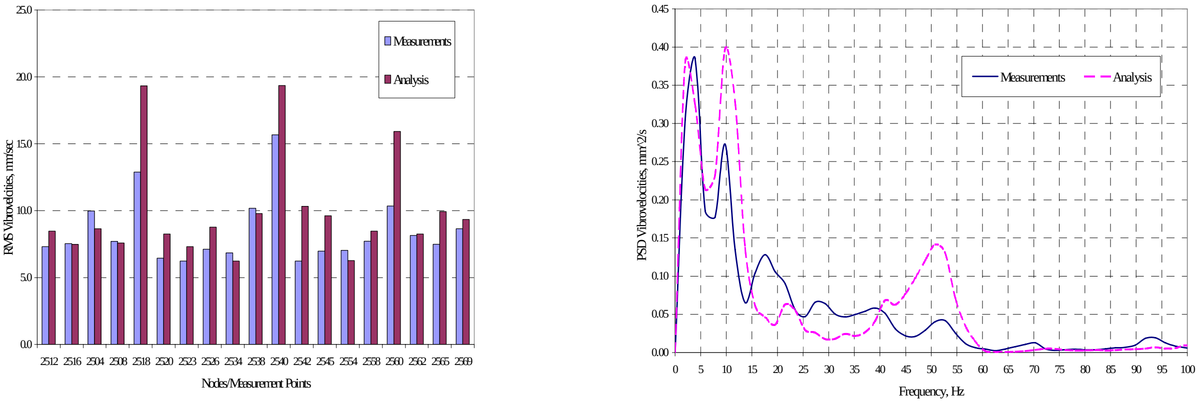
DYNAMIC ANALYSIS

Dynamic analysis of piping subjected to mutual acoustic-mechanical resonances could be divided into three main tasks: a) simulation of vortex initial excitation in restrictions; b) acoustic analysis with definition of joint medium acoustic and piping mechanical resonance modes; c) modelling of a piping and its support mechanical system; d) resolving of mutual acoustic-mechanical problem of flow-induced vibration having forced or self-excited nature. Among these tasks the most problematic is the task (a) due to lack of experimental data for the natural scale elements with different geometry. Task (b) could be resolved in general but with essential undefined errors as shown in [7] where Loviisa feedwater system was examined comprehensively. Task (c) is the most verified and reliable in the presented row. If one resolves successfully all the (a), (b), (c) the (d) task would be a matter of technique. Unfortunately problems exist with a) and b) tasks make direct solution impractical.

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 vibrovelocities, creation of PSD Spectra for selected points.

The input vibration excitation has been generated using analysis results (piping natural frequencies and mode shapes) and experimental results obtained in piping vibration measurements. Excitation was defined as a set of multi-harmonic modal forces at piping resonance frequencies with random phase angles and amplitudes developed by iterative procedure. The values of modal forces amplitudes shall to produce analytical piping vibration PSD spectra that correspond or envelop experimental one obtained in vibration measurements. The same requirements were approved for RMS values of vibrovelocities. This technique is realized in the dPIPE piping software, [8]. The Figure 5 illustrates this procedure.

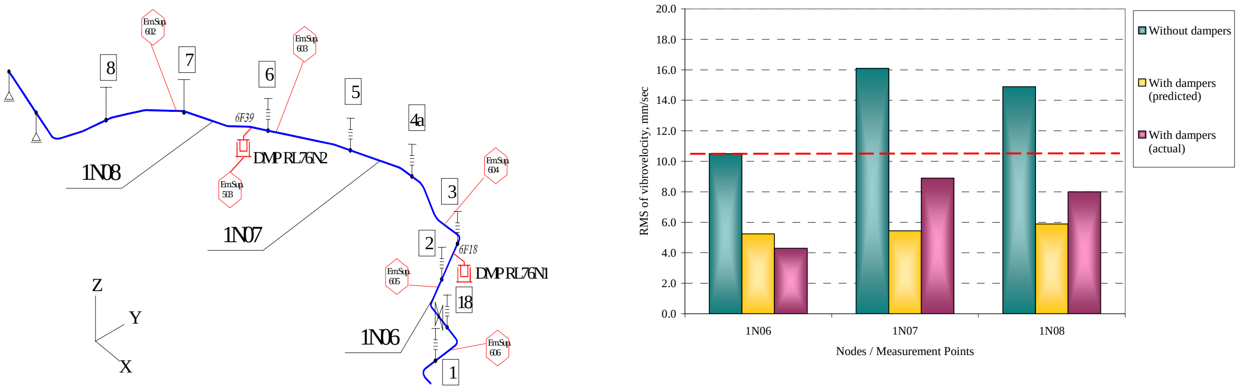


a) vibration distribution along the piping b) PSD spectra in the control point

Fig. 6 Experimental and analysis results of piping vibration

Negative experience with implementation of additional elastic piping supports (fig. 2) and piping analysis using developed analytical procedure have shown that the most effective solution for vibration reduction of Loviisa NPP piping is installation of High Viscous Dampers (HVD).

Figure 7 demonstrates 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).

ELIMINATION OF PIPING VIBRATION

In this project two types of high viscous dampers have been used: VD, VES and VRD manufactured by GERB Co., Berlin. Dampers do not care static load and respond on dynamically applied loads only using shear effects in a special high viscous liquid.

VD type damper has low temperature influence on its characteristics and could be located in the points with different and variable environmental temperatures. VES as well as VRD damper's types should be installed at the plant's points with initially defined environmental temperature limits. Dampers are located in a vertical position having working grease under atmospheric pressure in a chamber.

High viscous dampers have some essential advantages against other devices, among them are: non-stuck soft operation with high damping ability; damping of any dynamic impact including operational vibration, water hammers, seismic and other extreme dynamic loads; six degree of freedom damping ability; low maintenance and inspection costs; unlimited service life; high temperature and radiation stability and so on, [9-12].

In result of dynamic analysis and cost analysis an optimal number of 95 dampers have been placed at Loviisa NPP: 71 dampers at RA steam lines and 24 dampers at RL feedwater lines. Among 95 dampers 48 were VRD, 8 VES and 39 VD type.

Dampers have been installed at Loviisa NPP in a three ways: a) damper's piston attached to the piping, housing to the rigid structure; b) housing at the piping, piston to the rigid structure; c) piston to one piping, housing to another piping using different dynamic properties of the lines with dampening of two lines by one damper. Assembling and location of dampers are shown in figures:

Fig. 8 VES damper at the RL76 in RB LO2 (damper's piston at the piping, housing at the RB wall)

Fig. 9 VD damper at the RA11 in Turbine Hall (damper's piston at the piping, housing at the TH horizontal floor)

Fig. 10 Connection by VD damper of two RA lines with different dynamic properties.

Fig. 11 VRD damper at RA10 line in Deaerator Building (damper's housing at the piping, piston at the vertical wall)

Typical results of dampers influence on vibration state of the piping in terms of PSD spectra are shown in the figure 12.

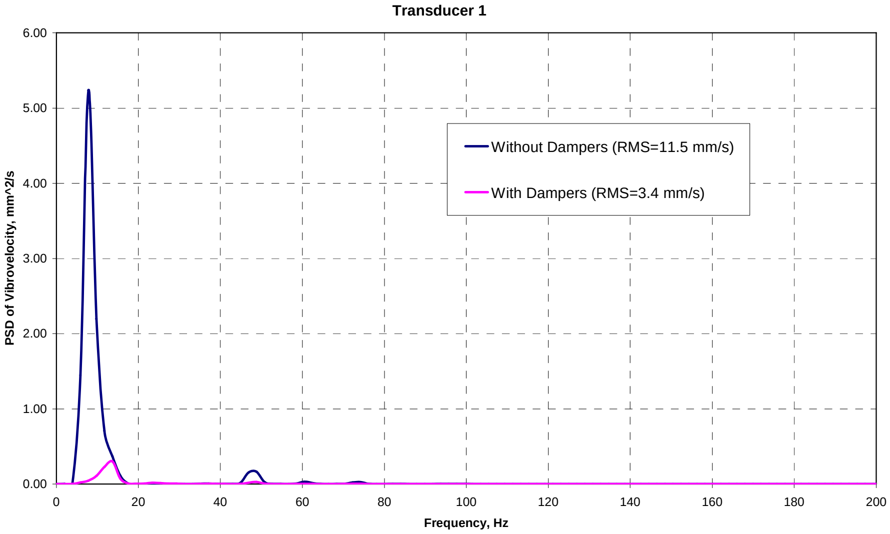


Fig. 12 PSD spectra of RA10 piping vibration before and after dampers installation

Referring to the maximal values of vibration registered at the Loviisa NPP in initial state (see Table 1) dampers installation provides to the system the following reduction in piping vibration, Table 2.

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

In the most problematic points along all RA and RL piping the reduction factor varies from 3.8 (maximal value) to 1.5 (minimal value) with the average factor approximately 2.5. It should be noted that dampers efficiency obviously depends on a number of dampers installed at the line. So presented results have been achieved with a minimal (optimal) number of dampers on a basis of a cost effective decision development. It is also necessary to put attention to the specific point 1F14 located at TH floor near Turbine 1 bearing No.1. The numbers shows that dampers connection to the building structure decreases vibration of the floor in spite of some predictions. Moreover, dampers installation not only dropped down vibration at the lines but also reduced noise and vibration in workshops and the Control Room that is very important from both environmental and safety points of view.

In the Table 3 is shown an overall dampers influence on vibration state of Loviisa NPP steam and feedwater piping versus approved criterion.

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

CONCLUSION

The operational vibration matter of steam and feed water piping at Loviisa NPP Units 1 and 2 has been successfully resolved using High Viscous Dampers Technology.

Dampers provide to the systems protection from different potential excitation sources as mechanical induced, pulsation induced, steam (gaseous) flow excited, liquid or mixed phase flow excited, pressure surge and hydraulic hammer, as well as seismic and other extreme dynamic loads.

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