Elimination of Chernobyl NPP Unit 3 Power Output Limitation Associated with High Main Steam Piping Flow Induced Vibration

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ABSTRACT

The paper deals with a significant operational problem encountered on Chernobyl Unit 3 during the last period of operation before December 2000 final shut-down of the plant. The eight main steam relief valves of Unit 3 were replaced in 1999 to the new set of SEBIM valves that caused abnormally high vibration in limits 80-100 % of nominal power and several shutdowns. Power output of the Unit has been strictly limited by 80 % of nominal load. After performing of special investigation the roots of vibration was discovered and corrective actions have been implemented for elimination of Unit 3 operational limits.

INTRODUCTION

Intensive vibrations of the main steam piping lines, section 12 were observed after the restart of the Unit 3 ChNPP following the replacement in 1991 of the Russian design Main Safety Relief valves by SEBIM Co. valves. The vibrations, found to be dependent on power level and were connected with local flow instabilities. The vibrations have caused fatigue failures in one of the pilot valve and resulted in two shutdowns of Unit 3 for repair and replacement. Further, in order to prevent failure during operation, the output of the Unit was reduced to 80% of nominal power (800 MWt) according to prescription of Nuclear Authority, until the root cause of the problem was properly identified and satisfactorily remedied. A comprehensive corrective action program was undertaken including:

- on site 3D vibration measurements along the piping and on the valves itself;
- creating of the analysis models of the piping and excitation and dynamic analysis of the system;
- developing and implementing measures for vibration reduction and excluding unit power limitation.

Six units of GERB High Viscous Dampers have been installed on the system without interruption of Unit operation. As the result vibration of the valves was reduced within an acceptance criteria.

SYSTEM WALKDOWN AND PRELIMINARY VIBRATION MEASUREMENTS

The system walkdown was performed in all parts of the pipelines and valves available according to radiation safety rules on operating unit, Fig. 1. Time available for walkdown and measurements was extremely limited by less than 30 minutes per day due to high radiation in the Box 801 where piping system 12 is located. This unforeseen strict limitation in the current project caused essential complexity in work performing. Several important differences in support system layout against project as well as some system's peculiarities that have a negative effect on operational parameters of hanger-support system were discovered. Basing on walkdown results certain changes in technical documentation and pipeline hanger-support system were recommended.

In order to carry out the vibration measurement two Multi-channel Portable Signal Analyzers (PSA) integrated in Notebook units (MERA Co., Russia) have been used. The vibration piezoelectric transducers were assembled on one magnetic platform in order to get simultaneous measurements in three orthogonal direction (3D) of vibration along the system. The following are the main features of vibration measurement processing:

- Frequency range of vibration measurements: from 2.0 up to 1000 Hz..
- Duration of registration on a hard disc for each point: 60 second.
- Sample frequency: 2000 Hz.
- Cut-off frequency of low pass filter: 800 Hz.

The results of vibration measurements were presented for each point of measurement in terms of RMS and Peak vibrovelocities so as in PSD plots in X, Y and Z directions, Fig.2, 3.

The vibration measurements on a limited 80% Unit power have shown that the vibration of Valve 1234 system is comparatively high and exceeds levels recommended by internationally-recognized criteria for piping systems that provide absolute vibration safety. Maximum of measured vibration is connected with the surrounding piping system (up to 28.4 mm/s

RMS) and SEBIM Valve 1234 body (up to 11.2 mm/s). It was found that the system has some dominant frequencies of vibration: 48.8; 19.5; 13.7 and 9.7 Hz. The most intensive vibration was associated with the frequency 48.8 Hz, Fig.

PIPING SYSTEM VIBRATION CRITERIA

The NPP operational experience in a lot of cases shows that the reliability and service life of NPP are very often essentially limited by dynamic behavior of the main and auxiliary piping systems. In contrast with other plant systems as turbine and different rotating equipment, there are not strict rules in limitation of piping vibration. Only a few recommendations and guidelines were developed based on operational experience of safety related piping subjected to vibration loads.

For example, in the R. Gamble and S. Tagart Method [1] on the basis of experience and failure analysis of more than 400 US NPP piping it is recommended to protect piping from vibration if displacements are more than 0.5 mm in frequency range less 10.0 Hz and 0.25 mm in frequency range 10.0 – 40.0 Hz. This limitation means that peak vibrovelocity shall be less than 6.28 mm/s at 2.0 Hz and 62.8 mm/s at 40.0 Hz.

The different criteria of piping vibration stability are considered in ASME OMa S/G-1991 STANDARD Part 3 [2] depending on piping responsibility. The values of allowable stresses, vibrovelocities and vibrodisplacements may be included in these criteria. The limit value of vibrovelocity is determined by the empirical dependence, which contains several coefficients reflected features of piping weld arrangement, properties of material, lumped masses and so on. When the peak value of vibrovelocity is less than 12.7 mm/sec, it may be assumed that piping has the sufficient dynamic capacity. If vibration exceeds this level the Guide recommends to accumulate additional information on potential reasons of vibration and to improve oscillation state of piping.

In the ASME BPVC (NB-3622.3), it is indicated that piping vibration has to be in limits that guarantee the safety operation but not pointed out the current limits of allowable vibration [3].

In France, the recommended threshold limit of piping root-mean-square (RMS) vibration is defined as 12 mm/s for the NPP 1300 MWt Units [4].

In Germany, operational vibration of NPP piping with RMS velocity more than 20 mm/s is defined like relatively dangerous and has to be reduced [5].

In Russia according to the Nuclear PNAE Code it is recommended only in general to shift and separate specifically natural frequency of piping systems from possible anticipated frequency range of external excitation [6]. According to Russian Boiler Standard RD 10-249-98 it is recommended to evaluate range of piping vibration (peak vibrovelocities) according to the following criteria. Less than 15.0 mm/s (good enough); 15.0-25.0 mm/s (specific measurements and analysis is recommended to confirm safety); more than 25.0 mm/s (recommended to improve vibration of the system), [7].

In France for gas industry piping the RMS vibration in frequency band 10-500 Hz less than 1.5 mm/s is defined as good; in range of 1.5 – 4.8 mm/s acknowledge as appropriate; 4.8-17.0 mm/s limited allowable and more than 17.0 mm/s not allowable absolutely.

ISO 2372 installs criteria for RMS vibrovelocities of piping depending on frequency range of vibration. For example, for frequency of vibration 10 Hz RMS less than 3.5 mm/s means good; between 3.5 and 7.0 mm/s means satisfactory; between 7.0 and 16 mm/s recommended improvement, but limited operation is possible under specific control; more than 16.0 mm/s not allowable. For low frequency range the RMS allowables are smaller and for high frequencies are higher.

Summarizing the presented references it may be concluded that vibration of piping system section 12 and valve 1234 Unit 3 ChNPP is moderately high and shall be improved. One important remark should be mentioned that all above pointed criteria is based on pressure boundary and supports piping safety and not on specific demands for systems or mechanical/electrical equipment installed on piping. In this particular case the specific criteria shall be established. On the other hand it’s obvious that specific piping equipment should be dynamically protected and ready to operate under any possible piping vibration and dynamic safety of equipment should be equivalent to piping itself.

In considered particular case the Nuclear Authority installed criterion of 8.0 mm/s RMS in each of the 3 vibration components for the SEBIM valve body using direct operational experience of valves’ piping elements fatigue failures.

VIBRATION ANALYSIS AND RECOMMENDATIONS FOR VIBRATION REDUCTION

The dynamic analysis of the system "Pipelines-SEBIM Valves" has been carried out basing on performed walkdowns and developed analytical models of examined piping systems and also using results of vibration measurements fulfilled in the initial stage of the project.

The methodology using the highest degree of approximation of geometrical and physical parameters of the system has been applied for developing of calculation models of pipelines. Simulation of vibration excitation was based on using of eigen value techniques and the main goal was to achieve the same distribution of vibration modes along the system as was experimentally defined in terms of RMS vibration and PSD spectra, Fig. 2, 3. The current technique does not contain

modeling of turbulence flow in piping and definition of flow excitation forces on piping elbows. Analysis experience shows that this way is not reliable enough and brings sometime improper results with significant errors even in quality evaluation of observed phenomena due to indefinite hydraulic characteristics of piping internals (tee elements, valves and elbows).
The calculations have been carried out with the help of CKTI-Vibroseism Co. “dPIPE” software complex which is worldwide used on nuclear and fossil power facilities for solving similar problems, [8].
The dynamic analysis of the considered systems was fulfilled under two principal conditions:
a) as built state without dampers; b) with high-viscous VES – type dampers located in different points of the system in order to achieve optimum in vibration reduction versus expenses for vibration elimination.
On the basis of dynamic analysis of the considered piping system and cost evaluation of possible upgrading, including such a measure like redesigning of piping and substituting of piping elements, the recommendations concerning vibration reduction were developed. Six high viscous dampers were recommended for installation during operation of the Unit: four – on the piping system of 1234 valve (two dampers on the valve body and two dampers on the connecting piping), and two on the valve 1211 body. This decision was also based on past successful experience of using High Viscous Dampers for seismic and vibration protection of the systems, [9-16].

VALVE VIBRATION MEASUREMENTS WITH INSTALLED DAMPERS

Direct Dampers Effectiveness Assessment

Measurements for dampers’ effectiveness assessment were carried out at the same operational conditions with constant 80% partial power level of 800 MW with dampers both attached and detached. The time interval between measurements was minimal as the result of ChNPP conditions which allowed to acquire reliable data on dampers' direct influence on the valves' vibration state. RMS vibrovelocity values in mm/s as well as peak vibrovelocity values acquired as the result of measurements of the system with and without dampers are given in Table 1.

Table 1. Vibration of the SEBIM Valves 1211 and 1234 Unit 3 ChNPP without and with GERB Visco-Dampers

Measurement Point	Measured Direction	Date of Measurement		Vibration Reduction Factor RMS/Peak
		06.07.2000 Without Dampers	07.07.2000 With Dampers	
		RMS/Peak, mm/s	RMS/Peak, mm/s	
Valve 1234 point 4	X	7,7/32.1	4,3/11.9	1,8/2.7
	Y	4,2/18.8	2,7/8.5	1,6/2.2
	Z	5,1/28.8	1,5/5.4	3,4/5.3
Valve 1211 point 1	X	3,0/8.2	1,1/4.0	2,7/2.1
	Y	1,6/6.1	1,4/5.0	1,14/1.2
	Z	1,5/5.0	0,8/3.2	1,88/1.6

In addition to the data presented in the table comparative Power Spectral Density curves for vibrovelocity before and after damper installation in similar measurement points for the valve 1234 are shown on Fig. 4 and 5.
Clearly the installation of dampers has resulted in substantial decrease of resonance effects in the piping system which is demonstrated by both numbers and spectra shape. Based on the acquired results a conclusion about dampers' effective operation at unit's power output of up to 800MW can be drawn.
Vibrovelocities RMS values on SEBIM 1234 valve which was subjected to highest vibration have been lowered on average by 2.3 times and peak values by 3.4 times. Approximately the same factors of reduction have been observed on valve 1211 where the overall vibration level is much lower.
At the same time the direct experiment for dampers' effectiveness assessment that was carried out did not give the answer to the main question: is the dampers' influence sufficient for assurance of acceptable level of vibration at unit's full power. This has to do with lack of reliable data of any sort about the valves' vibration at full power, which from the very beginning caused difficulties in determining the necessary and sufficient measures for vibration decreasing.

Valves Vibration at Unit Power Increase and Root Cause of Vibration

The goal of this stage was to determine the dependence of vibration level on valves 1211 and 1234 from step-by-step power incrementation. According to preliminary data, mainly acquired from witnesses' descriptions the valves' vibration dramatically increased with the increase of Unit power, achieving its maximum at around 90-100% power level. This circumstance did not allow to make final conclusions about sufficiency of the undertaken measures basing only on the results of measurements at 800 MW (80% of nominal power level).

Measurements on the valve 1211 have shown vibration maximum at power level of 90% (3.0 mm/s RMS in X direction). Vibration levels have remained low for all conditions which demonstrates the sufficiency of undertaken measures and possibility for valve's normal operation in the whole range of Unit's power levels.

Below in Table 2 RMS vibrovelocities on valve 1234 are presented (control measurement point 1), mm/s

Table 2. Vibration of the SEBIM Valve 1234 at Unit 3 ChNPP Power Increase

RMS vibrovelocities	Unit Power, %					
	85	90	95	100 24.07.00	100 25.07.00	100 (*) 14.08.00
Vx	2.99	3.19	3.16	3.13	2.98	3.32
Vy	7.38	8.61	10.02	9.24	9.48	6.61
Vz	1.61	1.68	1.1	1.44	1.63	1.29
V(**)	8.12	9.33	10.56	9.86	10.07	7.51

(*)Upgraded Dampers Attachment (**) $V = \sqrt{V_x^2 + V_y^2 + V_z^2} < Vall$

The acquired vibration picture of valve 1234 at Unit power increase has clearly shown the substantial dependence of intensity of vibration excitation in the T-elements of pipelines 20 and 21 from the steam speed in the main pipeline, Fig. 1. Judging from all measurements it can be stated that the valve 1234 system is subjected to maximum excitation at power level of 95-100%, and the correlation between vibration of various points is also power level dependent.

Considering the data acquired at 80% power level and the tendency of vibration growth, discovered at Unit's power level increase from 85 to 100% it can be concluded that valve 1234 after its assemblage (before damper installation) at full power could have a rather high vibration level on the system's characteristic frequency of 48.8 Hz. Possible range of vibrovelocity RMS values is 15-30.0 mm/sec. Caused by this vibration the previously observed phenomena at valve's operation with fatigue failure of valve's small bore piping elements and shutdown of the Unit as consequence seems quite natural.

It was also concluded that the most present mode shape is the twist mode around the valve's 1234 vertical axis at frequency 48.8 Hz. The measurements at full power and the determining of the system's main mode shape along with the results of calculation analysis have allowed modeling the full picture of the observed phenomenon.

Root Cause of Vibration

The piping system and valve 1234 form a closed acoustic loop, one of the natural frequencies of which is 48.8 Hz which is confirmed by the calculations. The closely located T-elements of piping 20 and 21 cause extreme turbulization and instability of the steam flow through the main line. The self-excited flow rupture phenomenon's intensity in the T-elements is linearly dependent on the steam flow speed (power output of the Unit) and its frequency is determined by Struhal Parameter and is greatly influence on actual geometrical properties of the T-elements. Basing on literature sources only the frequency range of 30-60 Hz can be given in this particular case, whereas the exact frequency and intensity dependence from flow can not be determined this way. Normally such characteristics are acquired through experimental data which was not possible to do within current project. At the same time basing on the carried out research it can be stated that the frequency range of the self-induced vibration phenomena at nominal flow speed lies near the 47-49 Hz range.

Generally the problem looks the following way. The increase in Unit's power level causes linear growth of flow rupture phenomena's frequency and intensity in the piping T-elements. At power level of 90-100% the flow turbulence intensity achieves its maximum and its frequency becomes equal to "piping-valve's 1234" system acoustic resonance frequency. As a result intensive waves are generated in pipelines that propagate through the line with the medium's (damp steam) speed of sound. The presence of bends in the system creates unbalanced oscillating pressure in runs. Since the wave initiation in lines 20 and 21 may differ in time and the distance traveled by waves in these lines is also different the two lines are subjected to pressures different in phase and amplitude. Therefore at any given moment in time valve 1234 is subjected to unbalanced forces from the two pipelines entering it.

Previous experience, particularly at Kozloduy NPP shows that such acoustic resonance phenomenon can cause pressure pulsation of up to 3-5% of nominal pressure in the line. This results in considerable unbalanced dynamic forces in bends (of up to several hundreds of kilograms). The phenomenon described above however is not so dangerous by itself and is present in practically all similar pipelines without affecting their operability. Only when the acoustic resonance frequency coincides with a natural frequency of the piping system very intensive vibration is observed that can cause malfunction of mechanical equipment, fatigue damage and other phenomena directly related to NPP's safe operation. In the present case the oscillating pressure component in the nearest bends to valve 1234 coincides with the natural frequency of the system of 48.8 Hz, which corresponds to a twist mode-shape of the system with valve 1234 oscillating around its vertical axis. This mode-shape has been analytically confirmed by calculations.

The particular intensity of the described phenomenon on ChNPP Unit 3 has to do with coincidence of several factors: close location of T-elements, which favorizes the steam rupture conditions, the system's general layout and its high flexibility, absence of support for the heavy SEBIM valve, coincidence of frequencies of acoustic and mechanical resonance. All of these factors have resulted in dynamic instability of valve's 1234 system and has directly influenced normal operation conditions of ChNPP Unit 3. It should be noted that the relatively stable situation of other valves on Unit 3 is mostly due to absence of frequencies coincidence.

The first experiments of power rise have indicated that the damping units are quite successfully damping the linear vibration modes in X and Z direction, but due to significant dynamic flexibility of the horizontal attachment beam in the Y direction the damping units could not provide full damping of twist vibration modes of valve 1234.

However the criteria of valve's allowable vibration, set by SEBIM Company have been fulfilled, regardless the discovered drawbacks of the damper attachment construction. The necessary upgrading of the attachment system has been performed and essentially improved dynamic behavior of the valve, see last column in Table 2. The acquired final data indicates the full achievement of the goal set for this project: operational vibration of valve 1234 has decreased to a minimal level in all directions and in all measurement points, Fig. 6-9.

Additionally the present technical solution has without any special measures provided seismic stability of the system for Safe Shutdown Earthquake level. Also reliable protection of valves and piping system 12 in case of valves 1211 and 1234 actuation and resulting considerable hammer impacts has been provided.

Comparison of Acquired Results with Set Criteria.

According to the criterion set by Regulatory Authority (DAYR) vibrovelocity RMS values of valves 1234 and 1211 must be lower than 8.0 mm/sec in each of the 3 components of measured vibration.

This criterion is met with a considerable safety margin in all points on the valve 1234 body. The main point 1 on the valve's periphery the maximal vibrovelocity RMS in Y direction is only 6.61 mm/sec, whereas at 80% power level one measurement has shown vibration almost twice as high. Vibrovelocity RMS in point 2 near the valve's central axis does not exceed 6.0 mm/sec. This level of vibration according to international experience should be regarded as rather low for NPP's piping systems dynamically excited by medium flow phenomena.

Final data concerning valve 1211 at full Unit 3 power has shown that RMS vibrovelocity does not exceed 3.0 mm/sec, which is the minimally possible level for this type of systems.

An additional criterion set by the valve producer SEBIM Company has been considered which in case of equal levels of vibration in all directions could be even stricter than the DYAR criterion.

In accordance with chapter 3.1.1 SEBIM Test Report LV 29789 “Vibration Endurance Tests on a SEBIM Control and Lines Assembly” maximal allowable RMS vibrovelocity for the valve’s body is installed as:

$$Vall = 12.2 \text{ mm/sec.}$$

Where, RMS vibrovelocity *Vall* in accordance with the same chapter 3.1.1 is calculated as:

$$V = \sqrt{V_x^2 + V_y^2 + V_z^2} < Vall\,,$$

where *Vx, Vy, Vz* – RMS vibrovelocity in directions X, Y, Z, correspondingly.

Analysis of presented data allows to make conclusion that vibration at the valve 1234 body is much less than SEBIM criterion and even can meet level of 8.0 instead of installed 12.2 mm/s, see results in Table 2.

SUMMARY AND CONCLUSION

- At the Unit’s 3 ChNPP intermediate 80% power level valve’s 1234 RMS vibration level has reached 11.2 mm/s and had a stable tendency for growth approximately with factor 2.0 to full Unit power. Vibration has caused fatigue failure of valves’ elements and interruptions in normal operating of the Unit. Main sources of the valves’ high vibration are intensive flow induced excitation in T-elements connections of the main and auxiliary lines, acoustic resonance in piping system 20 and 21 and coinciding of acoustic and mechanical resonance of the system on frequency 48.8 Hz.
- On the basis of comprehensive analysis of the system the most cost effective and simple technical decision for vibration reduction has been found. Installation of GERB Visco-Dampers was recommended and has been realized without any interruption or changing operation mode of the Unit 3.
- As the result of installation of 6-component High Viscous Dampers Unit’s full power maximum vibrovelocity was reduced with factor more than 2.0 to: 2.81 mm/**s** RMS at valve’s body 1211 and 6.61 mm/s RMS at valve’s body 1234. These levels are lower than the installed by Nuclear Authority (8.0 mm/s) and essentially lower than criteria level installed by valves’ manufacturer SEBIM firm. The valves’ vibration level became safe and allows to operate Unit 3 without any limitation due to vibration of the valves.

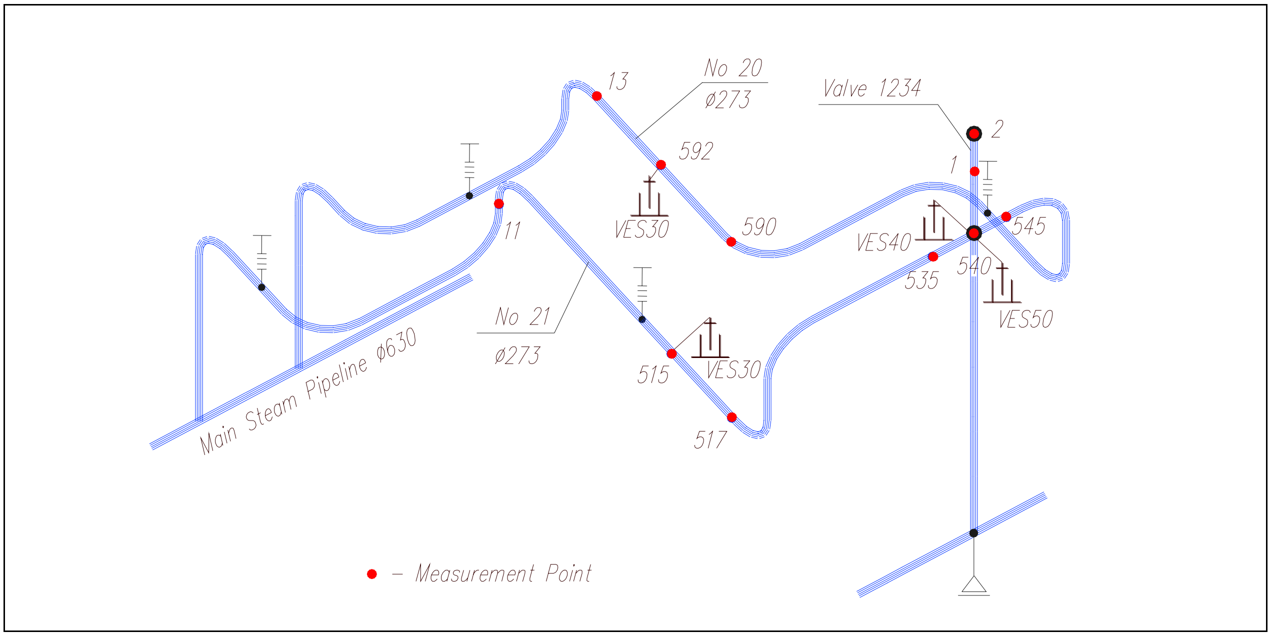

Figure 1. Measurement Points and Location of Dampers on Pipeline Section 12 Chernobyl NPP Unit 3.

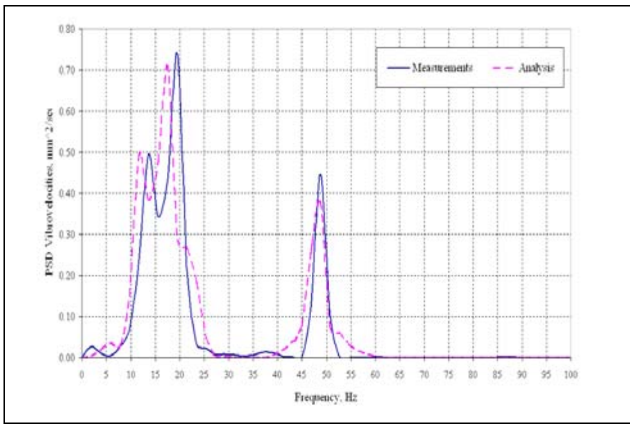

Figure 2. Comparison of Measured Experimentally and Analytical PSD Vibrovelocity (Eigen Value Analysis) for Measurement Point 1 (Valve 1234 Body).

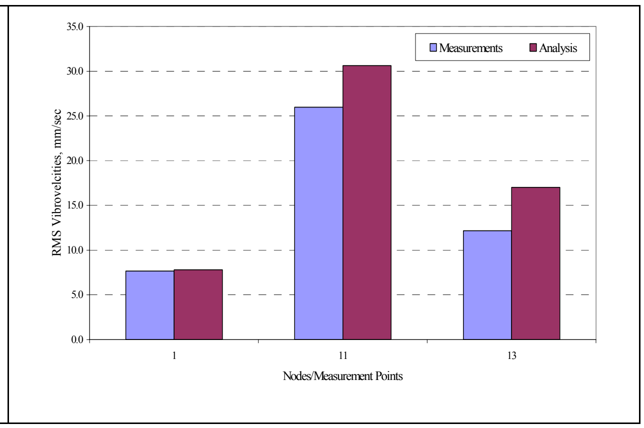

Figure 3. Comparison of Measured and Calculated RMS Value of Vibration for Principal Nodes of the System (1-Valve 1234 Body, 11-Piping 21, 13-Piping 20).

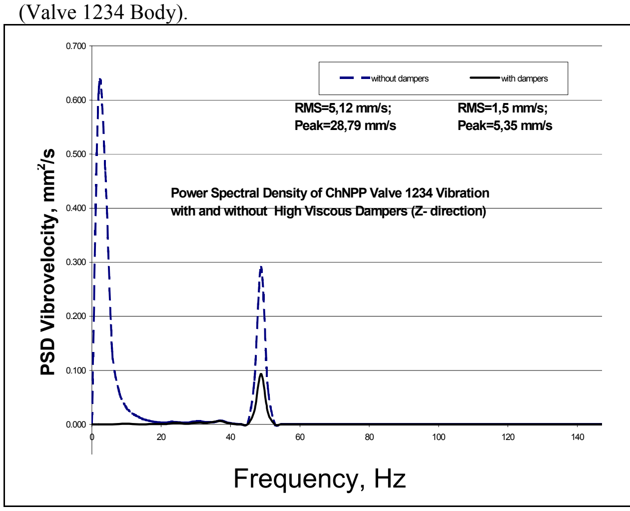

Figure 4. Vibrovelocity PSD before and after Damper Installation. Valve 1234, Measurement Point 1, direction Z.

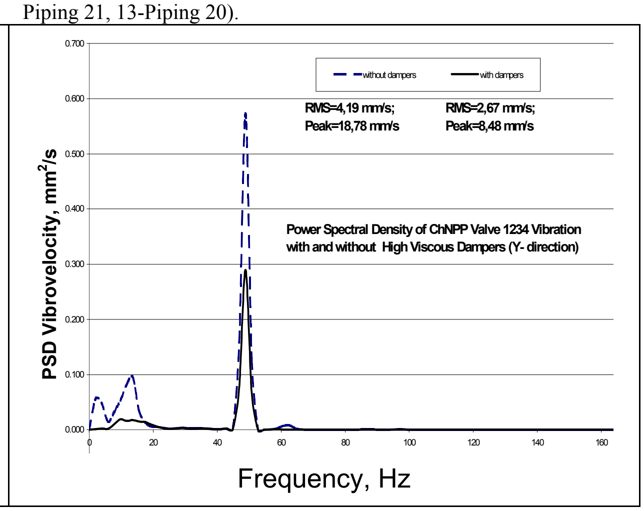

Figure 5. Vibrovelocity PSD before and after Damper Installation. Valve 1234, Measurement Point 1, Direction Y.

Figure 6. Vibration Measurement using 3D magnetic platform on the Valve 1211 Body.

Figure 7. General View of the Dampers on the SEBIM Valves 1211 (front) and 1234.

Figure 8. Vibration Measurements on the Valve's 1211 Damper Plate.

Figure 9. Installation of Transducers on the Damper's Clamp, Piping 21. VES30 Damper is Installed Directly on the Piping Horizontal Run.

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