UPGRADING OF DYNAMIC RELIABILITY AND LIFE EXTENSION OF PIPING BY MEANS OF HIGH VISCOUS DAMPER TECHNOLOGY

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ABSTRACT

The presented paper contains the evaluation of dynamic impact influence on integrity, fatigue and service life of highly loaded NPP piping. The analysis was performed on the base of on site measurements of piping operational vibration and strength study of phenomena by methods of fatigue and fracture mechanics. The 3D High Viscous Dampers (HVD) were successfully applied for protecting primary loop piping welding from flaw growth due to operational flow induced vibration as one of the flaw propagation sources, as well as many other primary and secondary part important piping systems were fully protected from hydraulic hammers, seismic excitation, shocks, two-phase flow excitation and other kind dynamic impact.

INTRODUCTION

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 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 base of experience and failure analysis of more than 400 US NPP piping it is recommended to protect piping from vibration in case of displacements more than 0,5 mm in frequency range less 10 Hz and 0,25 mm in frequency range 10 - 40 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, vibro-velocities and vibro-displacements may be included in these criteria. The limit value of vibro-velocity 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 vibro-velocity is less than 12.7 mm/sec, it may be assumed that piping has the sufficient vibro-capacity. If vibration exceeds this level the Guide recommends to accumulate additional information on potential reasons of vibration and to improve piping system.

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 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.

In distinction with operational vibration which is quite ordinary for plant conditions and may not prevent energy supplying for long period, the NPP design seismic excitation case has very low probability with return periods less than 10^{-3} event per year. This dynamic loading is rather well standardized due to high intensity of impact and possibility of immediate collapse with obvious heavy consequences. The

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allowable seismic forces and stresses in piping systems are strictly limited by national and international codes and standards. That is why the procedures of seismic design and upgrading of piping are more evident than in design case of piping subjected to potential operational vibration and shock loading. At the same time the per year losses of utilities from excessive operational vibration of piping and fatigue failures are rather essential to be neglected and furthermore, may cause serious accident in case of rupture of safety related high energy piping that took place on a number of utilities.

PIPING VIBRATION SOURCES

The piping operational vibration strongly depends on external and internal sources of dynamic excitation. The external sources include dynamic effects with usually definite frequencies from rotating machines, so as random seismic and kinematics excitations. The internal sources are connected primarily with non-stationary turbulent flow in piping and valves stimulating stable wave resonant in tubes, so as with two-phase shell flow heavily effected on piping elbows and system in whole.

The main distinguishing feature of piping external and internal excitations is wide-band frequency spectra. It is the reason of high vibration sensitivity of commonly low damped and flexible piping. The modal properties of the piping with closely spaced frequencies lead to high-density spectra, which easily tuned on one of the excitation frequencies. That makes less or more unsuccessful any attempt of decreasing operational vibration by changing, shifting and adding elastic low-damped supports or restraints to the system. The wide band excitation in this case will find always the new resonant frequency with low damping ratio that will bring an essential amplification to the system on the other natural mode. That is why only either excluding of vibration excitation forces, that is very costly and need usually serious modification of the system itself, or implementing of essential damping to the system can practically decrease vibration of piping and protect it from fatigue failure.

The world experience shows that the operational vibration of piping can achieve values of 10-1000 mm/sec and can heavily influence on reliability and safety of NP and FP plants [1]. The frequency of intensive vibration that practically impeded to normal operating of the plants is in range of 0.5 to hundreds of Hz with relatively small level of stresses in piping (less than 10 MPa). Another possible impact like water hammer in piping may lead to shocks in the system and brings displacement up to scores of centimeters and causes stresses in piping and their supports on yield to ultimate strength level. Under seismic impacts the acceleration of piping may be greater than 10g, displacements more than one meter on the first natural frequencies that are usually lower than 5 Hz.

High level of operational vibration leads to a steady flaw and crack growth in base metal and welding materials and through a limited operation time can cause failure of piping, fatigue damages of supports and pendulum system, break of attached small bore pipes, malfunction of valves, relays, drives and so on. In the case of intensive seismic impact or water hammer all these malfunctions or collapse of piping support system may occur in a moment.

INFLUENCE OF OPERATIONAL VIBRATION ON PIPING RELIABILITY

The influence of operational vibration on a piping reliability can be shown on practical example and analytical study of the high energy and heavy loaded NPP 800-mm diameter primary loop system, figure 1. This system has a number of micro-cracks and flaws in on site fabricated weld joints of piping that is the result of shortcomings in welding technology and unfavorable characteristics of base metal. In several weld joints the essential cumulating of flaw growth was observed in relatively short period of operation. Many of improvements of welding technology were implemented into the system before operational vibration became one of the actual potential sources of damage cumulating to be considered.

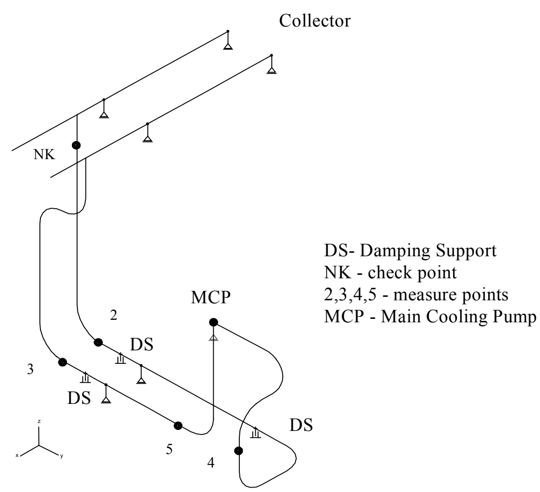

Figure 1. Sketch of Pipeline ∅ 800mm (Primary Loop System of RBMK-type NPP)

The fatigue analysis of piping weld material has been undertaken according to Russian Code PNAE that is rather close to methodology of the ASME BPVC, Section III. Additionally more accurate fracture mechanics flaw growth analysis has been carried out according to the ASME BPVC using the actual parameters of flaw and cracks in welding zones.

As input data for the analysis of stresses distribution in welding zones the experimental actual piping vibration obtained by direct multi-channel measurements along the piping were used. The measurements were carried out during special hot test of primary circuit with the parameters of the water flow equivalent to the normal operational one. By means of CVS FEM computer code dPIPE the results of vibration measurements were initially converted to the same distribution of accelerations and displacements along the piping as obtained in the experiment and then have been transferred to the equivalent stresses distribution in piping elements and welding zones.

For more reliable and demonstrative representation of analysis results the wide range of static and dynamic factors of piping loading that influence on fatigue were taken into account.

At first the basic analytical fatigue curves (amplitude of dynamic stresses to cycles) for specific material properties of welded zones with different possible asymmetric ratios were developed as shown on figure 2. It should be noted that essential decreasing of allowable number of loading cycles under permanent vibration amplitude is observed only for the asymmetric ratio more than 0.6 and dynamic stresses higher than 20 MPa. These, seems to be critical values, are in the range of usual severe operation conditions for high pressure and hot NPP/FPP piping. In general that means high sensitivity of such piping to a crack propagation under operational vibration load case.

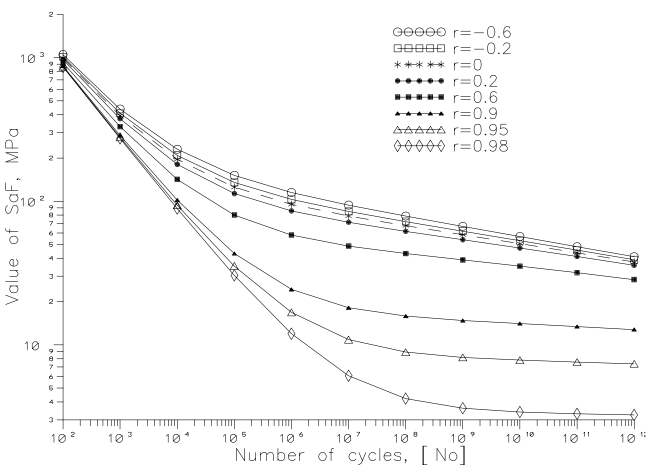

Figure 2. Analytical Fatigue Curves calculated with different asymmetry ratio r (r = $\sigma_{min}/\sigma_{max}$)

The influence of welding residual stresses on Cumulative Usage Factor (CUF) for different level of operational stresses in piping is illustrated by figure 3. It has to be mentioned that level of residual stresses in the range of 20 to 50 % or more to the specified yield strength may occur in site made welds rather often. It is obvious from figure 3 that even in case of relatively small residual stresses and quite common level of Normal Operating Loading (NOL) stresses for in site made welded zone of piping the CUF coefficient may exceed the allowable limit. The NOL sustained stresses were calculated as a result of pressure, dead weight, piping thermal expansion and local temperature load combination.

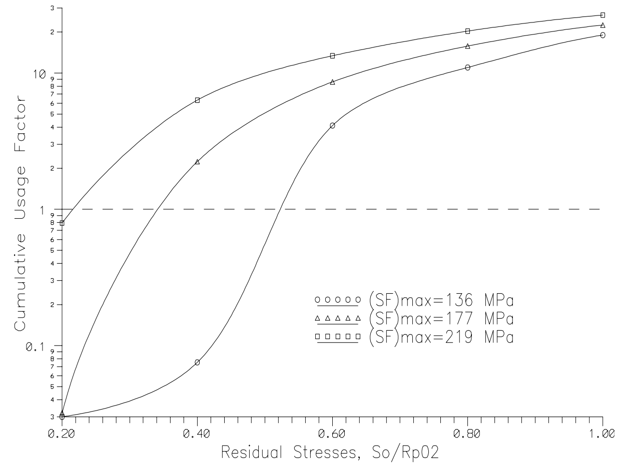

Figure 3. CUF of the welded joint zone due to different levels of operational and residual stresses. (Calculations were made for 3 years operational period with value of root-mean-square velocity Vrms=15 mm/sec)

The results on figure 4 show the significant influence of piping vibration on CUF coefficient for the range of NOL stresses that are quite common for high-energy piping. The curves were generated for the 3-year operational maintenance period of piping that reflects the actual utility situation. It can be concluded that high operational vibration may cause problems for piping integrity even in case of relatively moderate level of operational static piping loading.

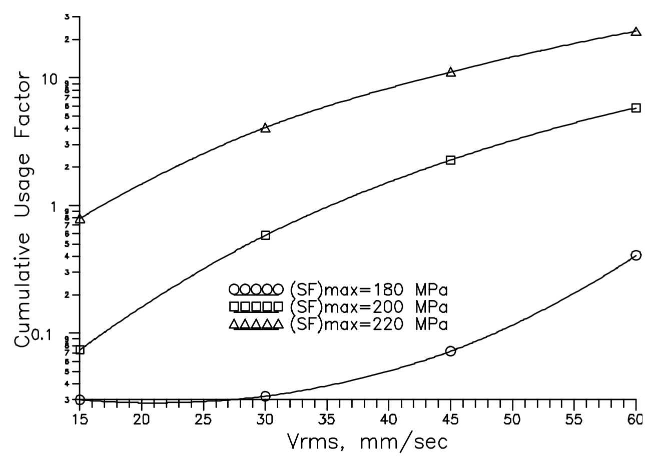

Figure 4. CUF of the welded joint zone (pipeline ∅ 800mm) as function of root-mean-square velocity. (Calculations were made for 3 years operational period. Residual stresses were assumed as So = 0.2•Rp02)

The performed wide band analysis of different factors influence on CUF coefficient allows to create the Generic Vibration Usage (GVU) curves, figure 5. These results obviously define that decreasing of operational vibration is very effective source of piping fatigue rupture protection. For example, reduction of RMS vibration from 30 to 4 mm/sec may lead to essential life extension of high energy piping service period and significantly increase reliability of high responsible safety systems of NPP.

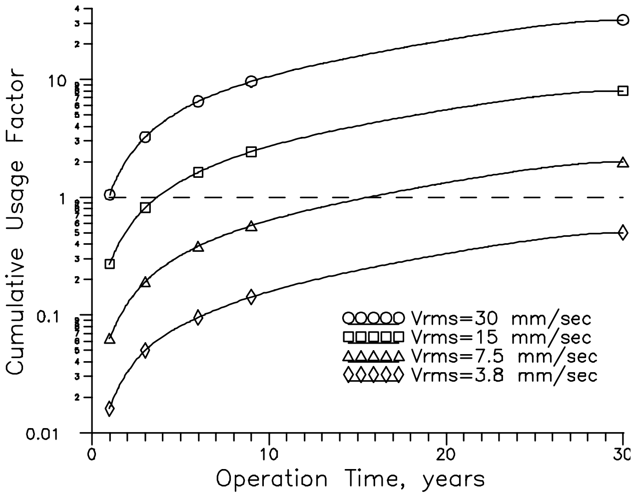

Figure 5. CUF of the welded joint zone (pipeline - collector nozzle) as function of Operational Period Time for different levels of operational vibration. (Calculations were made for Residual Stresses So=0.2•Rp02, (SF)max = 219 MPa)

Approximately the same qualitative result was obtained in evaluation of crack growth by methods of Fracture Mechanics according to ASME BPVC, Section XI, C-3000. In the present study the largest hypothetical flaw of on site welding was under consideration. The criteria for flaw growth was assumed as crack propagation up to the nearest external surface of welding joint. The results of the fracture mechanics analysis confirmed the main conclusion made by fatigue study. The intensive operational vibration has significant influence on service life of high energy piping subjected to intensive loading by pressure, weight, thermal expansion, temperature and residual stresses, figures 6 and 7.

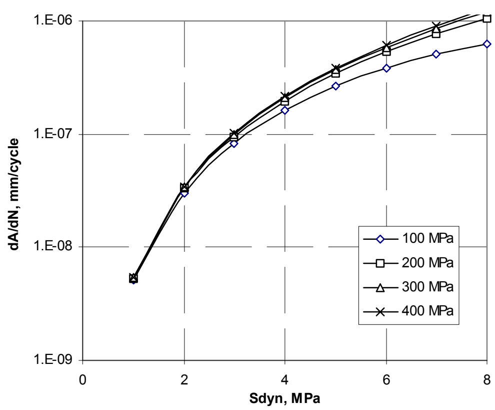

Figure 6. Influence of Flaw Growth Rate due to Cyclic Fatigue from Level of Sustain Load

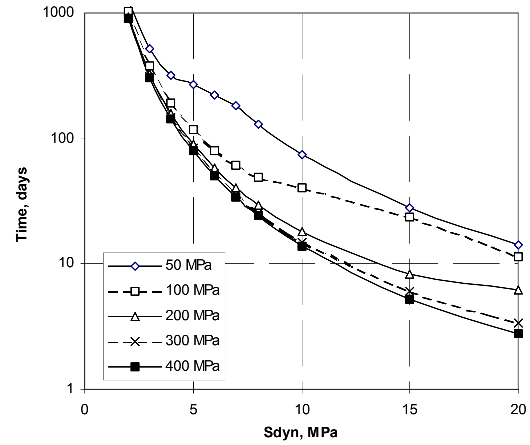

Figure 7. "Time -- Dynamic Stresses" Fatigue Flaw Growth Dependencies for Different Level of Sustained Load

Thus, in many practical situations the piping life extension can be accomplished by essential decreasing of piping operational vibration level. Obtained results demonstrate that level of RMS piping vibration less than 10 mm/s seems to be the appropriate limit for safety operation of piping under wide range of sustained loads even for severe conditions. The best way to protect piping from vibration, shocks, hammer and seismic impacts is installation of special damping devices that provide dynamic safety for all piping service conditions and at the same time do not resist to thermal expansion of piping.

MODERN DEVICES FOR DYNAMIC PROTECTION OF PIPING

In energetic and petrol-chemical industry several types of piping vibration protection devices are widely dispersed: mechanical and hydraulic snubbers; axial high-viscous dampers; elasto-plastic absorbers; stoppers; magnetic liquid dampers; resonance absorbers; multi-component high-viscous GERB dampers or CVS-HVD [6-12].

General requirements for energetic and industry plant damping devices can be postulated as follows:

- universal high damping ability for any dynamic impact (vibration, shock, seismic, etc);
- long service life without repairing;
- radioactive and thermal resistance;
- negligible reaction force to piping or system under thermal expansions;
- lack of time delay under dynamic load;
- ability to overloading without loosing functionality and integrity;
- ability for regulation of damping necessary for the system;
- low primary, inspection and maintenance cost.

The snubbers, axial high viscous dampers, stoppers and multi-component high-viscous dampers (HVD) have the widest circulation among other devices. Obviously that the best device has to accumulate and meet all or most of all previously mentioned demands. One of the perspective constructions for dynamic protection of piping seems to be HVD that integrated many of advantages and fortunately escape some principal shortcomings of other devices.

CONSTRUCTION OF THE HIGH VISCOUS DAMPER.

The High Viscous Dampers (HVD) VES type were designed by GERB Co. for absorbing different dynamic effects in piping, equipment, isolation and other systems. One of the alternative HVD design of VD type damper is shown on figure 8. The construction of VD damper consists of metal housing (1) filled with high viscous working liquid (2) under atmospheric pressure and metal piston (3) dropped into the grease. Special damper high viscous silicon grease is nontoxic, fire, explosive and radioactive resistant, biologically inert, protect from corrosion and may be used in temperature range -60°C to +250°C. The free plunged thin shells (5) between housing and piston and the core (4) inside the piston are installed for up-grading and regulation of HVD damping force. The core, shells and piston do not rigidly connected and restrained each other, so horizontal and vertical thermal expansion and dynamic limits of damper are defined only by clearances between housing and piston. The internal space of VD is protected by elastic sealing (6). The damper is fixed by flanges and clamp from piston side to vibrated object and from housing side to relatively rigid construction, figures 9, 10. Depending on diameter of housing (100-800 mm) reaction force of damper on dynamic load may change from 2.5 kN up to 300 kN providing 3D free thermal expansions to the damped system up to +/- 200 mm. One unit of HVD is working in 6 degree of freedom coincidentally that brings to the system high damping effect even in case of installation to the vibration nodal point were linear displacement do not exist. In this particular case rotating or rocking parts of damping force is influenced not on linear but on angle vector of vibration mode. That provides high effectiveness of HVD independently from positioning on the system and gives possibility for essential decreasing number of devices to be installed. Additionally damping force of each HVD can be many times changed by variation of shell's number and that way has been tuned optimally to the actual system.

CHARACTERISTICS AND MATHEMATICAL MODEL OF HIGH VISCOUS DAMPER

In order to derive dynamic characteristics of HVD, a series of harmonic excitation tests for HVD of various typical sizes has been made in a wide range of frequencies and amplitudes of displacements. The piston displacement and response amplitudes as well as the phase have been measured during the tests. The obtained experimental data have shown that the elastic and viscous components of the damper dynamic stiffness have clearly expressed frequency dependence and a slight dependence on the piston displacement's amplitudes. It was found that such dynamic behavior of HVD is good enough approximate by a linear system consisting of two Maxwell models connected in parallel. This model is described by four independent parameters (k1, k2, c1, c2) which variation leads to a well agreement with the experimental dependencies, Figure 11.

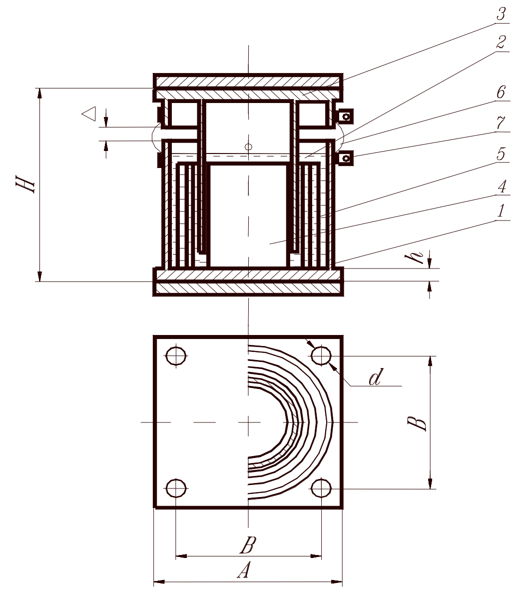

Figure 8. High Viscous Damper of VD type (1-housing, 2-viscous liquid, 3-piston, 4-core, 5-shells, 6-sealing)

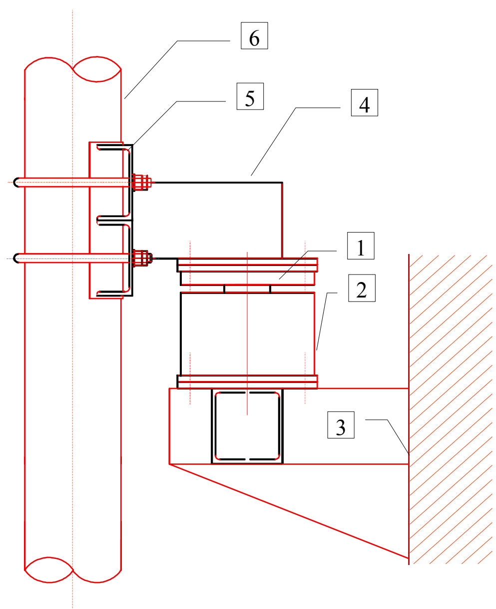

Figure 9. Example of HVD Installation to the NPP Feed Water Line (1-HVD Damper Unit, 2- Damper's Support Structure; 3-Wall, 4-Connecting Beam; 5-U-Bolts with Saddle Support; 6-Piping)

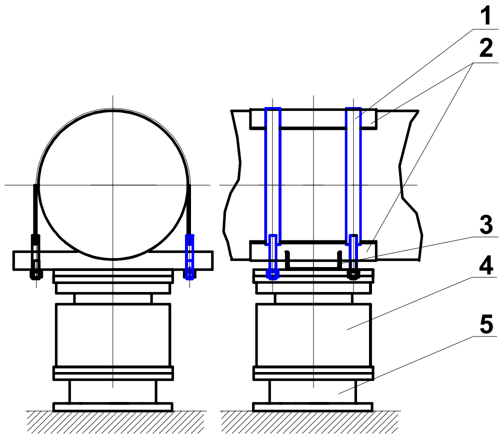

Figure 10. Example of HVD Installation on the Primary Circuit. (1-U-Bolts, 2-Saddles, 3-Damper Unit, 4-Damper's Support, 5-Floor)

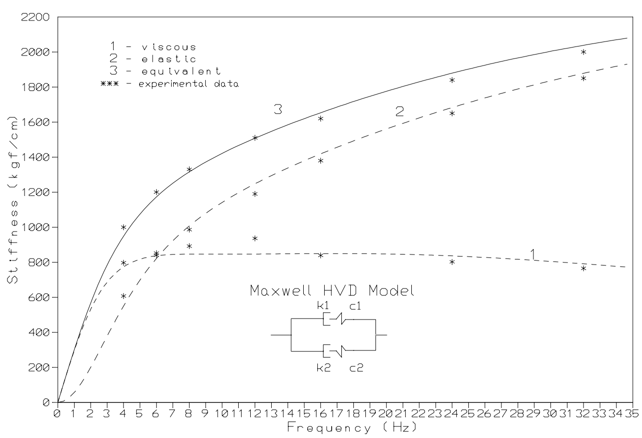

Figure 11. Experimental characteristics and analytical curves for mathematical model of HVD

EXPERIMENTAL CONFIRMATION OF HVD EFFICIENCY

The comparative analysis has shown that High Viscous Damper Technology (HVDT) has outstanding advantages practically for all scope of above pointed general requirements to damping devices. There are a lot of experimental data that confirm damping efficiency and cost benefits of HVDT due to several thousands cases of installation on NPP's and FPP's all over the world. To illustrate the positive features of HVD some actual examples of damper application are presented below.

The figures 1 and 10 show the HVD installation on PCLS of RBMK-type NPP for damping of operational vibration. In this actual case using of HVD essentially decreased level of vibration and extended piping service life essentially, figures 5, 12.

Using of HVD for dynamic protection of 630 mm hot (560°C) steam piping system (1200 MWt Unit of Kostroma FPP) reduced the maximal level of flow-induced operational vibration more than for 20 times, figure 13. In the considered case piping thermal displacements achieved in some points more than 200 mm due to high temperature and 120 meters length of the system. At the same time the HVD do not resist to thermal expansion of piping, since the value of damper's thermal reaction during cold start-up of the Unit was less than 100 N.

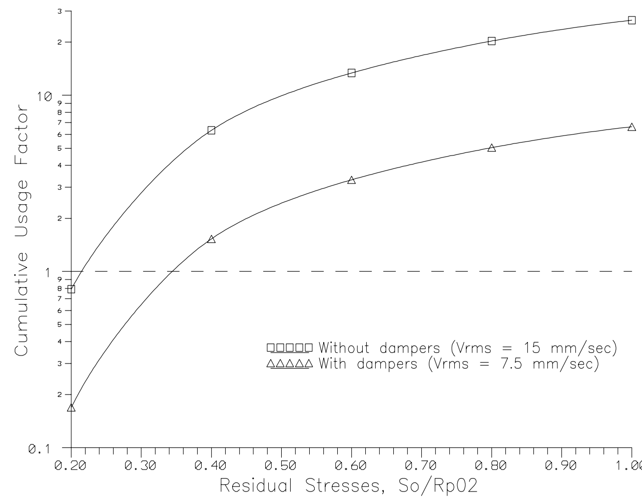

Figure 12. CUF of the welded joint zone (pipeline - collector nozzle). Influence of the damping support installation.

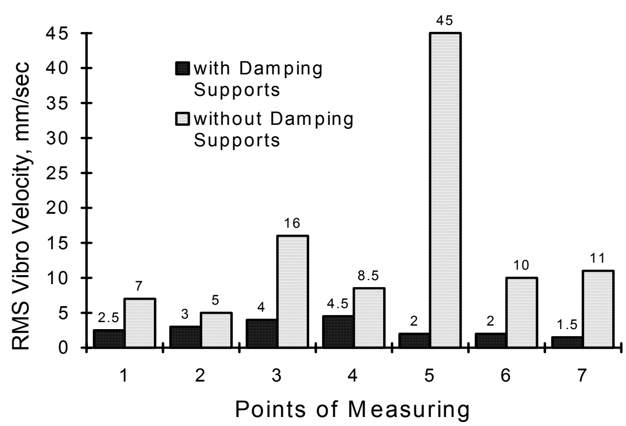

Figure 13. Influence of HVD installation of flow induced vibration of the steam piping system (∅ 630 mm), 1200 MWt Unit, Kostroma FPP.

The results of special vibration and seismic accurate testing of large-scale piping model (165 mm diameter, 15 meters length) on the 3D 35 tons Ishikawadzima Harima Industries Co. Shaking Table are illustrated by figures 14-16, [6]. The only one unit of HVD attached to the system excludes practically all resonance of piping due to multi-component features of the damper, figure 15.

The testing of the same piping system under seismic excitation demonstrates the radical reducing of resonant amplification for dynamic response which provides full seismic protection of piping too, figure 16.

The other application of HVDT can be shown on example of upgrading of seismic capacity of NPP Primary Loop. The full finite-element analytical model of VVER-440 piping systems located in Steam Generator and Main Cooling Pump Box is shown on figure 17.

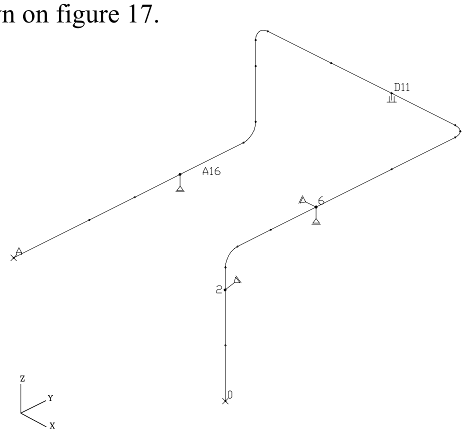

Figure 14. Piping Test Model (IHI Co. 35 tons Shaking Table)

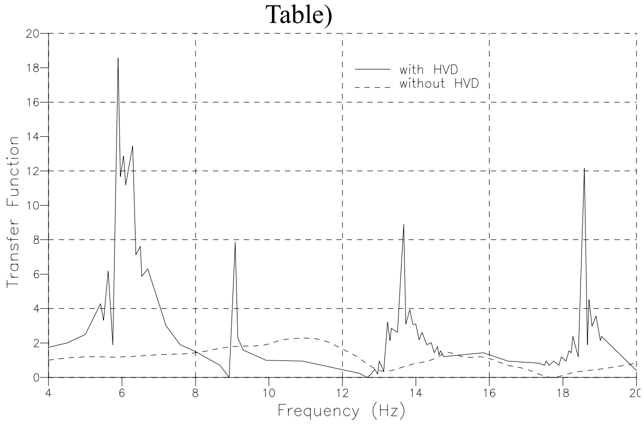

Figure 15. Transfer Function of Piping under Sinusoidal Sweep Excitation (IHI Co. 35 tons Shaking Table)

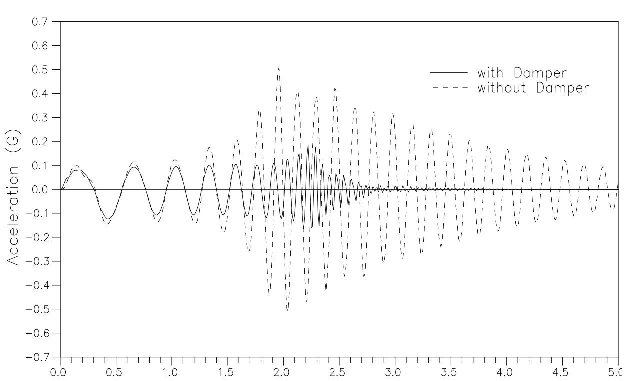

Figure 16. Response of Piping System under Seismic Wave Excitation with/without 1 HVD-159 (IHI Co. 35 tons Shaking Table).

It was founded from analyses that high flexibility of Primary Coolant Loop System (PCLS) (first natural frequency is 0.39 Hz) leads to intensive seismic response of structure, that obviously makes necessary seismic restraining of the system. Original design performed in 80's stipulated using of 9 units of hydraulic snubbers, figure 18. However, recently the new more intensive Reference Earthquake Level was prescribed for the plant. That is why the seismic reanalysis of the PCLS was necessary to carry out according to the modern international practice. The accurate comprehensive non-linear TH analysis of this system has been performed to obtain the realistic dynamic response of the PCLS and snubber's reactions. Dynamic characteristics of the snubbers based on their direct testing including specific velocity locking limits of the snubber's piston recommended by manufacturer [13] were involved in this analysis, figure 19. This kind of analysis shows that there are not problems in seismic capacity of PCLS itself. However the snubbers in this case was overloaded for several times, that makes necessary double increasing of their number. To solve this problem the possibility of HVD installation on the PLCS instead of snubbers was analyzed, figures 19, 20. Time History Analysis of PCLS with HVD shows that four units of VD-630/426-15 or six units of VES-300/40/80 is enough to provide sufficient seismic resistance of the Loop, instead of 13 units of hydraulic snubbers.

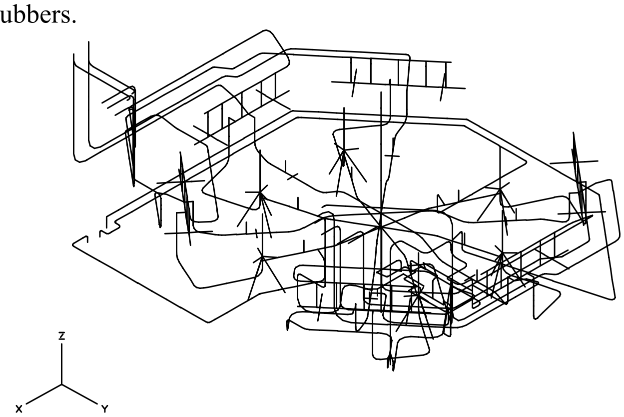

Figure 17 Complex Analytical Model of SG and MCP Box piping

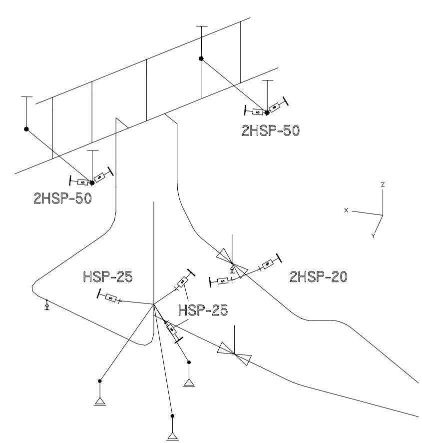

Figure 18. Snubber's Location for Loop No 1 of PCLS

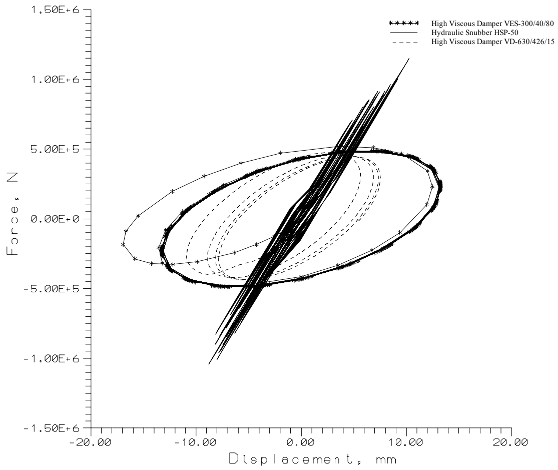

Figure 19. Dynamic characteristics of the ST Hydraulic Snubbers and High Viscous Dampers under sinusoidal 1 Hz excitation

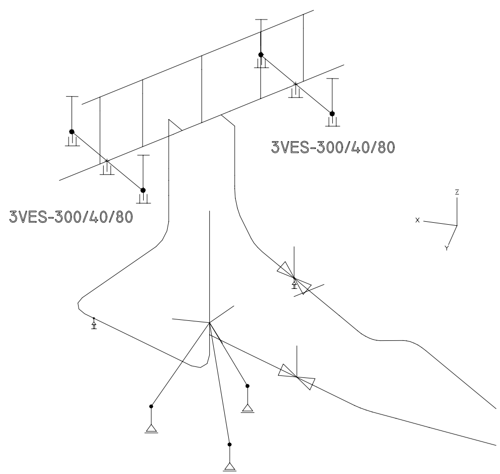

Figure 20 HVD location for Loop No 1 of PCLS

CONCLUSIONS

1. The analysis and testing of NPP piping subjected to operational vibration show that RMS level of vibration velocity less than 7.5 mm/s (Peak 15 mm/s) provides the safety of piping operation even for the cases of high energy and high loaded piping system. In the range of RMS 7.5-15 mm/s (Peak 15 - 30 mm/s) it is recommended to investigate the reasons and to evaluate potential dangerous of fatigue damage of piping due to vibration. In cases of piping vibration more than 15 mm/s RMS (Peak more than 30 mm/s) the special measures have to be implemented to improve piping and reduce vibration. This approach is proposed like initial standardization background for guide and code developing and for practical usage in piping operation on Nuclear and Fossil Power Plants, so as in Industry.
2. In case of seismic protection of piping and systems using of HVD technology brings essential benefits not only for reliability and safety of protected systems, but also in optimum number of devices and minimizing of primary and maintenance cost.
3. Actual study confirms the essential advantages of HVD technology in protecting of NPP and FPP piping systems from operational vibration, seismic and shock impacts so as from flaw growth. Thus application of HVD is recommended for upgrading of piping dynamic reliability and life extension purposes.

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