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Damage prevention design of the branch pipe under pressure pulsation transmitted from main steam header

Yeon-Whan Kim[1] and Young-Shin Lee[2,*]

[1]*Korea Electric Power Research Institute Munji-dong, Yuseong, Daejeon, 305-380, Korea*
[2]*Director of BK21 Mechatronics Group, Department of Mechanical Design Engineering, Chungnam National University*

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Abstract

Vibration has severely increased at the branch pipe of the main steam header since the beginning of commercial operation of nuclear power plants. Intense broadband disturbance flow at a discontinuous region such as elbows, valves or headers generates an acoustical pulsation which is propagated through the piping system. The pulsation becomes the source of low frequency vibration at the piping system. If it coincides with the natural frequency of the pipe system, excessive vibration results. High-level vibration due to the pressure pulsation related to high dynamic stress, and ultimately, to failure probability fatally affects the reliability and confidence of the plant piping system. This paper discusses steady-state high vibrations appearing in the branch piping system due to the effect of acoustical pulsations transmitted from the large main steam header by broadband turbulence in a 700 MW power plant. The excitation sources and response of the piping system are investigated by using on-site measurements and analytical approaches. Energy absorbing restraints with additional stiffness and damping factor were designed and installed to reduce vibration damage.

Keywords: Branch pipe; Low frequency; Steady-state vibration; Turbulence; Acoustic pressure pulsation; Dynamic stress; Resonance avoidance

1. Introduction

Although piping designers mainly study static pressure loads and thermal loads during the design phase of a power plant, in actuality piping vibration is forced, repetitive, and occurs over a relatively long period of time. The force causing the vibration can be generated by acoustic pressure pulsations or fluid flow in the piping system. Flow-induced vibration or acoustic pulsation mechanisms can introduce catastrophic failures in a piping system. The occurrence of acoustic pressure pulsations in a power plant is recognized to be one of the major safety issues.

The excitation sources of piping vibration are the turbulence and vortices generated by flow separation. Fluid flow in the piping system of a power plant generally generates broadband turbulence which can excite low frequency acoustic resonances [1, 2]. Complex piping systems in power plants are often endangered by the occurrence of acoustic resonances associated with dividing junctions [3, 4]. This paper presents a case history pertaining to steady-state high vibration appearing at dividing junction piping branching from the main steam balancing header in a 700 MW nuclear power plant. The branch piping system is designed to bypass the main steam from the balancing header during startup of the power plant. Despite the fact that there is no steam flow in this system during normal operation, the high vibration occurs.

[*]Corresponding author. Tel.: +82 42 821 6644, Fax.: +82 42 821 8894
E-mail address: leeys@cnu.ac.kr
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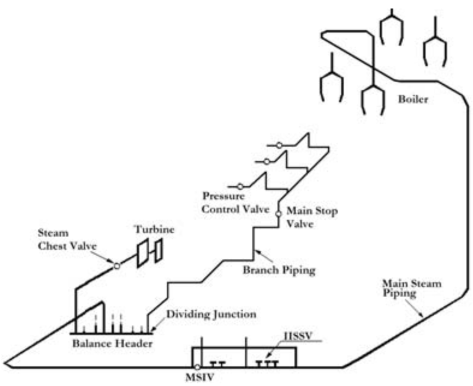
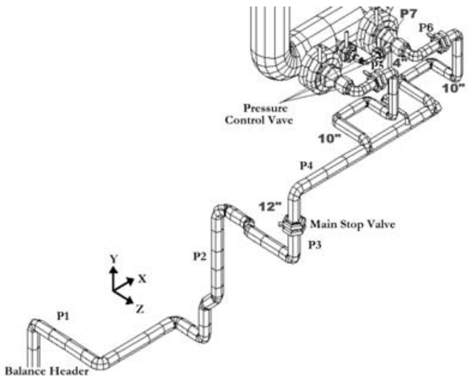
2. Description of main steam piping system and branch piping

The main steam piping system (660 mm in diameter, 19.5 mm wall thickness) shown in Fig. 1(a) supplies the main steam from the steam boiler to a high pressure turbine via balance header. The velocity of steam flow on a normal load is 35.2 m/sec and the sound velocity is 502.6 m/sec. This flow at elbow, valves, junction and balancing header assumes turbulence which has high energy density on low frequency range with vortices. The configuration of the main steam piping system is shown in Fig. 1(a). The piping system shown in Fig. 1(b) is an isometric drawing of a branch piping system of a balance header. The main steam header, 1,562 mm in diameter shown in Fig. 1(a) balances the vertical inflow of the main steam through four pieces of the main steam pipes from boiler to the middle position of the header.



(a) Main steam piping system



(b) Branch piping system

Fig. 1. Configuration of main steam piping system in a power plant.

Then it vertically forwards the main steam to the turbine from both ends of the header or to a condenser through the dividing branch piping system mounted at the right end of the header shown in Fig. 1(a). This branch system consists of three kinds of pipes: the 12" piping is the main pipe of the branch piping system dividing from the balance header and two pieces of 10" pipes and 4" pipe are divided from the 12" piping shown in Fig. 1(b) and Table 1. The material of the branch piping is low carbon steel.

3. Site measurement on steady-state vibration in branch piping without flow

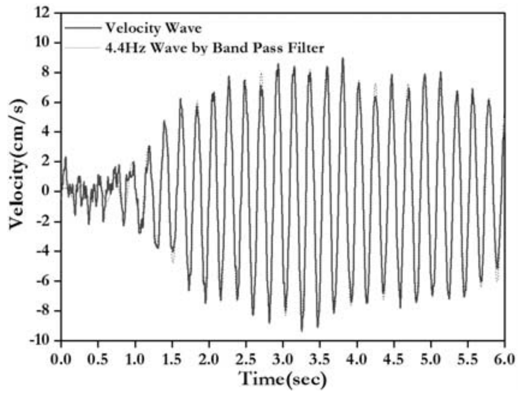
Table 2 shows the allowable vibration amplitudes calculated by code ASME OM-part3 [5] for each dividing pipe in the branch piping system. Vibration measurement was taken at points 1 to 6. Large violent vibrations were observed in both 4" dividing piping and the 12" pipe part equipping the main stop valve. The vibrations shown in Fig. 2 were 2.5 times higher than 3.5 cm/s zero-to-peak, which is the allowable amplitude of Table 3 for point 3 in 12" pipe and 4 times higher than 2.2cm/s zero-to-peak, which is the allowable amplitude of Table 3 for point 7 in the 4" dividing piping. Heavy valves are located at points 3 and 5 which were exhibiting the maximum vibratory velocity. The steady-state response in branch piping shown in Fig. 2 was dominated by 4.4 Hz. It is assumed that 4.4 Hz is excited by pressure pulsation transmitted from the balance header. A PCB 086C20 impulse hammer and B&K 4381 piezoelectric accelerometer were used for the field impact test, and PIPEPLUS code was used for analytical approaches for the branch piping system. Fig. 2(b) was obtained through analytical modal analysis and field impact tests. The 4.4 Hz's mode shown in Fig. 2(b) exhibits maximum deflection in 4" dividing piping and also large deflection in part to locate the main stop valve.

Table 1. Dividing junction sizes of branch piping system [unit : mm].

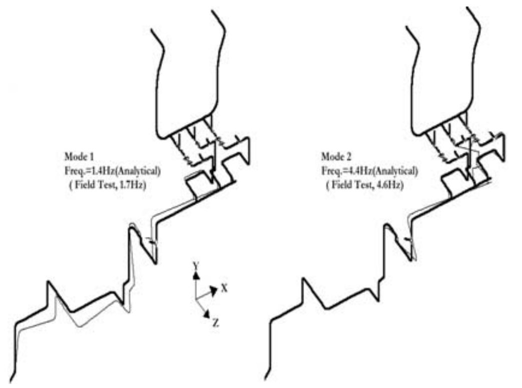
Item	12" pipe	10" pipe	4" pipe
Outside Diameter	323.85	273.05	114.30
Inside Diameter	298.45	254.51	102.26
Wall Thickness	12.70	9.27	6.02

Table 2. Allowable peak velocity in branch piping system.

Pipe Size	12"	10"	4"
Velocity (cm/s, peak)	3.5	2.0	2.2

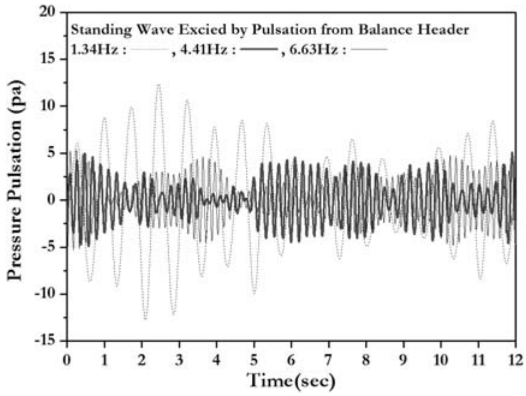


(a) Vibration of point 7 in 4" dividing pipe

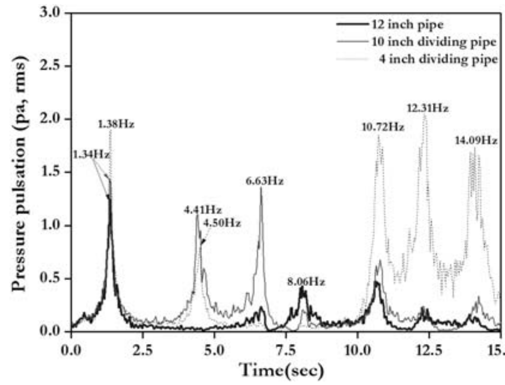


(b) Major mode shapes of natural response

Fig. 2. Violent vibration waves in branch piping and major mode shapes in branch piping.



(a) Excited pressure pulsation waves



(b) Spectrums of pressure pulsation

Fig. 3. Acoustic standing waves in branch piping.

4. Excitation of acoustic standing resonance in branch piping by pulsations transmitted

Main steam flow going through the balance header strengthens low frequency pressure pulsations of acoustic standing waves that are excited from the upstream main steam piping. In steady-state normal operation, the main stop valve located in 12" piping is in open condition and three pressure control valves located in 10" and 4" dividing pipes are closed, and the sound velocity is identical with that of the main steam balance header. The branch pipe is 75-85m long with open-close boundary and has quarter-wave resonance that the open end located at the pipe inlet from the balance header is a pressure antinode, and the close end is located at the pressure control valve of 4" pipe or 10" pipes dividing from 12" piping. Therefore, pressure pulsation waves were measured downstream. The main steam pipes are about 2 times long of the branch piping with open-open boundary condition and have half-wave resonance that open ends locate at the balance header and boilers, respectively. Therefore, the pulsation frequencies 1.5Hz, 4.6Hz, 10.7Hz resulting from Eq. (1) and Eq. (2) are nearly coincident with standing waves 1.4Hz, 4.4Hz, 10.2Hz of the branch piping. Then the balance header transmits low frequency pressure pulsations, playing the role of Strouhal turbulence wave to the branch piping system. The acoustic resonance frequencies f for this branch piping can be estimated from Eq. (1).

$$f = \frac{(2n-1)a}{4L} \tag{1}$$

The resonance frequencies of the branch piping are **1.4, 4.4,** 7.3**, 10.2,** ... Hz. The acoustic resonance frequencies f for the main steam piping located upstream of the balance header can be estimated from Eq. (2).

$$f = \frac{nC}{2L} \tag{2}$$

The Strouhal turbulence frequencies that are identical to those of the acoustic resonance frequencies of the main steam piping transmitted from the balance header to the branch piping are **1.5**, 3.0, **4.6**, 6.1, 7.6, 9.1,**10.7,** ... Hz. Where C is the speed of sound; n is the acoustic mode order and L is the total effective length.

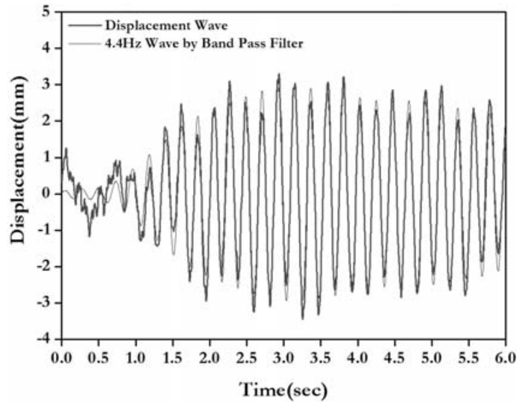
PCB 112A05 quartz pressure transducers were installed for measuring the pressure pulsation at the drain lines of the branch piping system. Fig. 3 shows acoustic standing resonances of branch piping excited by pressure pulsation transmitted from the balance header. It confirms that the pulsation frequencies are nearly coincident with standing waves of the branch piping in spite of the condition that is without steam flowing. Therefore, vibration sources of the branch piping are the low frequency pressure pulsations excited by half-wave resonance of the main steam pipes and transmitted from the balance header system. The pulsation frequencies also happen to coincide with standing waves by quarter-wave resonance in the branch piping. In spite of the fact that the branch piping can be shaken at 1.34 or 1.38, 4.41 or 4.50, 6.63, 8.06, 10.72 ...Hz shown in Fig. 3(b) to be the standing resonance frequencies amplified by low frequency pressure pulsations playing the role of Strouhal turbulence waves, the energy and thus pulsation amplitudes are small, on the order of 5-15 pa, zero-to-peak shown in Fig. 3.

5. Evaluation of mechanical integrity in branch piping

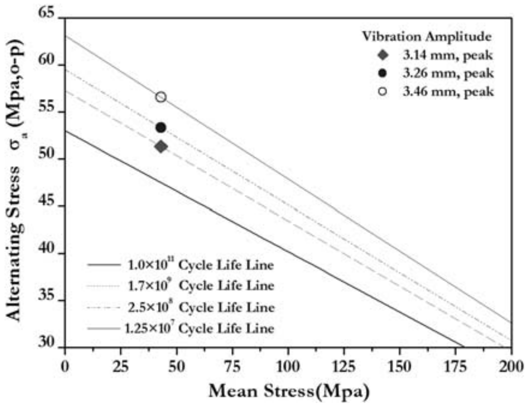
The vibration deflections were more than 7.7 mm peak-to-peak at point 3 in 12" piping and 6.3 mm peak-to-peak at point 5 in 4" piping shown in Fig. 4 (a). The maximum dynamic stress appeared in the elbow on the 4" dividing pipe of the branch piping system shown in Fig. 5. Maximum fatigue stress shown in Table 3 was calculated at 57.3Mpa on the elbow near the pressure control valve in the 4" dividing pipe of the branch piping system. The resulting life to failure is not more than 1.7×10^9 on the 4" dividing pipe shown in Fig. 4(b). It confirms that fa-

Table 3. Results of stress analysis for 4" dividing pipe of branch piping system.

Vibration (mm, peak)	Mean stress (Mpa)	Dynamic stress (Mpa, o-p)	Fatigue stress (Mpa)
3.178	43.02	53.36	59.55
2.460	43.02	56.60	63.17
4.913	43.02	80.34	89.66



(a) Displacement wave of piping



(b) Haigh diagram

Fig. 4. Dynamic stress by vibration and cycle life.

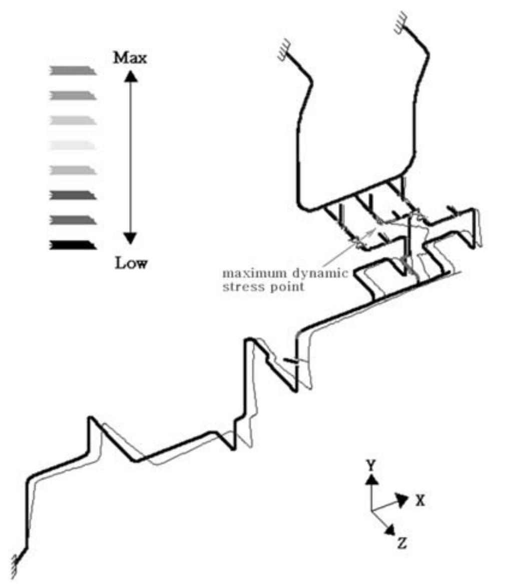


Fig. 5. Dynamic stress contour along the branch piping system.

tigue in the branch piping was cumulating.

6. Vibration reduction measures

Vibration reduction measures for mechanical integrity of the branch piping system focused on resonance avoidance method [6]. Fig. 6 shows the configuration of 'WEAR' type supports and struts added or changed for vibration reduction measures in the branch pipe. Fig. 6(a) shows a photograph of 'WEAR' restraints installed at the 4" pipe.

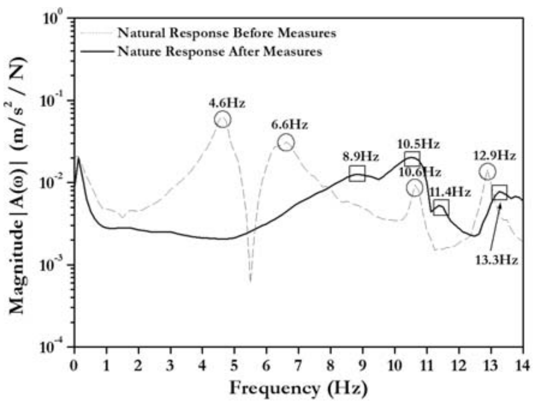
The installation positions of the restraints are where the vibration level is expected to be high. Subsequent to application of the measures, the 1st natural frequency in the 12" pipe changed to 12.4Hz, and the 1st natural frequency in the 4" pipe shifted to 8.9Hz by increasing system stiffness, shown in Fig. 6 (b). In order to verify the effectiveness of the restraints, vibrations are measured in the field. The velocity is reduced from 8.6 cm/s, zero-peak to 0.5 cm/s, zero-to-peak in 12" pipe and from 9.4 cm/s, zero-to-peak to 1.0 cm/s, zero-to-peak in 4" pipe. The displacement is reduced 1/42 times than 7.7 mm, peak-peak to 0.18 mm, peak-to-peak in 12" pipe and 1/48 times than 6.28 mm, peak-to-peak to 0.13 mm, peak-to-peak in 4" pipe as shown in Fig. 7.

Also, in order to confirm the validity of the restraint, stress analysis is carried out in case of sustained, expansion stress and checked to determine if it satisfies allowable stress or not. When we consider additional other effects of restraint, it is thought that the vibration reduction method is very effective. All in all, it is found that stresses with installing the restraint satisfy the allowable stresses. Therefore, we confirm the reliability of the piping system.

7. Conclusions

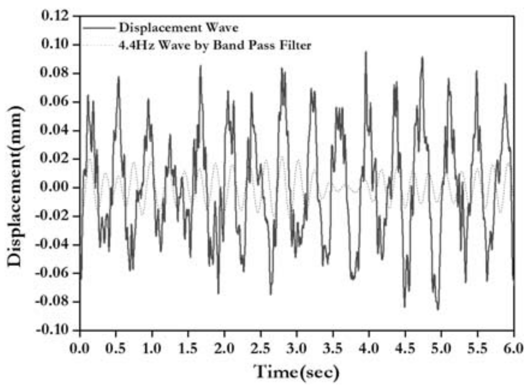
The following conclusions can be drawn from the case history pertaining to steady-state high vibration at the dividing junction piping branching from the

(a) Added 'WEAR' type supporters

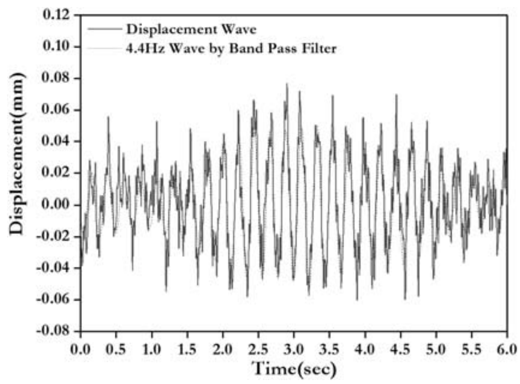


(b) Natural responses at point 7 in 4" pipe

Fig. 6. Vibration reduction measures for resonance avoidance at on-site.



(a) Vibration at point 3 of 12" pipe



(b) Vibration at point 7 of 4" pipe

Fig. 7. Vibration reduction through countermeasure.

main steam-balancing header in a 700MW power plant.

1) Steady-state high vibrations at low frequency range in the branch piping system were iterated generally and increased at normal operation condition without steam flow after commissioning operation.

2) The vibration sources of the branch piping are the low frequency pressure pulsations excited by half-wave resonance of main steam pipes and transmitted from the balance header system. The pulsation frequencies also happen to coincide with standing waves by quarter-wave resonance in branch piping.

3) Though the standing resonance in branch piping is excited by low frequency pressure pulsations, the energy and thus pulsation amplitudes are small. However, it confirms that when the pressure pulsations are transmitted to the piping, the vibrations are easily amplified at 4.4-4.5 Hz frequency, which nearly coincides with its natural mechanical frequency, 4.6 Hz or 4.7 Hz.

4) Therefore, passive reduction measures adding or changing 'WEAR' type supports and struts for separation of acoustical and mechanical resonances from each other and from excitation frequencies were selected. Then the high vibration was reduced more than 1/40 times by countermeasure. It means that although the pulsation amplitudes are small, when they coincide with a pipe system's natural mechanical frequencies, the mechanical resonant amplification of the steam piping system in power plant is more than 40 times.

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