VIBRATION ASSESSMENT METHOD AND ENGINEERING APPLICATIONS TO

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Small Bore Piping in Nuclear Power Plant
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Fatigue failure of small bore piping caused by vibration in Nuclear Power Plants is a universally concerned problem, and so the vibration assessment of small bore piping is becoming an important part of the daily work and aging management work of Nuclear Power Plants. Measurement method and corresponding assessment criterion for piping vibration levels are introduced based on ASME OM-3 and EDF experience respectively. Based on the effective velocity assessment method, the vibration measurement and assessment of 926 small bore pipes of GuangDong DaYa Bay Nuclear Power Plant were performed. The analysis of peak velocities and effective velocities indicates that effective velocity is a better parameter representing steady-state vibration levels for small bore piping. At the same time, the calculation for the allowable effective velocity of the pipes indicates that the screening value of 12mm/s (effective velocity) may be not conservative for some of the small bore pipes. Dynamic stress analysis and coresponding monitoring and inspecting program are performed to prevent vibrational fatigue or failure occurring.

KEY WORDS: Vibration assessment, Small bore piping, Allowable peak velocity method, Allowable effective velocity method.

1. INTRODUCTION

Steady-state and transient vibration of piping systems in Nuclear Power Plants(NPPs). can be deduced by pressure pulsation of pipe fluid and vibration of connecting machines, such as pump and reciprocating compressors. The fatigue failure problems introduced by piping vibration can result in occurrence of fatigue crack, leakage of pipe fluid, and even pipe fracture, all of which significantly influence the basic function of the piping system and safety function of NPPs. As a result, more and more attention is being paid to piping vibration fatigue failure in NPPs.

The statistics of EDF (France) indicates that pipe crack caused by vibration fatigue mainly occurred at nozzles with diameter below 2 in., such as some pipes used as instrument lines, drains and vents. Vibration fatigue of small bore piping mentioned above are classified as “sensitive piping” problem. The small bore pipes are called “sensitive pipes”. According to the American experience, small bore piping fatigue failure in primary loop mostly occurred at the socket weld joint[1]. Fatigue tests on socket-welded flanges were performed by Markl & George [2], which showed that for a properly fabricated socket weld, fatigue cracking is usually associated with the weld toe in the case of a joint stressed in the transverse direction. Re-audit of these experiment data shows that the test performed by Markl & George represent relatively high-level, low-cycle fatigue of weld joints, but do not represent the typical high-cycle vibratory fatigue conditions present in the field[3]. Site experiences shows that vibratory fatigue failures of socket welds have occurred predominately at weld roots. If the weld is incorrectly proportioned, either through bad design or through faulty fabrication, the stress across the weld throat may be sufficient to initiate a crack at the weld root. Usually, such a crack propagates through the weld metal and breaks the surface near the center of the weld face. The presence of a discontinuity such as a lack of penetration at the weld root degrades the fatigue strength greatly.

In DaYa Bay NPP, several small bore pipes in the nuclear auxiliary system have been found to crack at the weld joint of tube socket connected with large pipe, some of which resulted in the leak of content.

As mentioned above, vibratory fatigue failures of socket welds have occurred predominately at weld roots. So the vibration assessment of small bore piping has become more and more important in NPPs. Appropriate methods should be applied to monitor the vibration level (displacement, velocity, and acceleration) in the initial start-up and during the operating conditions. In this paper, criteria proposed by ASME OM-part3[4] and the effective velocity assessment method deduced by Sébastien Caillaud[5] are applied to assess the vibration level of small bore piping in some CI(Conventional Island) systems of DaYa Bay NPP. Potential sensitive pipes are screened by the effective velocity method. Solutions and some monitor methods are discussed to reduce vibration of these small bore pipes.

2． SIMPLLIFIED VIBRATION ASSESSMENT METHOD

2.1 Vibration Monitoring Groups and Corresponding Assessment methods

Three vibration monitoring groups and corresponding assessment criteria are introduced in ASME OM-part3. The visual method employed in the evaluation of VMG3 is most fundamental and provides the most simplified means for determining whether any significant vibrations exist in the system. Evaluation of vibration levels using this method is based upon experience and judgment, which provides an acceptable basis for assessment. With respect to the pipes in VMG2, vibration measurements are to be implemented to determine whether the vibration displacement/velocity exceeds the limited value. For pipes exceeding the maximum displacement/velocity limits defined in VMG2, VMG1 should be applied to determine the vibration stresses. The vibration stresses in the pipes are often obtained from the vibrational behavior by two acceptable techniques, Modal Response Technique and Stress Testing Technique.

Stress testing are the most directly method to determine the stress caused by vibration. However this method is difficult to apply to pipes operating at high temperatures because of safety problem and gauge characteristic limits. Therefore, simplified method is more convenient to monitor or assess the piping vibration. Displacement and velocity criteria are deduced in OM-3 as simplified assessment method4]. Accelerator transducers are used in site measurement. It needs only one integral step to get velocity data from accelerator signal, but to get displacement data it needs two integral steps which will bring large numerical errors. So velocity method was used to evaluate the vibration level of small bore pipes.

2.2 Measurement of vibration velocity

Pipes are divided into some characteristic spans, and the node points (zero deflection points) of them are generally found at restraint points, but could be located between constraints on long runs of piping. Since points of largest displacement will normally correspond to points of highest velocity, initial measurements are to be taken at points on the piping that appear to be undergoing the largest displacements. The locations of valves, elbows and supports are always key positions to apply vibration measurements. At each such point, measurements can be taken around the circumference of the pipe to find the magnitude of the maximum velocity. Measurements may be confined to directions perpendicular to the axis of the pipe at that point. In addition, the maximum velocity should be obtained only from the actual velocity-time signal. The readout of the signal should be of sufficient duration to ensure a high probability that the maximum velocity has in fact been obtained for that point in that direction.

2.3 Allowable Velocity Criteria

Allowable peak velocity criteria and allowable effective velocity criteria are developed by ASME-OM-part3 and Sébastien Caillaud respectively. The latter is based on the criteria of allowable peak velocity and the transform factor C_0 between peak and effective value are introduced to get the effective value.

2.3.1 ASME OM-3 allowable peak velocity method

The basic relationship between the allowable velocity and stress is developed from the assumption that the vibratory mode shape matches the mode shape at the first natural frequency, which can be written as

$$V_{\text{allow}}^{\text{peak}} = \frac{C_1 C_4}{C_3 C_5} \times \frac{3.64 \times 10^{-3}}{C_2 K_2} \times \frac{0.8 S_A}{\alpha} (in/s) \qquad (1)$$

Where

$V_{\text{allow}}^{\text{peak}}$ = the allowable peak velocity;

S_A = the alternating stress at 10^6 cycles for carbon steel and low alloy steel; or at 10^{11} cycles for non-corrosive steel from ASME S-N curve, psi;

C_1 = the correction factor to compensate for the effect of concentrated weights, such as valves, along the characteristic span of the pipe;

$C_2 K_2$ = the stress reinforcement factor as defined in ASME Code, and for most pipes, $C_2 K_2$ is not greater than 4;

C_3 = the correction factor accounting for pipe contents and insulation;

C_4 = the correction factor for end conditions different from fixed ends and for configurations different from straight spans, and it is greater than 0.7 for most pipes;

C_5 = the correction factor to account for off-resonance forced vibration;

α = the allowable stress reduction factor, 1.3 for carbon steel and low alloy steel and 1.0 for non-corrosive steel.

Conservative values were used for the correction factors to derive a screening peak velocity of $V_{\text{screen}}^{\max}$ =12.7mm/s (0.5in./s) applicable to most piping configurations in appendix D. Piping systems with measured vibration peak velocity ($V^{\max}$) lower than the screening value would require no further analysis, while for pipes with $V^{\max}$ higher than the screening value, the calculation of $V_{\text{allow}}^{\text{peak}}$ is needed. If $V^{\max} \le V_{\text{allow}}^{\text{peak}}$, the pipe vibration level is acceptable, otherwise, further dynamic stress analysis and comparison to the allowable stress must be implemented.

2.3.1 The allowable effective velocity method[5]

For most pipes in NPP, steady-state vibration is usually companied by transient events, which may result in a large peak velocity exceeding the allowable value defined in OM-3. But the peak velocity is not representative for long time duration to consider the vibration acceptability. Based on much engineering experience, the study of Sébastien Caillaud indicates that correction factor C_4 is lower than 0.7 for most situation, while C_1 is usually larger than the value calculated using the formula in OM-3. In addition, the computing formula of $V_{\text{allow}}^{\text{peak}}$ is developed from the assumption that the vibratory mode shape matches the mode shape at the first natural frequency. However, vibration responses of the nuclear piping are usually multi-modal in fact. Considering the reasons stated above, Sébastien Caillaud builds 3700 characteristic span models including 3D models using finite element method (FEM), and then calculates the values of C_1C_4 and the allowable effective velocities considering multi-modal vibration. Based on the above calculation results, an effective velocity assessment method was deduced. The modified formula for allowable effective velocity criteria is as follows:

$$V_{\text{allow}}^{\text{rms}} = \frac{C_1 C_4}{C_0 C_3} \times \frac{\lambda}{C_2 K_2} \times 0.8 S_A (mm/s) \tag{2}$$

where

$V_{\text{allow}}^{\text{rms}}$ = the allowable effective velocity in [mm/s];

C_0 = rms-to-peak transform factor , 3.5 for stationary pipe vibration;

λ =13.4mm/(s• MPa).

Conservative correction factors were used to calculate the allowable effective velocities for 3700 setups by Eq.(2). The calculation results indicates that approximately only 200 setups among the 3700 ones (5%) have allowable effective velocities lower than 12 mm/s, and allowable effective velocities of the other 3500 pipes are greater than it, which is defined as a common threshold for vibration monitoring of piping systems. Pipes with effective velocity (V^{rms}) less than 12 mm/s are considered to be safe from a vibratory stress standpoint and require no further analysis. If V^{rms} is greater than 12mm/s, the value of $V_{\mathrm{allow}}^{\mathrm{rms}}$ is required to be computed using Eq.(2). If $V^{rms} < V_{\mathrm{allow}}^{\mathrm{rms}}$, the vibration level is acceptable, otherwise, further vibratory stress calculation and assessments are required to determine the acceptability of piping vibration level.

2.4 Vibratory stress analysis and assessment method

For small bore pipes not satisfy the corresponding assessment criteria in VMG2,dynamic stress assessment should be performed in order to decide whether any modification or special monitoring program should be performed. In 3.2.1.2 of OM-3, the allowable stress is computed as follows.

$$S_{alt} \leq \frac{0.8S_A}{\alpha} \tag{3}$$

Where,

α =allowable stress reduction factor defined in ASME BPV Code, Section III.

S_A = the alternating stress defined in ASME BPV Code, Section III.

The maximum vibration stress σ_{max} should be compared to the allowable stress σ_{allow} derived from Eq.(3). If $\sigma_{\mathrm{max}} \geq \sigma_{\mathrm{allow}}$, this small bore pipe has been in the danger of vibration fatigue or even crack, and so corresponding vibration reduction steps or modification should be taken.

The vibration stresses of pipes are usually acquired from two methods. One is the stress measuring technique using strain gauges to measure the dynamic strain of the key points directly. The vibration stress is then calculated based on the stress-strain relationship. Another effective method is numerical simulation which calculates the maximum dynamic stress of pipe key points using appropriate numerical methods.

2.5 Flow chart for assessment of small bore piping

On the basis of the above discussion, the flow chart for vibratory assessment is concluded as shown in chart1.

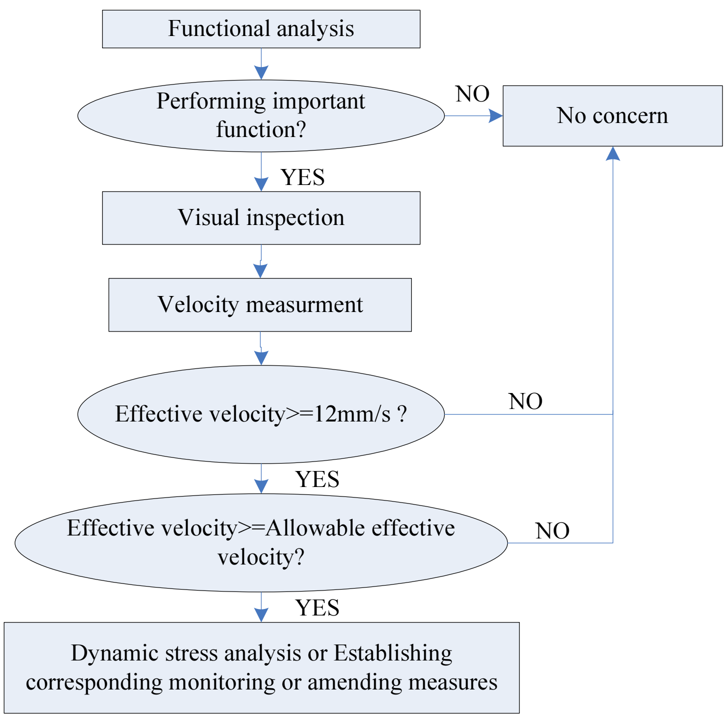

Chart 1 Flow chart of vibration assessment procedure

3. METHODS TO REDUCE PIPING VIBRATION

Fatigue caused by high-cycle vibration may lead to pipe cracks. Possible mitigations taken in practical situation to reduce piping vibration including (1) reducing or getting rid of the excitation source; (2) revising the pipe structure to demodulate the resonant pipe spans; (3) changing the operating program to decrease the operating conditions liable to incidents. When step 2 and 3 are difficult to implement, one effective method to eliminate the influence of the vibration is altering frequencies of the exciting force. Other effective means include adding rigid elements to pipelines, such as adding supports for heavy valves, setting stiffness elements at T joints between branches and large bore pipes, augmenting the fillet weld size to enhance the socket weld intensity and so on. Based on much engineering practice, several effective methods to reduce pipe vibration are as follows:

(1) Methods to improving the mechanical property of the main pipes: using reinforced sleeving For example, locally increasing the wall thickness (equal or equivalent to 40S), applying CRT tube socket, shortening extension length (shorten the branch length between tube socket and valve to approximately 100mm). This method is more applicable to cracked sensitive tubes.

(2) Improving the mechanical behavior of the small bore pipes by substituting light valves for massive ones, shortening pipe length between tube socket and valve, welding main pipe and tube socket using TIG method, altering the supports layout of small bore pipes, changing the structure and pipe run, redesigning the pipes, magnifying the pipe diameter and reducing bend numbers, etc.

(3) Canceling the sensitive pipes if they are ineffective via system functional analysis.

(4) Decoupling piping vibration. Installing connecting hose at downstream of the isolated valves, and the pipe behind the hose should be supported. This method is applicable for piping systems with operating temperature below $110^{\circ}C$, and operating pressure below 20 bar.

(5) Altering the vibration sources. Adopting cavitation protection control valves, multistage orifice plate,, and reducing pump vibration to decrease the vibration source.

4. CASE STUDY

Based on the requirement of ageing management, it is necessary to assess the vibration levels of 2100 small bore pipes in DAYA BAY Nuclear Power Plant. Following the vibration assessment procedure given in Chart.1, the vibration measurement and velocity assessment for 2100 small bore pipes are proceeding as displayed in table 1.

Table 1 Assessment procedure for 2100 small bore pipes

Project name	Pipe numbers
Total number of small bore pipes	2100
Concerned pipes-by functional analysis	926
Pipes needing vibration measurement	326
Pipes having peak velocity over 12.7 mm/s	67
Pipes having effective velocity over 12 mm/s	15
Pipes having effective velocity over allowable value	8

926 pipes are selected as concerned ones by functional analysis. Visual inspection of these pipes showed that 326 of the 926 ones vibrate significantly and need to be measured and assessed. The measurement results of these 326 pipes indicate that vibration responses of the nuclear piping systems are usually multi-modal and lower than 300Hz. Peak velocity analysis indicates that 67 pipes having peak velocities over the threshold of 12.7mm/s. However, among these 67 pipes only 15 ones have effective velocities over the threshold of 12mm/s, and for most pipes the average vibration level is much lower than the peak velocity, which indicates that the effective velocity is more representative than the peak velocity to assess the pipe vibration level. At the same time, much workload can be reduced by the effective velocity method.

The allowable effective velocities of these 15 pipes have been calculated which indicate that 8 pipes have effective velocities exceed the allowable values as shown in table 2.

Table 2 8 small bore pipes having effective velocities over allowable values

Number Of Piping	Functional role	V^{rms} (mm/s)	V_{allow}^{rms} (mm/s)
PIPE01	DRAIN TO LIQUID WASTE COLLECTION SYSTEM	50.37	4.96
PIPE02	DRAIN TO LIQUID WASTE COLLECTION SYSTEM	38.11	27.52
PIPE03	DRAIN TO LIQUID WASTE COLLECTION SYSTEM	55.46	25.01
PIPE04	DRAIN TO LIQUID WASTE COLLECTION SYSTEM	16.9	13.34
PIPE05	MAIN STEAM. TO FEED WATER PUMP TURBINE	23.71	9.23
PIPE06	DRAIN TO TURBINE BYPASS SYSTEM	18.74	13.74
PIPE07	DRAIN TO TURBINE BYPASS SYSTEM	14.85	12.61
PIPE08	SITE DISPLAY AND MAIN CONTROL RECORD	22.28	18.19

From table 2, we can find that the allowable effective velocities of PIPE01 and PIPE05 are lower than the screening velocity 12mm/s. It indicates that the effective velocity assessment method may be not conservative to evaluate the vibration level for several pipes. This result is consistent with the conclusion in reference [5].

In order to get accurate vibration fatigue assessment of the 8 small bore pipes, further vibration stress analysis is necessary. However, because of the non-conservative of the effective velocity method, attention should be paid to these pipes with significant vibration or feedback by the site-engineers. Based on the experience of American, France and Daya Bay mentioned above, we can know that vibration fatigue failure of the small bore piping systems has significant relationship with the weld quality. In addition, fatigue induced by thermal cycle is also an important reason for piping fracture. As a result, corresponding monitoring and inspecting methods are established for the 8 potential sensitive pipes except for the vibration assessment introduced above.

5. CONCLUSION

Based on vibration assessment procedure in ASME OM-3 and on-site vibration acceleration measurements, the vibration assessment to the small bore piping systems in Daya Bay nuclear power plant is achieved Comparison of the peak and effective velocities showed that for most pipes effective velocity can be more representative of the steady state vibration level than peak velocity. The effective velocity method is more appropriate for vibration monitoring and assessment of small bore pipes.

The calculation results of the allowable effective velocity also indicate that the allowable effective velocities of some pipes are lower than the screening value 12mm/s. So the allowable effective velocity method may be non-conservative for some pipes.

Calculation results of allowable effective velocities shows that 8 small bore pipes effective velocities are higher than the allowable values. Further dynamic stress analysis and corresponding monitoring and inspecting measures are proceeding for these small bore pipes vibrating intensely.

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