Fatigue Life Estimation of Piping System for Evaluation of Acoustically Induced Vibration (AIV)

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ABSTRACT

One of the key design parameters to a process plant with large capacity is the risk of AIV (Acoustically Induced Vibration) on the flare piping system. AIV is a piping vibration phenomenon exhibiting high frequencies caused by large acoustic power generated by the pressure drop across a PRV (Pressure Relief Valve). The evaluation method for susceptibility of piping to AIV fatigue failure was first proposed by Carucci and Mueller around 30 years ago. Since then, several developments were reported. However, there has not been publication with reference to fatigue life estimation in relation to the AIV phenomena. This paper proposes a procedure to calculate the fatigue life for the AIV based on actual operating condition, design fatigue life curve, etc. In this procedure vibration stress level can be obtained from the expected sound power level. The stress level was then used to estimate the fatigue life using design fatigue life curve and AIV experimental data. It is hoped that this procedure would allow for possible AIV failures to be classified corresponding to the actual plant operation. This kind of AIV evaluation would be useful to determine the priority of the countermeasure to mitigate piping failure caused by AIV in the existing plant.

Keywords: Acoustically Induced Vibration, Sound Power Level, Fatigue Life Evaluation, Pressure Relief Valve

1. INTRODUCTION

In process plants with large capacity, large sound power generated by PRVs (Pressure Relieving Valves) or blowdown valves with restriction devices sometimes result in severe piping vibrations with high frequencies at flare piping systems. This vibration phenomenon is called as AIV (Acoustically Induced Vibration) and first reported by Carucci and Mueller (1, 2). Carucci and Mueller showed that the AIV failure possibility is related to the sound power generated through a device with large pressure drop and pipe diameter based on actual failure data caused by AIV. Eisinger proposed an AIV fatigue diagram corresponding to the relations between sound power level and D/t (pipe diameter ratio to wall thickness) (3). Energy Institute published a guideline for piping vibration with an evaluation method for the AIV failure possibility based on the LOF (Likely Of Failure) concept related to type of branch connection, main pipe diameter ratio to branch pipe, etc. in addition to sound power level and pipe diameter ratio to wall thickness (4). In inter-noise 2012 several papers reported to improve the AIV evaluation method (5, 6, 7, 8), however, it seems that there is no paper which show the fatigue life estimation for the AIV.

This paper shows a new suggested evaluation approach for AIV taking fatigue life evaluation into account. Vibration stress level could be obtained by the excess amount of sound power level from the allowable one and fundamental vibration model for random vibration (8). Using this expected vibration stress and design fatigue curve the maximum allowable number of the vibration could be derived. Fatigue life estimation could be executed from this allowable number of the vibration and occurrence frequency of the vibration based on experimental data. Thus the expected fatigue life consumption could be estimated for one PRV or blowdown operation. Possibility of the piping failure caused by the AIV could be judged with this estimated fatigue life consumption and

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frequency of the PRV or blowdown operation.

2. PROCEDURE OF FATIGUE LIFE ESTIMATION

2.1 Overall Procedure

Figure 1 show the overall procedure to estimate fatigue life for AIV proposed in this paper. The fatigue life estimation procedure consists of the following steps;

Step1: Calculation of Sound Power Level (PWL) at Piping Evaluation Point
Step2: Evaluation of Allowable PWL
Step3: Stress Level Estimation Based on Excess of PWL from Allowable PWL
Step4: Evaluation of Allowable Number of Vibration Cycles from Design Fatigue Curve
Step5: Evaluation of Occurrence Number of Vibration Cycles per Second
Step6: Estimation of Fatigue Life Consumption for One PRV or Blowdown Operation

2.2 Calculation of Sound Power Level (PWL)

Carucci and Mueller proposed the following equation to calculate PWL for AIV (1, 2):

$$PWL = 10\log_{10}\left\{\left(\frac{p_1 - p_2}{p_1}\right)^{3.6} \cdot W^2 \cdot \left(\frac{T_1}{M_W}\right)^{1.2}\right\} + 126 \tag{1}$$

Here, PWL : Sound Powel Level (dB)
p_1 : Upstream Pressure of Restriction Device (Pa)
p_2 : Downstream Pressure of Restriction Device (Pa)
W : Mass Flow Rate through Restriction Device (kg/s)
T_1 : Upstream Temperature (K)
M_W : Molecular Weight of Reliving Gas (kg/kmol)

In the above equation, the process conditions such as the pressure, mass flow rate and temperature should be determined based on the reliving scenario with PRV or blowdown. Also the duration of relieving could be determined with this reliving scenario and the system condition such as gas amount in the system.

Equation (1) should be applied to calculate the sound power level at each source of the AIV. The sound power level attenuates due to the friction loss in accordance with the following equation (1, 2, 4):

$$Att_{PWL} = 0.06\frac{L}{D} \tag{2}$$

Here, Att_{PWL} : Attenuation of Sound Powel Level due to Piping Friction (dB)
L : Pipe Length (m)
D : Pipe Internal Diameter (m)

In the gas reliving system, the velocity in the pipe increases as pressure decreases through the discharge piping and sometimes velocity reaches to the sonic at the expanding point such as reducer or combining tee. If the velocity reaches to the sonic condition the sound power should increase corresponding to the rapid expansion of the gas just after the reducer or combining tee and this effect would be expressed by additional PWL of 6 dB (1, 2, 4).

If there would be more than one source of the AIV, the sound power level should be expressed by the following equation (3) as summation of the sound powers.

$$PWL = 10\log_{10}\left[10^{\frac{PWL1}{10}} + 10^{\frac{PWL2}{10}} + ... + 10^{\frac{PWLn}{10}}\right] \tag{3}$$

Here, $PWL1$: PWL for 1st source of AIV (dB)
$PWL2$: PWL for 2nd source of AIV (dB)
$PWLn$: PWL for nth source of AIV (dB)

2.3 Allowable Sound Power Level

In the EI guideline (4), the AIV failure possibility should be checked for each welded discontinuity, e.g. SBC (Small Bore Connection), welded tee, welded support based on LOF (Likelyhood Of Failure) scoring at the main line. LOF is the function of PWL, D/t (main diameter ratio to the wall thickness), D/d (main diameter ratio to the branch) and type of branch connection, and if LOF is larger than 1.0 a countermeasure is required to keep LOF less than or equal to 1.0. This means that the allowable sound power level could be defined so that the calculated LOF would be equal to 1.0.

2.4 Vibration Stress Estimation

Generally the vibration stress is proportional to the sound pressure in the pipe and the sound pressure has the relation with the sound power (8, 9). From these relations, the following equation which expresses the relations between the vibration stress and sound power can be derived;

$$\sigma^2 \propto p^2 \propto SP = 10^{\frac{PWL}{10}} \tag{4}$$

Here, σ : Vibration Stress (Pa)
p : Sound Pressure (Pa)
SP : Sound Power (W)

Equation (4) can be rewritten by equation (5) with constant C as follows:

$$\sigma = C 10^{\frac{PWL}{20}} \tag{5}$$

If the vibration stress would be fatigue limit, σ_a, PWL should be the allowable limit, PWL_a. Therefore, the constant C could be expressed as follows;

$$C = \sigma_a \Big/ 10^{\frac{PWL_a}{20}} \tag{6}$$

From equation (5) and (6), the vibration stress can be written as follows with the function of the fatigue limit and the excess of the PWL beyond the allowable limit;

$$\sigma = \left(\sigma_a \Big/ 10^{\frac{PWL_a}{20}} \right) 10^{\frac{PWL}{20}} = \sigma_a 10^{\frac{PLW - PWL_a}{20}} \tag{7}$$

2.5 Fatigue Life Estimation

The allowable number of the vibration stress can be defined as a function of the vibration stress using design fatigue curve. Figure 2 shows an example of the estimation of the allowable number of the vibration stress using the design fatigue curve.

Since the vibration characteristic caused by the AIV is so complicated that the actual occurrence frequency of the vibration is difficult to count accurately. The vibration has the characteristic of random vibration in which the vibration frequency and vibration magnitude change as time passes. Especially the vibration would have several vibration frequency components of high vibration modes with several petals in the circumferential direction. From these situations mentioned here the occurrence frequency of the vibration caused by the AIV should be determined based on some empirical data of the AIV. One of possible calculation of the occurrence frequency for the vibration caused by the AIV would be the following equation under the assumption in which the occurrence frequency of the vibration would be proportional to the fundamental natural frequency of the pipe for shell mode defined as follows;

$$N_o = \alpha \ f_n \tag{8}$$

Here, N_o : Occurrence Number of Vibration (1/s)

α : Empirical Constant (-)
f_n : Fundamental Natural Frequency of Pipe for Shell Mode (Hz)

In the above equation, the constant, α, should be determined by the empirical data. The vibration modes generated by the AIV might be related to not only the structural but also acoustic mode, and this means that the constant, α, might be affected by the combined effects of the structural and acoustic modes. Such kind of the vibration characteristic for the AIV is desired to be investigated to get more reliable relations related to the vibration frequency in detail. From equation (8) and the allowable number of the vibration stress obtained by the design fatigue curve the fatigue life consumption of one PRV or blowdown operation can be estimated.

2.6 Frequency of PRV or Blowdown Operation

The estimation method of the fatigue life consumption is described for one PRV or blowdown operation from 2.1 to 2.5. In addition to this estimation, it is quite important to investigate the frequency of the PRV or blowdown operation to determine the appropriate priority of the countermeasure to mitigate the possibility of the piping failure caused by the AIV. One of approach to determine the frequency of the PRV or blowdown operation would be the usage of the SIL (Safety Integrity Level) classification workshop (10).

3. EXAMPLE OF FATIGUE LIFE STUDY

Figure 3 shows a piping system in which the fatigue life assessment described here would be applied as an example. In this system there would be three PRVs simultaneously in operation. The governing case of the pressure relieving is discharge blockage of the compressor and the duration of one PRV operation is assumed to be 10 minutes corresponding to the gas amount in the system. The PRV relieving frequency would be once in 10 years. The PWL just after one PRV is 184.4 dB (point 1) and the PWL becomes 189.1 dB after the combining of three AIV sources in the sub header (point 2). The PWL reduces to 188.1 dB due to the distance attenuation at the combining point to the main header (point 3). The PWL at the small bore connection downstream the combining point is estimated to be 186.6 dB (point 4). Table 1 shows the results of the AIV fatigue assessment with no countermeasure. As shown in this table the fatigue life consumptions become larger than 1.0 at evaluation points 2 to 4 and this means that the fatigue life would be fully consumed by only one PRV operation. There would be two types of countermeasures. One is to apply full pad reinforcements and the other is to apply a reliable instrument system to reduce the frequency of the PRV operation. The effect of the full pad reinforcement pad would be assumed to increase the allowable PWL by 5 dB in this evaluation study. Table 2 shows the results of the AIV fatigue assessment with countermeasures. As shown in this table the fatigue failure possibility caused by the AIV can be largely reduced by the countermeasures.

4. CONCLIUSION

A fatigue life evaluation method for the AIV is proposed based on the actual operating condition, design fatigue life curve, etc. In this procedure the vibration stress level can be obtained from the excess of the sound power level calculated by Carucci and Mueller equation from the allowable level and the fatigue life could be estimated using the design fatigue curve and AIV experimental data. A calculation example is shown for this evaluation and the effect of countermeasure could be quantitatively evaluated with this procedure. This kind of AIV evaluation would be very useful to determine the priority of the countermeasure to mitigate the piping failure possibility caused by the AIV for the existing plant. Since this evaluation method requires the empirical data which shows the occurrence of the vibration, it is desired to develop this method more accurately to fit the actual experiences in the future.

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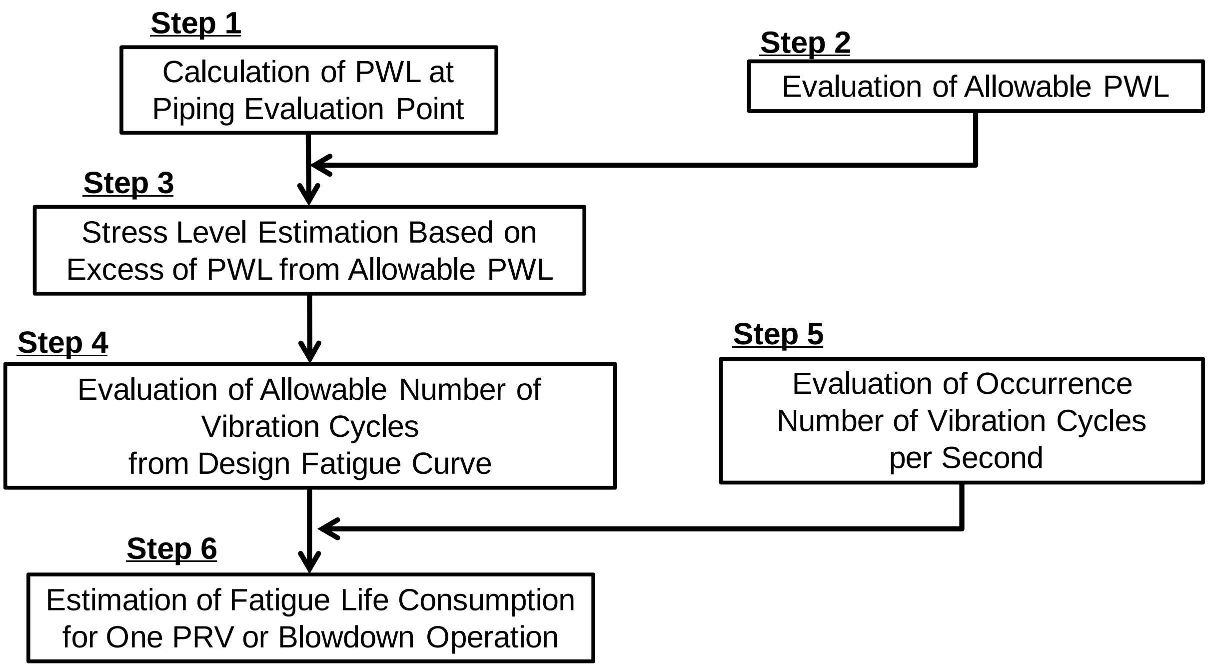

Figure 1 – Procedure of Fatigue Life Estimation of AIV

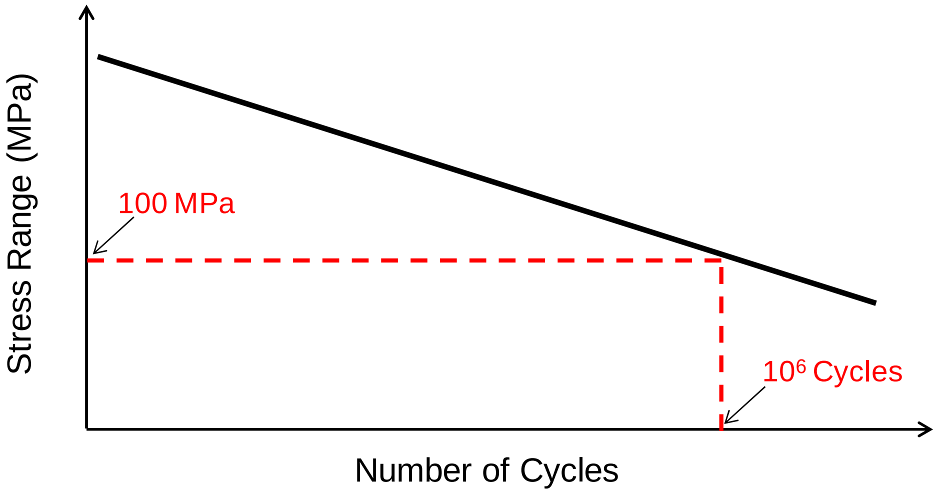

Figure 2 – Allowable Number of Vibration Stress

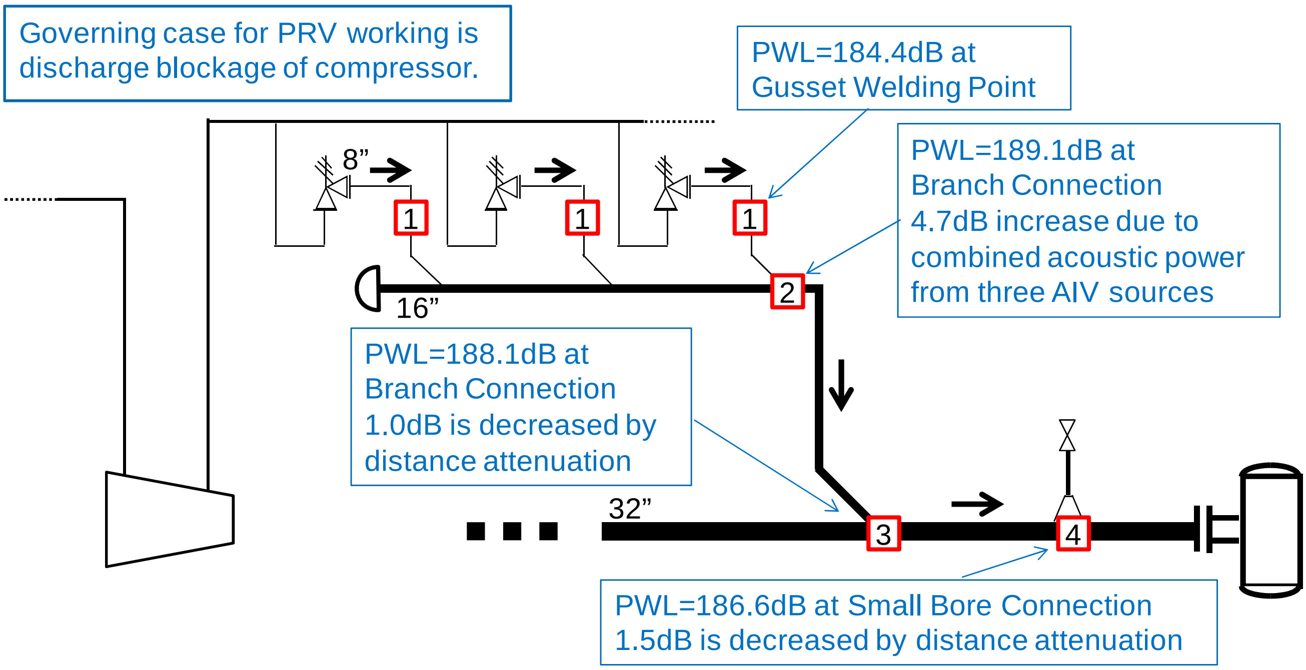

Figure 3 – Piping System Example for Fatigue Life Estimation of AIV

Table 1 – Results of AIV Fatigue Assessment with No Countermeasure

Evaluation Point	Pipe Size	D/t	PWL (calc.)	PWL (allow.)	Allow. Number of Vibration	Fatigue Life Consumption for One PRV Operation	Frequency of PRV Operation
1	8”	31.1	184.4 dB	179.4 dB	5.0×10^5	0.29	Once 10 years
2	16”	42.6	189.1 dB	176.0 dB	2.0×10^4	1.90	
3	32”	85.3	188.1 dB	168.6 dB	1.0×10^4	1.44	
4	32”	85.3	186.6 dB	168.6 dB	1.2×10^4	1.2	

Table 2 – Results of AIV Fatigue Assessment with Countermeasure

Evaluation Point	Pipe Size	D/t	PWL (calc.)	PWL* (allow.)	Allow. Number of Vibration	Fatigue Life Consumption for One PRV Operation	Frequency of PRV Operation
1	8”	31.1	184.4 dB	184.4 dB	6.0×10^6	0.015	Once 10000 Years**
2	16”	42.6	189.1 dB	181.0 dB	1.7×10^5	0.41	
3	32”	85.3	188.1 dB	173.6 dB	2.0×10^4	0.72	
4	32”	85.3	186.6 dB	173.6 dB	3.0×10^4	0.48	

* : Full reinforcement pad is assumed to have the increase effect of allowable PWL by 5 dB.

** : Applying pressure HH trip system with 2 out of 3 to reduce the frequency of PRV operation.