ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25oct1557

Best Practice to Analyze Vibration in Piping Systems: Case Study

Khalid H. Alwayli[1]; Prasanta Dey[2]

[1,2]Aramco Aramcoasia

Publication Date: 2025/11/12

Abstract: Excessive sound power, which may be caused by the flow of gas through a high pressure drop device such as a valve or orifice plate, can excite pipe shell modes. Valves and orifice plates are not the only elements that can cause excessive sound, but they are the most prominent high pressure drop devices that need to be addressed. This mechanism of excitation can lead to failures and is called Acoustic Induced Vibration (AIV) and flow Induced Vibration (FIV) The configuration of the discharge piping and velocity of the discharge gas in the piping have a direct effect on whether acoustic vibrations may cause fatigue failure of the discharge piping. This study explains the calculations and criteria to be used in calculating and evaluating potential for Acoustically Induced Vibrations (AIV) and flow Induced Vibration (FIV) in piping systems. This paper also covers the screening and detail methods for determining if a piping system is at risk from AIV and FIV. This procedure requires.

- **Mitigate the risk from AIV and FIV**
- **Bring to the attention of all systems that were determined to be at risk from AIV and FIV**
- **Identify the methods employed to mitigate the risk of AIV and FIV**

How to Cite: Khalid H. Alwayli; Prasanta Dey (2025). Best Practice to Analyze Vibration in Piping Systems: Case Study. *International Journal of Innovative Science and Research Technology*,10 (10), 3069-3078. https://doi.org/10.38124/ijisrt/25oct1557

I. INTRODUCTION

➢ *Background*

- Overview of piping systems in industrial applications.
- Importance of vibration analysis in ensuring structural integrity and operational efficiency.

➢ *Objectives*

- To analyze the mechanisms of FIV and AIV.
- To explore the impact of these vibrations on piping systems.
- To present mitigation strategies and best practices.

II. FLOW-INDUCED VIBRATION (FIV)

➢ *Definition and Mechanisms*

Flow-induced vibration (FIV) in piping systems is a phenomenon that occurs when fluid flow generates forces that can cause the pipes to vibrate. This vibration can lead to various issues, including fatigue, wear, and even failure of the piping system if not properly managed. Here's a detailed description of the key aspects of flow-induced vibration in piping:

➢ *Causes of Flow-Induced Vibration:*

- *Fluid Flow:*
  The movement of fluid through pipes creates dynamic forces due to changes in velocity and pressure.

- *Turbulence:*
  High-velocity flows can create turbulent conditions, leading to fluctuating pressure forces on the pipe walls.

- *Vortex Shedding:*
  As fluid flows past obstacles (like bends, valves, or fittings), vortices can form and shed, creating alternating forces that can induce vibrations.

- *Acoustic Waves:*
  Changes in flow conditions can generate sound waves that may be coupled with the structural modes of the piping, leading to vibrations.

➢ *Types of Vibration:*

- *Steady-State Vibration:*
  Continuous vibrations that occur under constant flow conditions.

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25oct1557

- *Transient Vibration:*
  Occurs during changes in flow conditions, such as startup, shutdown, or changes in flow rate.

- *Resonance:*
  When the frequency of the induced vibrations matches the natural frequency of the piping system, leading to amplified vibrations.

➢ *Factors Influencing FIV:*

- *Fluid Properties:*
  Density, viscosity, and flow rate of the fluid can significantly affect the vibration characteristics.

- *Pipe Geometry:*
  The size, shape, and configuration of the piping system (e.g., bends, supports, and fittings) influence how vibrations propagate.

- *Support Conditions:*
  The way pipes are supported (fixed, free, or guided) can alter their natural frequencies and response to induced vibrations.

- *Flow Regime:*
  Laminar vs. turbulent flow conditions can lead to different vibration behaviors.

➢ *Determination of FIV Risk*

The likelihood of failure (LOF) is a form of scoring to be used for screening purposes. The likelihood of failure is not an absolute probability of failure nor an absolute measure of failure. LOF equal to one (1.0) where corrective actions are required.

- *1st Step: Fluid Viscosity Factor (FVF)*
  The amount of turbulent energy partially depends upon the fluid viscosity. This is taken into account by the FVF. The FVF is equal to one (1.0) for liquid and multi-phase fluids. The FVF of gas system is calculated as below.

$$\mathrm{FVF} = \frac{\sqrt{\mu}}{\sqrt{1 \times 10^{-3}}}$$

- *2nd Step: Support Arrangement*
  The support arrangement is determined according to below table: -

Table 1 Support Arrangement's Criteria

Support Arrangement	Span Length Criteria	Typical Fundamental Natural Frequency
Stiff	$L_{span} \leq -1.2346 \times 10^{-5} {D_{ext}}^2 + 0.02 D_{ext} + 2.0563$	14 to 16 Hz
Medium Stiff	$L_{span} > -1.2346 \times 10^{-5} {D_{ext}}^2 + 0.02 D_{ext} + 2.0563$ $L_{span} \leq -1.1886 \times 10^{-5} {D_{ext}}^2 + 0.025262 D_{ext} + 3.3601$	7 Hz
Medium	$L_{span} > -1.1886 \times 10^{-5} {D_{ext}}^2 + 0.025262 D_{ext} + 3.3601$ $L_{span} \leq -1.5968 \times 10^{-5} {D_{ext}}^2 + 0.033583 D_{ext} + 4.429$	4 Hz
Flexible	$L_{span} > -1.5968 \times 10^{-5} {D_{ext}}^2 + 0.033583 D_{ext} + 4.429$	1 Hz

- *3rd Step: Flow Induced Vibration Factor (Fv)*
  The flow induced vibration factor (Fv) is determined according to below table: -

Table 2 Determination of Flow Induced Vibration Factor (Fv)

Support Arrange-ment	Range of Outside Diameter	Fv	α	β
Stiff	60 mm to 762 mm	$\alpha \left(\frac{D_{ext}}{T}\right)^{\beta}$	$446187 + 646 D_{ext} + 9.17 \times 10^{-4} {D_{ext}}^3$	$0.1 \ln(D_{ext}) - 1.3739$
Medium Stiff			$283921 + 370 D_{ext}$	$0.1106 \ln(D_{ext}) - 1.501$
Medium	273 mm to 762 mm	$\alpha \left(\frac{D_{ext}}{T}\right)^{\beta}$	$150412 + 209 D_{ext}$	$0.0815 \ln(D_{ext}) - 1.3269$
	60 mm to 219 mm	$\exp\left[\alpha \left(\frac{D_{ext}}{T}\right)^{\beta}\right]$	$13.1 - 4.75 \times 10^{-3} D_{ext}$ $+1.41 \times 10^{-5} {D_{ext}}^2$	$-0.132 + 2.28 \times 10^{-4} D_{ext}$ $-3.72 \times 10^{-7} {D_{ext}}^2$
Flexible	273 mm to 762 mm	$\alpha \left(\frac{D_{ext}}{T}\right)^{\beta}$	$41.21 D_{ext} + 49397$	$0.0815 \ln(D_{ext}) - 1.3842$
	60 mm to 219 mm	$\exp\left[\alpha \left(\frac{D_{ext}}{T}\right)^{\beta}\right]$	$1.32 \times 10^{-5} {D_{ext}}^2$ $-4.42 \times 10^{-3} D_{ext} + 12.22$	$2.84 \times 10^{-4} D_{ext}$ $-4.62 \times 10^{-7} {D_{ext}}^2 - 0.164$

In case of piping diameter over the 762 mm, Flow induced factor (Fv) is determined according to below table: -

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25oct1557

Table 3 Determination of Flow Induced Vibration Factor (Fv) (When Pipe Diameter >762mm)

Support Arrange-ment	**Range of Outside Diameter**	**Fv**	**α**	**β**
Stiff	Over 762 mm	$\alpha\left(\frac{D_{ext}}{T}\right)^{\beta}$	$419373.9 + 859.398D_{ext} + 0.4803D_{ext}^2 - 1.624 \times 10^{-4}D_{ext}^3$	$0.1001\ln(D_{ext}) - 1.3577$
Medium Stiff			$246340 + 502.1626D_{ext} - 0.1218D_{ext}^2 + 3.3195 \times 10^{-5}D_{ext}^3$	$0.0916\ln(D_{ext}) - 1.2502 \times 10^{-5}D_{ext} - 1.3797$
Medium			$195015 + 179.1321D_{ext}$	$0.1533\ln(D_{ext}) - 7.0013 \times 10^{-5}D_{ext} - 1.7675$
Flexible			$42.2095D_{ext} + 52778$	$0.0180\ln(D_{ext}) - 0.2233$

- *4th Step: Calculation of LOF*

The likelihood of failure (LOF) is calculated by the following equation.

$$\text{Flow Induced Turbulence LOF} = \frac{\rho v^2}{F_v} FVF$$

Once the main likelihood of failure (LOF) is determined, the corrective actions are required for LOF = 1.0.

- *Recommended Corrective Action*

The initial recommendation is to select between span length modifications and changes in process conditions.

For the majority of the lines failing, corrective actions shall be implemented by restricting the maximum span length of the line. The span length is measured between two effective supports, considering a horizontal straight pipe run.

When line stiffness changes are not possible, it is necessary to take action to reduce the energy in the line (ρv^2) below acceptable levels.

For small bore branches two inches and below, it is recommended to brace them back to the header by bracing them in two planes in case LOF is over than 0.5.

➢ *Consequences of FIV:*

- *Fatigue Damage:*

Repeated vibrations can lead to material fatigue, resulting in cracks or failures.

- *Wear and Tear:*

Continuous vibration can cause wear on pipe supports, hangers, and other components.

- *Operational Issues:*

Excessive vibrations can lead to noise, reduced efficiency, and operational disruptions.

➢ *Mitigation Strategies:*

- *Design Considerations:*

Proper design of piping systems, including the use of bends, expansion joints, and supports, can help minimize FIV.

- *Damping Solutions:*

Incorporating dampers or vibration isolators can reduce the amplitude of vibrations.

- *Flow Control:*

Adjusting flow rates or using flow straighteners can help reduce turbulence and associated vibrations.

- *Monitoring:*

Implementing vibration monitoring systems can help detect and address FIV issues before they lead to significant problems.

➢ *Analysis Techniques:*

- *Computational Fluid Dynamics (CFD):*

Used to simulate fluid flow and predict FIV behavior.

- *Finite Element Analysis (FEA):*

Helps in understanding the structural response of piping systems to induced vibrations.

- *Experimental Testing:*

Physical testing of piping systems under controlled flow conditions can provide insights into FIV characteristics.

➢ *Case Study:*

Based on an understanding of the vibration mechanisms that occur in piping, Appropriate general design guidelines can be developed and implemented during the design phase. A typical approach may become overly conservative in attempting to account for all possible scenarios. However, the developed general design guidelines could potentially eliminate the need for a FIV assessment.

When conducting a piping design for FIV assessment, the most common action to mitigate the risk of flow-induced fatigue failure is to design the piping support spacing of main piping system to be more rigid(stiff).

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25oct1557

The table and figure below show typical case where the vibration risk in piping system has been assessed. As explain above, during the design phase, the piping system's vibration risk can be reduced by adjusting pipe support spacing. This process determines the minimum pipe span and incorporates it into the actual design to prevent vibration risk.

➢ *The Below Table & Figure for Case Study for FIV Assessment*

Table 4 Case Study for FIV Assessment

Line No.	10"-AP-61133-3SD0P02			Rev.	0
INPUT	SYMBOL	UNIT	VALUE	REMARK	
External Pipe Diameter	D_{ext}	mm	273		
Structural Natural Frequency	F_n	Hz	NA	Ref. Frequency	14 Hz to 16 Hz
Max. Span length Between supports on line of interest	L_{span}	m	6.0		
Wall thickness of main pipe	T	mm	9.27		
Fluid Velocity	v	m/s	2.65	For Multi-Phase, Effective Volocity is needed.	
Gas dynamic viscosity	μ_{gas}	Pa s	NA	for gas systems only	
Fluid Density	ρ	kg/m3	942	For Multi-Phase, Effective Density is needed.	
Fluid phase	-	-	S	S: SINGLE M : MULTI	
Fluid	-	-	L	L : LIQUID G : GAS	

For LOF Assessment			
* Fluid Kinetic Energy : ρ v2 (kg/(ms2) =	6615.2	* Fluid Viscosity Factor (FVF) =	1.0000
* Note - For single Phase : ρ v2 = (actual density) x (actual velocity)2 - For multi Phase : ρ v2 = (effective density) x (effective velocity)2		* Note - For GAS syste, FVF cal. Is valid. - For Liguid and multi-phase fluids, FVF = 1.	

* Support Arrangement				
Support Arrangement	Typical basic Fn (Hz)	Span length Criteria		
		Cal.1	Cal.2	Cal.3
STIFF	14 Hz to 16 Hz	6.60	9.37	12.41
* Note IF flexible system with LOF ≥ 1 and Fn is between 1~3 Hz, this LOF shall be assessed using "Advanced Screening Method Option"				

* Flow Induced Vibration Factor (Fv)				
Support Arrangement	Range of OD	α	β	Fv
STIFF	60mm to 762mm	641202.6644	-0.81	40992.1
* For Advanced Screening FIT LOF				
Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable

Flow Induced Turbulence (FIT) Likelihood of Failure (LOF) of Main Line	
FIT LOF	0.1

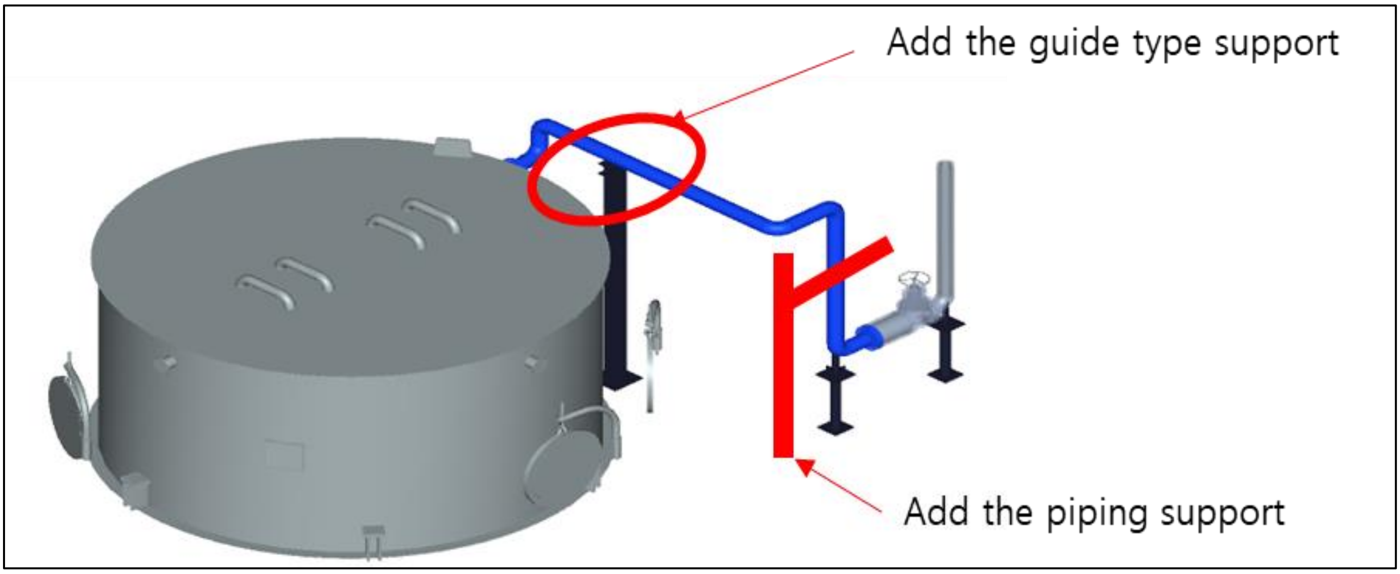


Fig 1 Case Study for FIV Assessment

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25oct1557

III. ACOUSTIC INDUCED VIBRATION (AIV)

➢ *Definition and Mechanisms*

AIV (Acoustic Induced Vibration) is a critical consideration in piping design, particularly in industries such as oil and gas, chemical processing, and power generation. AIV occurs when sound waves, typically generated by turbulent fluid flow or mechanical equipment, induce vibrations in piping systems. These vibrations can lead to fatigue failure, leaks, and ultimately, system failure if not properly managed. Here's a detailed analysis of AIV in piping design.

➢ *Causes of Acoustic Induced Vibration:*

AIV is primarily caused by high-velocity fluid flow, especially in systems with turbulent flow regimes. It can also be exacerbated by the presence of bends, valves, and other fittings that disrupt flow.

Frequency of AIV: The frequency of the induced vibrations is often related to the flow velocity and the geometry of the piping system. It can resonate with the natural frequencies of the piping, leading to amplified vibrations.

Pressure let-down systems discharging to the closed systems meeting any one of the following criteria warrant AIV evaluation; (Systems discharging directly to the atmosphere through a short piping length of tailpipe, without vent silencer, need not be considered.)

- Systems with gas or steam flow. (Systems liquid flow need not be considered.)
- Pressure let-downs (including PSV, blowdown/ de pressuring valve, control valve, RO and branch connection with critical pressure drop).
- Control valves with the Vendor's predicted noise value more than 115dBA @ 1m, under any operating condition. (Generally, the noise level of the selected control valve is less than 115 dBA @ 1m as per noise control philosophy. In that case, AIV study for control valve is not required.)

➢ *Pipe Internal Sound Power Level*

The internal pipe sound power levels will be calculated using the following equation:

$$Lw = 10\ log\left[\left(\frac{\Delta P}{P_1}\right)^{3.6} W^2\left(\frac{T_1}{m}\right)^{1.2}\right] + 126.1 + K$$

Where

Lw = Internal pipe sound power level (dB)

W = Flow rate of the gas (kg/s)

ΔP = P1-P2, Pressure drop (bar)

P1 = Upstream pressure (bar abs)

P2 = Downstream pressure (bar abs)

T1 = Temperature of upstream gas (K)

m = Molecular weight of flowing gas

K = if sonic conditions exist then K=6; otherwise K=0

P1, P2, T1, and m will be based on operating conditions.

If more than one parallel and/or series source generates noise (e.g. multiple relief devices venting simultaneously), the sound power levels shall be added at the pipe junctions where the piping from the sources meets as shown as follows:

$$\sum L = 10 log\ [10^{lw1/10} + 10^{lw2/10} + \cdots + 10^{lwn/10}]$$

➢ *Attenuation of Sound Traveling Along with a Pipe System*

The attenuation of the internal sound power levels will be taken into account and predicted by established acoustic rules.

The following attenuations shall be considered.

- *Attenuation Along a Pipe*

Attenuation along a pipe shall be taken as 3dB per 50 diameters (50D) of length.

$$Attenuation = \frac{3\ x\ L}{50\ x\ D} = 0.06\ x \frac{L}{D}$$

L = Pipe length (m)

D = Pipe diameter (m)

- *Table & Figure for Attenuation at Branch Connections*

Attenuation at a branch connection shall be taken as indicated below:

Table 5 Attenuation at Branch Connections

Angle between branch and upstream header (deg)	Attenuation in upstream header (dB)	Attenuation in downstream header (dB)
45	6.9	1.0
60	5.8	1.3
90	4.3	2.0

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25oct1557

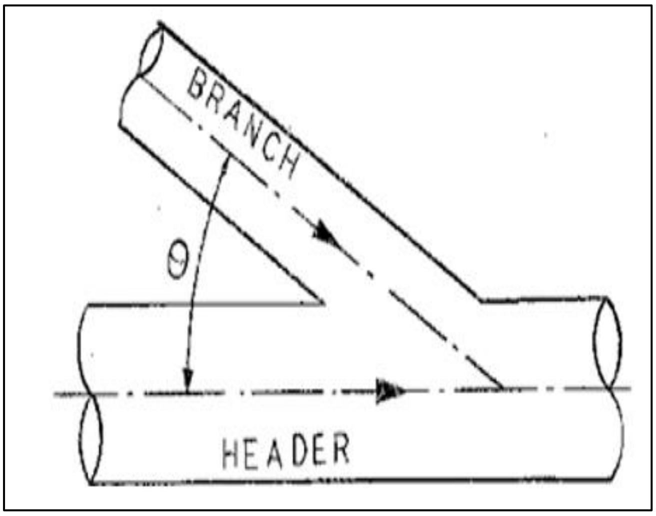


Fig 2 Attenuation at Branch Connections

- *Attenuation Due to Diameter Changes*

Attenuation due to expansion in pipe diameter shall be calculated by the equation below.

Attenuation = 2 X (D2/D1) – 2

Where

D1 = Upstream (small side) pipe diameter

D2 = Downstream (large side) pipe diameter

➢ *Limits for Sound Power Levels*

The calculated sound power level from sections 3.3 and 3.4 above shall be compared with the design limit shown in the Figure-1 below, based on the pipe diameter where the Lw has been calculated. Pipe systems in which the calculated Lw exceeds the design limit in Figure -1 are at risk of AIV. The design limit for larger than 200 of D/t shall be 155 dB.

The risk shall be evaluated along the downstream pipe until the sound power level to be below 155 dB considered with some attenuation or reached to KO drum. The sound power level shall be used total sound power level where multiple devices blow.

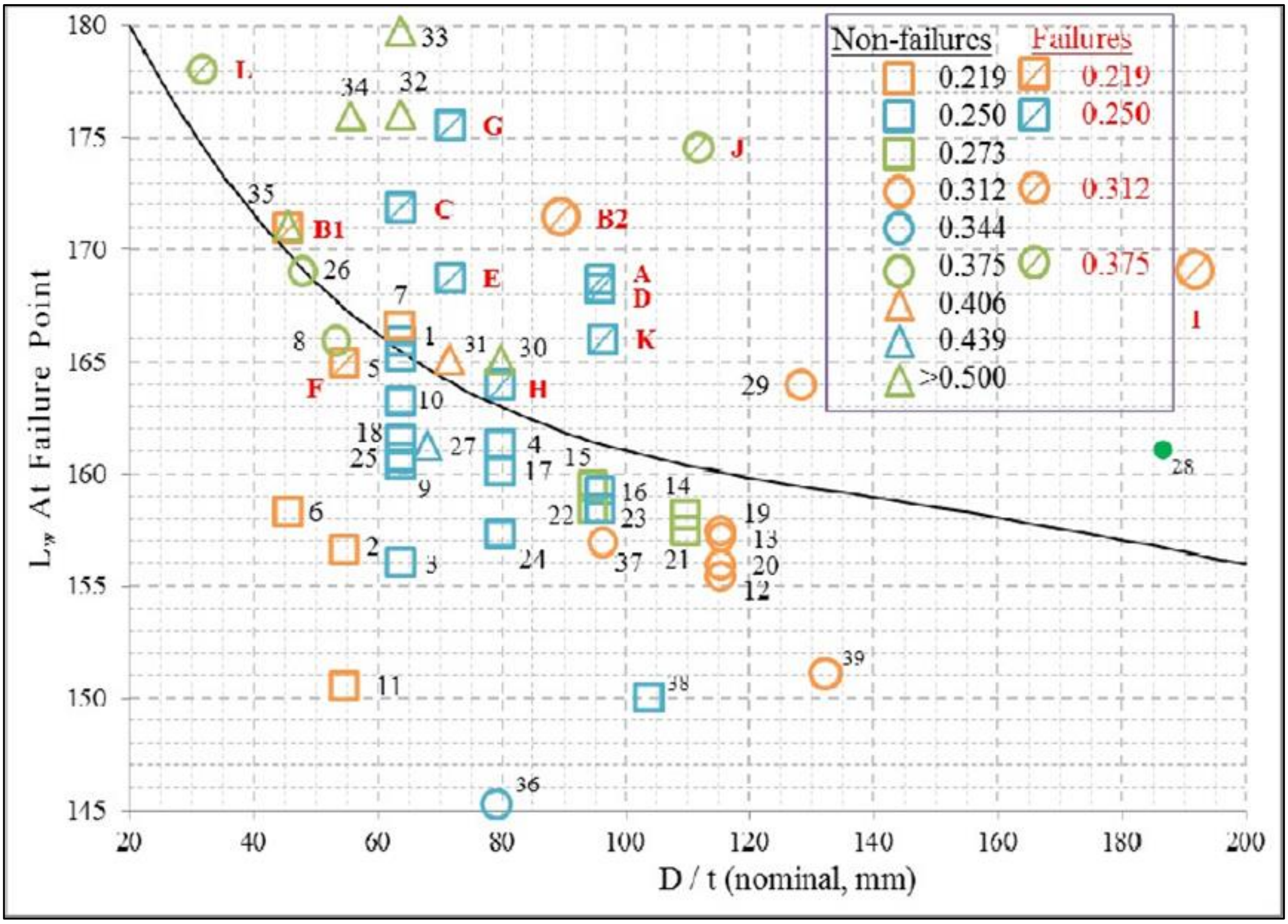


Fig 3 Recommended Safe Design Limit Based on Experience of Acoustically Induced Piping Vibration (Extract from "Solving AIV Problems in the Design Stage" CSTI Report of InterNoise2012)

$$Design\ Limit\ Curve = 4.2914 \times 10 - \left(\frac{D}{t}\right)^4 - 2.8195 \times 10 - 5\left(\frac{D}{t}\right)^3 + 0.006781\left(\frac{D}{t}\right)^2 - 0.7549\left(\frac{D}{t}\right) + 192.6125$$

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25oct1557

Where

D = pipe diameter (mm)

t = nominal pipe wall thickness (mm) or total wall thickness (mm) of the nominal run-pipe thickness (mm) and nominal reinforcement-pad thickness (mm)

➢ *Corrective Design for Piping Systems at Risk*

- *Reduce Acoustic Energy within Pressure Let - Down System*

If the predicted internal sound power level exceeds the Design Limit in Figure-1, then the pressure let - down system should be designed to incorporate multiple holes orifice.

For high-capacity systems, consider pipe routing and/or parallel pressure reducing valves with separate downstream lines to the header.

When it is impractical to incorporate the above measures or it is not possible to reduce acoustic energy within pressure let down systems, structural improvement described in the below section shall be applied.

- *Structural Improvement*

✓ *Detail of Structural Improvement*

Use a full encirclement reinforcement-pad at all branch connections greater than DN50 (NPS 2) diameter. (See Attachment 1) Weldolets or a partial reinforcement-pad shall not be used. Using a tee, including reducing tee, meeting the conditions of the applied grade below is acceptable.

The total minimum thickness (t) of the nominal run-pipe thickness (t1) and the nominal reinforcement-pad thickness (t2), or minimum thickness (t) of the tees shall be as follows.

D/t is the ratio of the nominal diameter of the run-pipe (D) to the thickness (t = t1 + t2).

Table 6 Grade Table with Respect to Pipe Thickness

Grade	**Total minimum thickness (t) of the nominal run-pipe (t1) and the nominal reinforcement-pad (t2), or minimum thickness (t) of tees**	**Note**
Grade 1	t > 2 t1	The nominal reinforcement-pad thickness (t2) will be as same as the nominal run-pipe thickness (t1).
Grade 2	t >2.5 t1	A thicker reinforcement-pad shall be applied. A thicker pipe wall is acceptable instead.

For pipe supports, where welded attachments are used, a full encirclement reinforcement-pad shall be applied at all support and restraint points. (See Attachment 1) The total minimum thickness (t) of the nominal run-pipe thickness (t1) and the nominal reinforcement-pad (t2) thickness shall be as above.

Any attachments directly welded on the run-pipe, such as bracing and lifting lug, should be avoided to the extent possible.

Eliminate small vents, drains, and other connections smaller than 2 inches or replacing with minimum 2-inch connections treated as discussed above.

NOTE1: When two or more branch connections are so closely spaced, a combined full encirclement reinforcement-pad is allowed if the branches distance satisfies other specifications or requirements.

✓ *Extent of Structural Improvement*

The above requirements are applied to the shorter of the following downstream piping of the reducing pressure system; The sound power level is above the design limit. (-3 dB / 50D. See section Attenuation Along a Pipe) Until the next large volume unit such as drum or tower.

➢ *Case Study*

This section presents selected results and mitigation actions derived from an actual AIV assessment for demonstration purposes.

- *The Below Table for Case Study: Sound Power Level Selection Table*

Table 7 Sound Power Level Selection

TagNo	**P1 Psi (abs)**	**P2 Psi (abs)**	**W (kg/h)**	**Te (K)**	**W (lb/h)**	**Te (F)**	**Mw (g/mol)**	**(Qty)**	**dB**	**Outcome**
PZV-6004A/B	1564.7	158.7	4,571	335.3	10078.0	144.0	27.8	1	139.5	Pass
PZV-6005A/B	1114.7	158.7	6,009	299.2	13247	79.0	19.8	1	142.3	Pass
PZV-6006A/B	1564.7	158.7	4,816	332.0	10617	138.0	27.9	1	139.9	Pass
PZV-6101A/B	1114.7	158.7	2,604	314.8	5740	107.0	36.2	1	132.2	Pass

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25oct1557

PZV-6102	1114.7	158.7	2,116	353.7	4664	177.0	25.5	1	132.8	Pass
PZV-6103A/B	1114.7	158.7	10,565	353.7	23291	177.0	22.6	1	147.4	Pass
PZV-6023AB/C	439.7	142.2	210,914	344.2	464986.0	160.0	44	2	166.1	Proceed detail assessment & mitigation action

- *The Below Figure for Case Study: Markup P&ID for Mitigation Action*

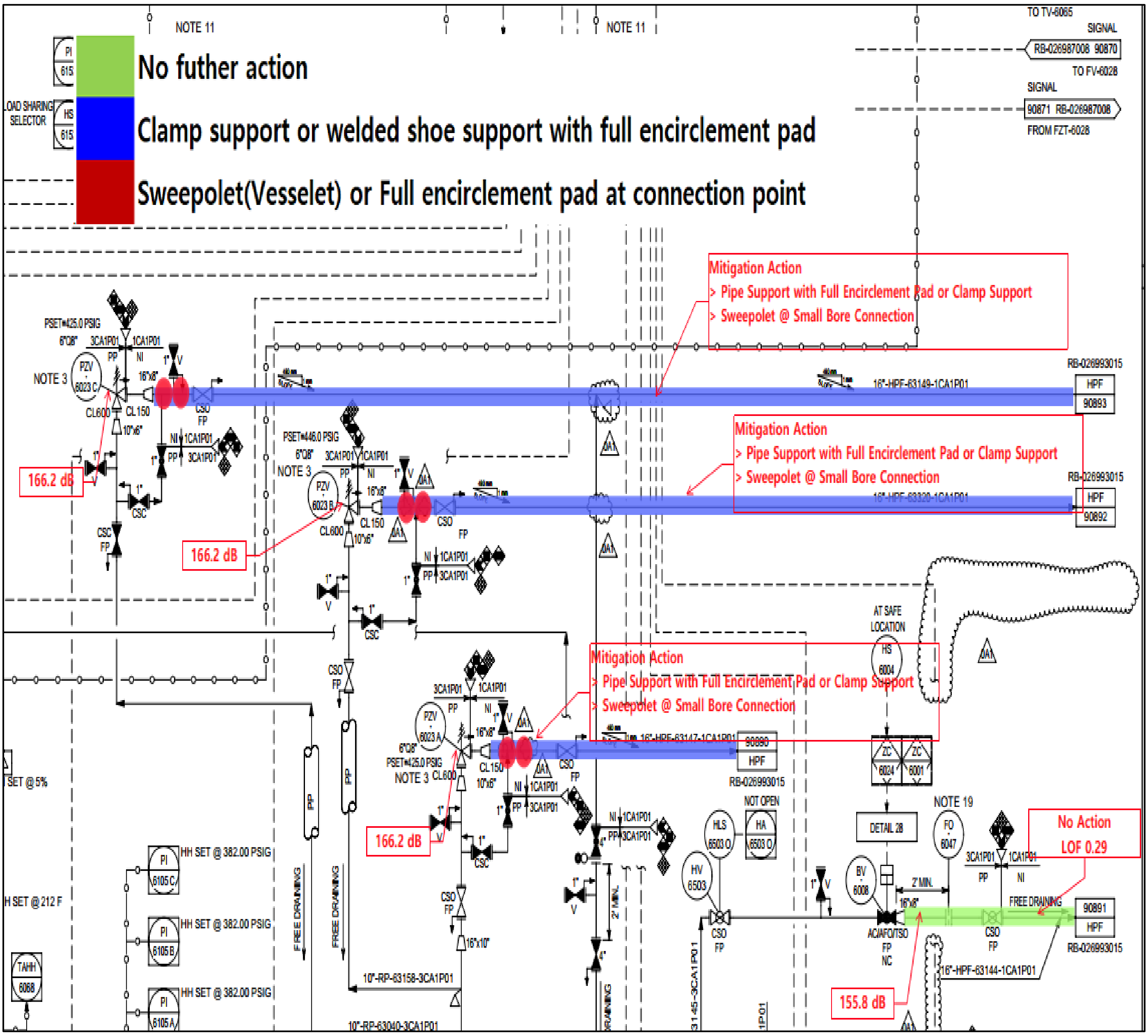


Fig 4 Markup P&ID for Mitigation Action

IV. CONCLUSIONS

For these FIV and AIV studies, Vibration risks for the various piping systems have been invested and mitigated. From the above study we can conclude that FIV, when the vibration risk is high, is generally controlled by designing a rigid piping support span spacing. And for AIV, the mitigation measures to eliminate piping discontinuity are most effective in reducing the risk of fatigue by shell-mode vibration. These effective mitigation measures should be coordinated with relevant design disciplines, process, piping and instrument, early in engineering phase, result in a successful design by reducing project schedules and minimizing material changes.

This study concludes that there are overall design approaches and effective mitigation methods for two categories, FIV and AIV, of pipe vibration.

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25oct1557

ATTACHMENT-1: REINFORCEMENT-PAD

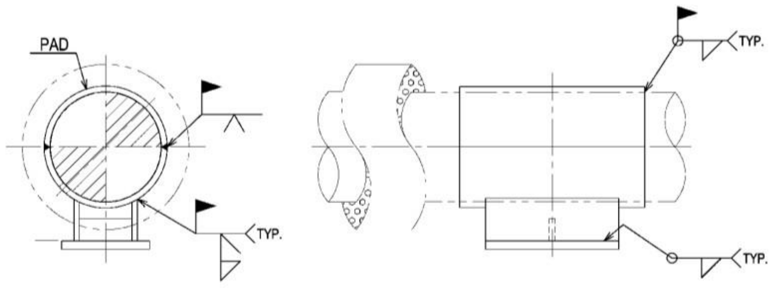
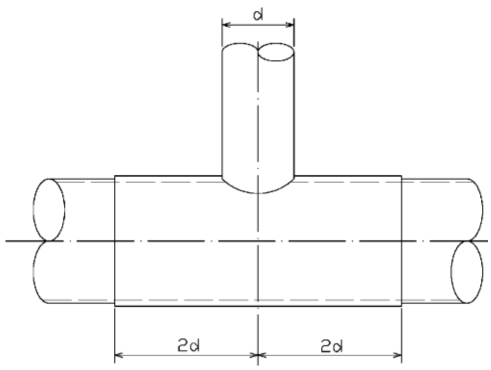
Full encirclement reinforcement-pad at pipe support	
Full encirclement reinforcement-pad at branch connection	

Fig 5 Reinforcement Pad Configuration

ATTACHMENT-2: STUDY FLOW

STEP 1: 1'st screening

For each pressure let-down device, the sound power level shall be calculated using the equation in section 3.2.

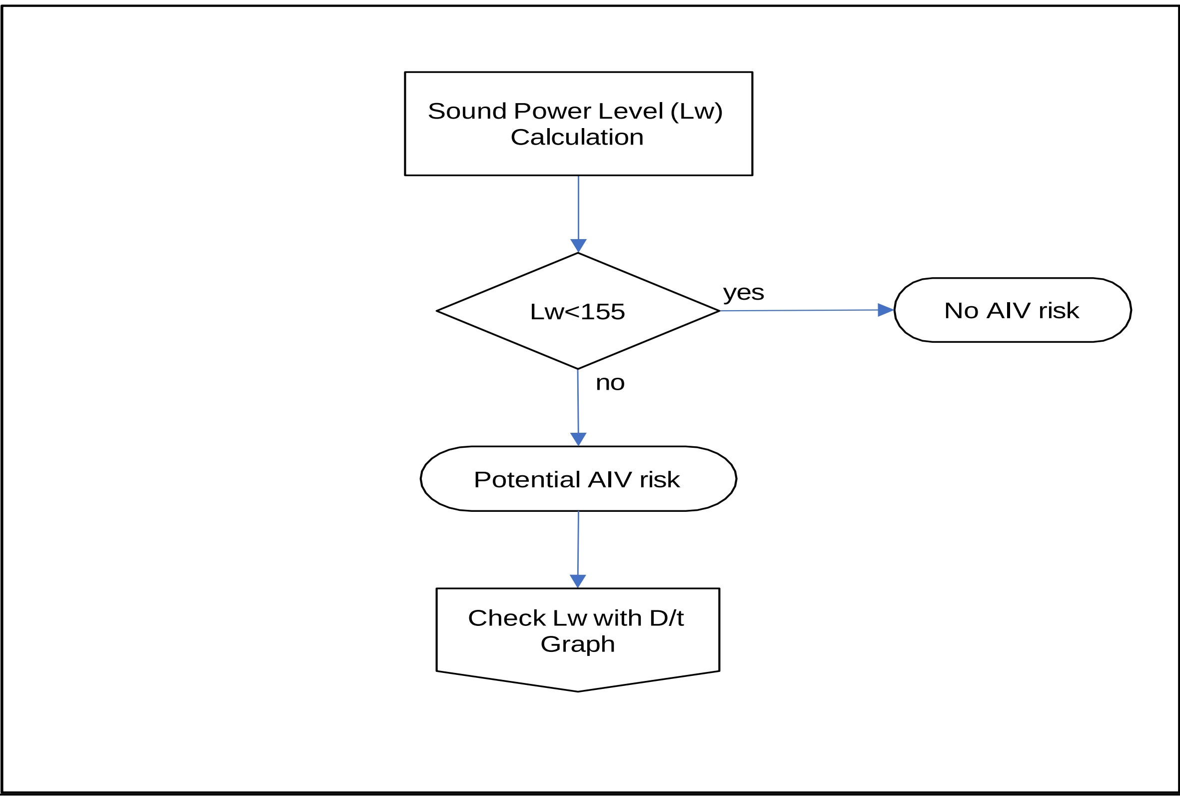


Fig 6 Flowchart for 1st Screening

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25oct1557

➢ *Step 2: Detail Study*

The detailed calculation shall be performed for the identified pressure reducing devices and the downstream piping system incorporating sound attenuation factors into the calculation.

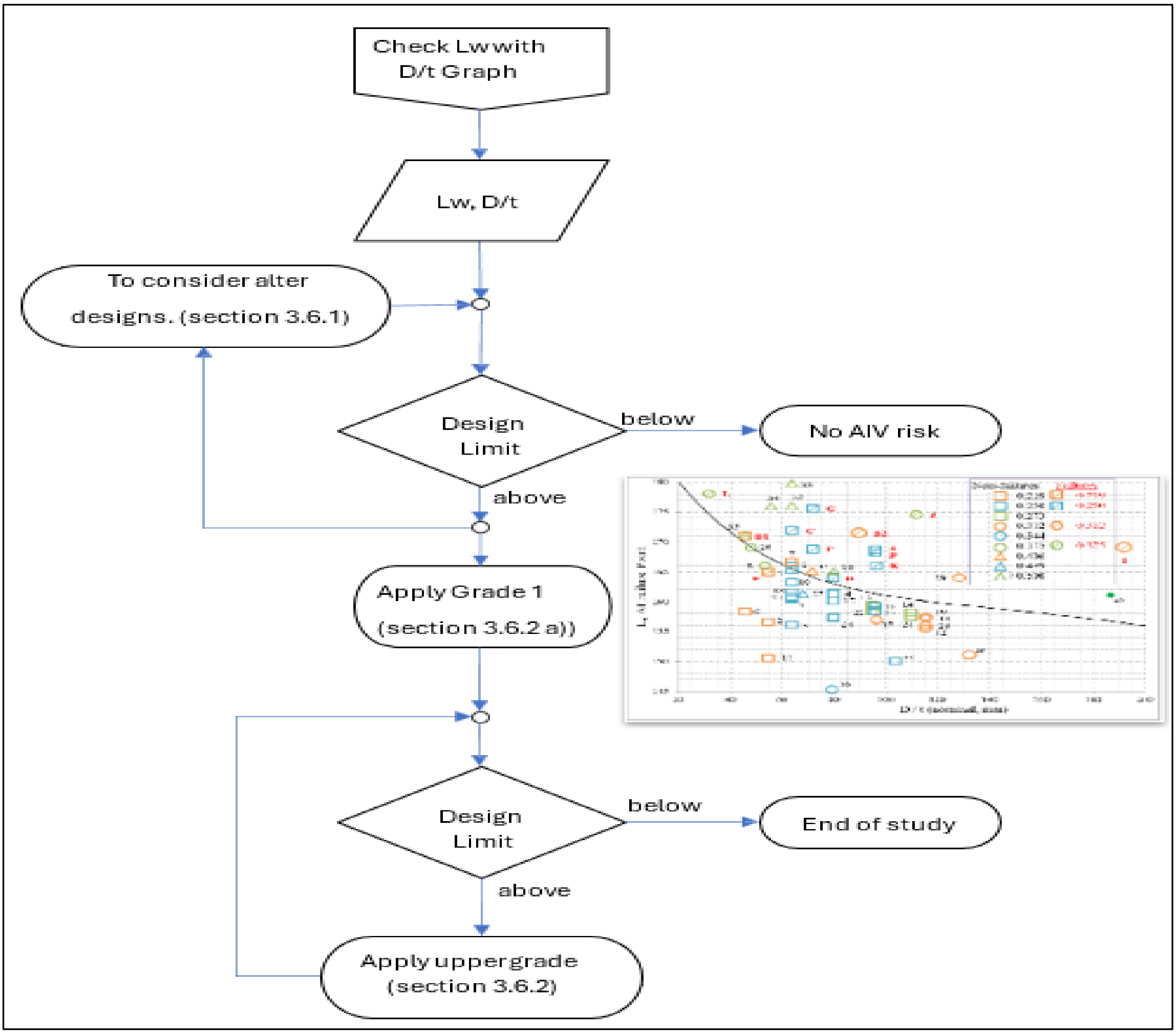


Fig 7 Flowchart for Detail Study

Author:

Mr. Khalid H. Alwayli, PMP

Mr. Prasanta Dey *(Chartered Engineer from The Institution of Engineers (India) Credential ID F-1297815)*

REFERENCES

[1]. ASME*1) Paper No. 82 WA/PVP-8, 1982. NOTE 1- The American Society of Mechanical Engineers
[2]. CARRUCCI, V.A., AND MUELLER, R.T., "ACOUSTICALLY INDUCED PIPING VIBRATION IN HIGH CAPACITY PRESSURE REDUCING SYSTEMS"
[3]. Inter-Noise 2012 report CSTI acoustic “SOLVING AIV PROBLEMS IN THE DESIGN STAGE”
[4]. Energy Institute “Guidelines for the Avoidance of Vibration Induced Fatigue Failure in Process Pipework”