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Differentiating Between Acoustic and Flow-Induced Vibration

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ABSTRACT

Acoustic-induced vibration (AIV) and flow-induced vibration (FIV) are phenomena that have been used interchangeably in the industry. Both phenomena cause fatigue failures in piping systems at stress discontinuities (pipe fittings, bends, reducers, and welded pipe supports), but their generation mechanism and mitigations are different (some mitigations are applicable to both phenomena). The intent of this paper is to provide a better understanding of the two types of vibrations and their effects on piping systems. This paper identifies differences between the two types of vibration, energy transmission, impact on piping systems, and mitigation options. The two phenomena are compared and contrasted to show important similarities and differences that should be understood by all engineers working on mitigating pipe vibration.

NOMENCLATURE

p_1	upstream pressure, Pa
p_2	downstream pressure, Pa
$\Delta p = p_1 - p_2$	pressure drop, Pa
T_1	upstream temperature, ^{0}K
W	flow rate of gas and liquid, kg/s
m	molecular weight
D	diameter, mm
t	pipe wall thickness, mm
v	velocity, meter/second
PWL	sound power level, decibels
ρ	density kg/m^3

INTRODUCTION

Basic Fluid Flow Concepts

Vapor or liquid flowing through pipes has force due to the kinetic energy (velocity and mass) and the pressure difference that drives the flow. As it flows, the fluid loses energy due to many factors:

- work done internally to produce fluid waves (small pressure disturbances that propagate through the fluid at multiple frequencies and amplitudes);
- work (units of energy) done by vibrating the pipe;
- friction (which irreversibly converts mechanical energy to internal energy at the wall and results from internal turbulence);
- work produced externally by flow through expanders (if any); and
- heat (in units of energy) lost to surroundings.

Additionally, some energy is expended when pipe vibrations create sound waves in atmosphere external to the pipe.

The fluid flow pressure drop may appear small, but it can cause substantial stress-related concerns.

Vibration Concepts

Many mechanisms create vibration in pipes, including pulsations from rotating equipment, external wind effects, vortex shedding, etc. However, the pipe vibrations discussed are limited to those induced by internal fluid forces. *This paper is not intended to cover the basic theory of vibration but rather to focus on mechanical aspects and mitigation.*

Waves that are created have frequencies between 1 hertz (Hz) (cycle per second) and 2,500 Hz. Waves in the 500– 2,500 Hz range are referred to as sound or acoustic waves since they are audible to humans.

The kinetic energy effects are measured as the kinetic energy per volume of flowing fluid or momentum flux (momentum per area per time). This is the pressure that kinetic energy transfers to the pipe wall, written as (ρ v2). The units of pressure are pascals or psi.

Low-frequency waves are less than 100 Hz and generally less than 15 Hz. Normally flexible piping has a fundamental mechanical natural frequency of 1 Hz [1].

Sound or acoustic waves have historically been measured as decibels of sound power level (PWL). The sound power level is a function of the pressure loss. Note that PWL is a log scale; the pressure loss in psi results in a smaller change in PWL (Figure 1).

$$\mathrm{PWL} = 10 \log \left(\left(\frac{\Delta p}{p_1} \right)^{3.6} W^2 \left(\frac{T_1}{m} \right)^{1.2} \right) + 126.1$$

Figure 1. Sound Power Level Formula (Downstream of Source)

Locations of Pressure Loss

Since it is the energy in the fluid that induces vibrations, systems with large kinetic energy due to high velocities and substantial mass flows are most susceptible, particularly at locations such as depressuring valves, restriction orifices, and relief valves. Choking of gases or flashing liquids are intense sources of vibration and waves since there are large pressure losses downstream of the choke point (see shaded box and Figure 2).

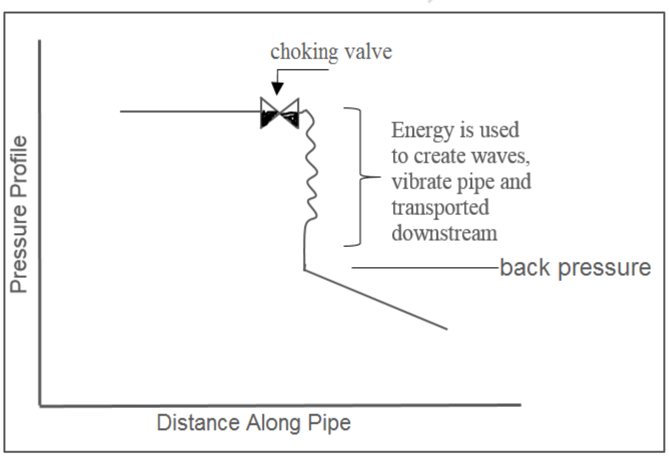

Figure 2. Pressure Profile Along the Pipe

> Choking of a fluid flow is an important phenomenon since it is related to large energy changes. Choking is calculated when the mass flux, or mass flow per flow area, is at a maximum and cannot increase regardless of the pressure drop and downstream pressure (given constant upstream pressure).
>
> Choking occurs when the fluid density decreases dramatically at expansions such as pressure-reducing valves or pipe expanders. Thus, choking may occur in gases, flashing liquids, and dense-phase fluids, depending on the amount of expansion due to the pressure ratio, but not in incompressible liquids. As a general rule, the upstream pressure must be twice the downstream pressure for a gas to choke.
>
> It is this large pressure region downstream of the choke point that produces waves and pipe vibrations.
>
> Choke flow leads to a wide frequency spectrum with peak values than can exceed 1,000 Hz.
>
> An upstream sound wave cannot cross a choke point since the velocity of sound does not exceed the bulk velocity of the fluid (Figure 3).

Additionally, large-pressure losses tend to produce a wider spectrum of waves with higher frequencies than locations with low-pressure losses. The high-frequency acoustic waves (500–2,500 Hz) tend to extend outward radially in the fluid and thus vibrate piping around the full pipe circumference. This force causes the pipe circumference to change shape in small amplitude displacements termed "circumferential displacement modes" or "shell modes." Thinner-wall pipe (relative to pipe diameter) is more vulnerable. The produced circumference stresses are called "hoop" stresses. Failures can occur rapidly, in minutes to hours, under hoop stresses.

On the other hand, at narrow spectrum of low-frequency waves (<100 Hz), these waves are not able to displace the pipe around the circumference but instead displace the pipe longitudinally along the beam of the pipe, which is termed "beam mode vibration." Low-frequency waves tend to have larger amplitudes than high-frequency waves due to beam mode phenomena caused by low-frequency vibration where amplitude is strictly dependent on the total energy of the system in the longitudinal direction of the pipe. For long, straight pipe runs, the displacement amplitude may be greater than one inch. Failures occur slowly over a longer period.

In general, low-frequency vibration is categorized as frequency less than 100 Hz, and the dominant high-frequency vibration is 500–2,500 Hz. The middle frequency between 100 Hz and 500 Hz is normally not a concern for fatigue failure because there is not enough acoustic energy to excite the pipe circumferential shell.

Transmission and Attenuation of Waves and Vibrations

The energy in the flowing fluid due to waves, pipe vibrations, and some turbulence may be transported downstream, which is important in the analysis and mitigation of vibration. Although the source of vibration occurs upstream, the vibrations are manifested downstream at mechanical piping junctions where stress is concentrated. Some piping vibrations may be carried past the mechanical junction to affect piping further downstream.

Attenuation results from pressure losses by friction [2] due to rough pipe and turbulence, work done by vibrating the pipe and heat lost to the surroundings.

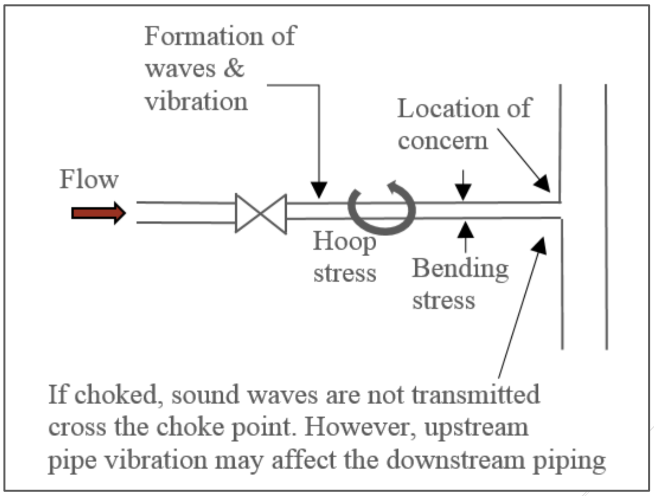

Figure 3. Choke Flow

Mitigation of AIV and FIV

Failure locations are the same for both AIV and FIV, and fortunately, many mitigation techniques are similar for the two types of vibration.

Mitigation efforts are applied throughout the piping configuration, from the source to the impacted downstream piping. Mitigation options common to both include lower velocities, thicker pipe, and the use of contour fitting. Specific options are discussed with each type of vibration.

History of AIV and FIV

AIV and FIV have been known in the industry prior to the 1970s. FIV has not been given the same level of attention as AIV due to its low-frequency nature (<100 Hz). Recognition of AIV dates to the 1960s, but the AIV phenomenon became well known in the industry through the Carucci-Muller [3] publication in 1982, which investigated actual AIV failures of thin-walled piping and developed the design curve based on failures/non-failures experience. The study plotted a curve showing the PWL limit as a function of pipe diameter. This was the most comprehensive paper published with mitigation options for lines subjected to acoustic energy.

In 1997 Eisinger [4] published a design curve that includes pipe wall thickness as a function of D/t ratio. Today, the most comprehensive guideline for vibration (AIV and FIV) is the Energy Institute Guideline [1]. There have been many publications pertaining to AIV such as NORSOK standard L-002 [5], Bruce "CSTI" [6], API 521 [7], and others. All these publications include some criteria for assessment and mitigations of AIV, but the phenomena are the same, and there is general agreement in the industry on the cause and effects of AIV.

ACOUSTIC-INDUCED VIBRATION

AIV refers to structural vibration excited by intense acoustic pressure in a piping system with vapor flow. The acoustic pressure is usually created from pressure-reducing devices due to high pressure drops and mass flows of vapor services. These acoustic energies excite the pipe wall circumferentially due to high-frequency sound waves in the range of 500–2,500 Hz, where most of the energy is captured. The circumferential mode of vibration causes the pipe to displace radially, and this leads to fatigue failures where stress concentrations occur downstream, such as at pipe fittings and welded pipe supports. Figure 4 depicts the circumferential displacement that the pipe undergoes under high-frequency vibration.

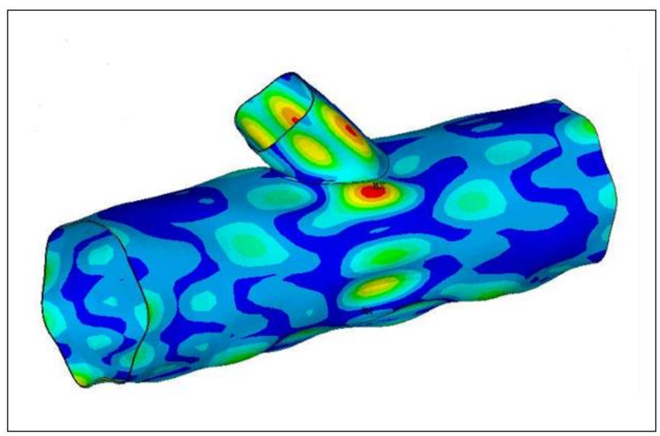

Figure 4. High-Frequency Vibration

AIV is not prevalent in liquid or two-phase fluid since the high fluid viscosity dampens the circumferential pipe displacements (radial) (Figure 5).

AIV is present wherever there are high pressure drops and flow rates in vapor services. Typical sources are relief valves,

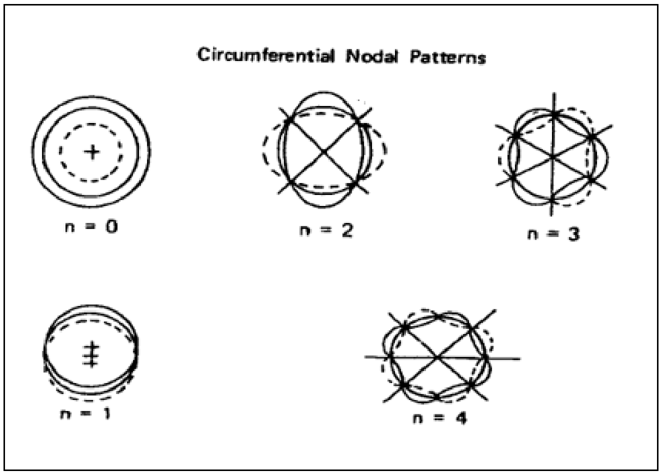

Figure 5. Circumferential Displacement Modes of Vibration (courtesy of ASME 82-WA/PVP-8)

vents, control valves, blow-down valves, compressor recycle valves, etc. The focus is always on the downstream piping where the acoustic energy is being concentrated. Most vibration concerns are downstream and associated with stress points at small-bore connections such as sockolet, weldolet, drain valves, and welded pipe supports. Resonance seldom occurs where the acoustic frequency matches the mechanical pipe natural frequency leading to drastic vibration amplitude and stress levels. Figure 5 shows different circumferential modes of vibration caused by high- frequency vibrations.

The acoustic power level immediately downstream of the pressure-reducing device used by Carucci and Mueller is given by the expression in Figure 1.

Noise Attenuation of AIV

The noise is transmitted downstream of the flow restriction losing energy to friction, work done by vibrating the pipe, and heat lost to surroundings. At a safe level below 155 dB, circumferential vibration is no longer a concern. Industry standards and experience [3, 5, 6] show acoustic energy attenuates 3 dB for every 50D of piping from the source.

More recent full-scale testing of AIV was executed by Southwest Research Institute (SWRI) at San Antonio, Texas [8], which yielded much higher attenuation of 0.2 dB/diameter. This indicates that the industry guideline is conservative or that radiated noise and decay are higher than at low levels.

Investigation into sound reduction in steel pipes in petrochemical plants revealed values between 0.1 dB/meter and 0.4 dB/meter in the frequency range of 250–4,000 Hz [2].

Mitigation of AIV

There are many mitigation options for high-frequency vibration. This discussion focuses on the most common mitigations done during the design stage of a project. Since failures can happen within minutes of operation and the most common mitigation requires welding to the piping pressure boundary (which is not acceptable once the system has been hydro/pneumatically tested), AIV mitigation should be instituted during design.

Since AIV is a low-amplitude and high-frequency vibration, countermeasures restrain the shell-mode vibration of pipe by using thicker pipe wall (higher pipe schedule) or lower D/t ratio. Decreasing flow velocity by increasing pipe diameter is also frequently used. In addition to making the pipe thicker, normal practice is to use smoother pipe fittings such as contour fittings or B16.9 tee, which ensures a smooth transition from branch to main header. Other types of branch connections such as stub-in or stub-on with full wrap-around or partial re-pad to dampen the circumferential displacement are acceptable based on acoustic power levels at that location. Clamp-on supports and stiffening rings are also used.

Common mitigation is to use a full wrap-around pad on welded pipe supports. Full wrap-around is more commonly accepted in industry standards than partial re-pad. However, published studies [9] have shown that partial re-pads could be used on high-frequency vibration and are effective in dampening the magnitude of vibration local to the welded components. Figure 6 below shows common AIV mitigations used in the industry.

Figure 6. Common Mitigations

FLOW-INDUCED VIBRATION (FIV)

FIV refers to vibration that excites the low-frequency regions of the pipe (<100 Hz). This usually takes place at pipe bends, reducers, and fittings and leads to beam mode vibration, which causes the pipe to displace longitudinally and transversely. Figure 7 shows beam mode vibration.

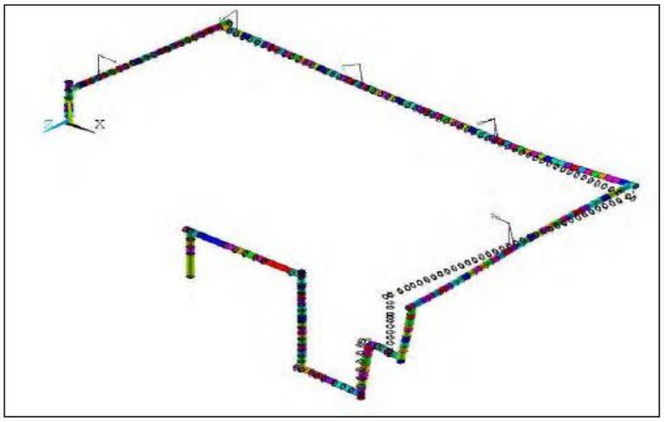

Figure 7. Low Frequency Vibration (courtesy of Energy Institute Guideline)

FIV fatigue risk is increased due to many factors such as high velocity, large densities, high D/t ratio, and flexible piping due to long spans or inadequate pipe supports and/or restraints. Normally flexible piping is characterized as a piping system that has a fundamental mechanical natural frequency of 1 Hz [1].

FIV is more important for liquid than gases if one considers momentum flux on the pipe wall (ρv^2 or the momentum per time per area). Thus, liquids with higher density have greater FIV concerns.

Attenuation of FIV

Attenuation is not significant at low frequencies. Vibration dampens to almost a steady state within 10–20 diameters.

Since FIV is a large-amplitude vibration and it takes longer to cause a fatigue failure, it is usually resolved after start-up when vibration is observed. The most common mitigation is to add supports or restraints, typically without welding to the pipe pressure boundary.

Mitigation of FIV

FIV is a large-amplitude and low-frequency "beam-mode vibration." Beam mode vibration, which could cause amplitude greater than 1 inch, is normally resolved by adding pipe supports or properly anchored restraints without welding to the pipe pressure boundary. These supports minimize shaking of the pipe, which could cause fatigue failure at locations where stress is concentrated such as at welded pipe supports and pipe fittings.

Stress concentration at branches is mitigated by contoured fittings and gussets on small-bore connections.

Another common mitigation in design to prevent FIV is to reduce flow velocity through the pipe by increasing pipe diameter one or two sizes. To some extent this approach also prevents choking, which causes very high stress at branch connections.

A common criterion is to limit kinetic energy per volume of a flow stream to a value of 100,000 Pascals (14.5 psi) for gas flow and 50,000 Pascals (7.2 psi) for fluids/two-phase flow [10].

DIFFERENTIATING BETWEEN AIV AND FIV

Figure 8 provides a high-level summary of the characteristics of the two types of vibration. It is interesting to note that the failure point is the same for both AIV and FIV.

	AIV	FIV
Source of Vibration	Pressure Reduction Devices (PRD)	Turbulence at Flow Discontinuities
Fluid Phase	Vapor	Vapor/Liquid/Two Phase
Vibration Frequency	500-2500 Hz	0-100 Hz
Vibration Magnitude	Invisible	Visible
Vibration Mode	Shell Mode	Beam Mode
Failure Mode	High Cycle Fatigue	Low Cycle Fatigue
Location of Failure	Branch Fittings and Welded Supports	
Effect of Choked Flow	Risks are significantly increased due to choked flow	
Mitigations	• Increase Pipe Wall Thickness • Use Contoured Fitting • Use Full Wrap Around Repad • Add More PRDs • Add Low Noise Trim	• Increase Pipe Wall Thickness • Use Contoured Fitting • Add More Rigid Supports • Increase the Pipe Size

Figure 8. Comparison of AIV and FIV

CONCLUSION

The information presented in this paper is intended to assist projects in assessing pipe vibration proactively, early in the design phase, so that mitigation measures can be developed and implemented before vibrations can cause issues after start-up.

ACKNOWLEDGMENTS

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