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AIV AND FIV IN PIPELINES, PLANTS, AND FACILITIES

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ABSTRACT

Acoustic-induced vibration (AIV) and flow-induced vibration (FIV) are two common phenomena that can lead to vibration-induced fatigue failures in piping systems. Pipeline facility managers, operators, designers, and engineers are faced with identifying and mitigating the risks of AIV and FIV to avoid catastrophic instances of vibration-induced fatigue failures in their facilities. This paper identifies common challenges to conventional AIV/FIV analyses methods, and discusses advanced techniques available to address these challenges.

Acoustic-induced vibrations are caused by the sound energy created by flow through pressure reducing devices like valves or restrictive orifice plates. This sound energy can cause the piping wall to vibrate, thus exciting, and possibly damaging, any nearby small-bore branch connections. Flow-induced vibrations are caused by pulsations induced by flow past dead legs in piping systems. These pulsations can create shaking forces that cause vibrations of piping, vessels, and equipment. The two phenomena will be compared and contrasted, while offering simple tips and best practices in identifying, evaluating, and solving these two common flow-induced issues.

A field case study utilizing pulsation and vibration measurements between a line heater and inlet separator for a gas plant will be presented and discussed. The case presents an opportunity to investigate mainline and small-bore piping AIV/FIV risks in plants, provides example data of clear AIV and FIV phenomena, and identifies complex situations that require more rigorous analysis. Advanced techniques for analyzing and solving complex issues that are commonly found in piping systems will be explored. Further, the case highlights the benefits of early screening and preventive considerations of upset conditions when dealing with flow-induced pulsation and vibration issues.

In this paper, the reader will gain an increased understanding of the importance of AIV/FIV in maintaining integrity of their facilities, and be provided with tools and knowledge to mitigate any risks that may be encountered.

NOMENCLATURE

F_V	Frequency of vortices [Hz]
S	Strouhal number
v	Fluid velocity [m/s]
d	Representative dimension of component [m]
F_S	Frequency of deadleg acoustic resonance [Hz]
$F_{S,n}$	Frequency of deadleg acoustic resonance, nth harmonic [Hz]
L_{branch}	Length of deadleg [m]
c	Speed of sound in gas [m/s]
n	1, 2, 3, …
PWL	Sound power level at source [dB] (with reference power of 10^{-12} W)
$P1$	Pressure upstream of PRD [Pa abs]
$P2$	Pressure downstream of PRD [Pa abs]
Te	Temperature upstream of PRD [°K]
W	Mass flowrate through PRD [kg/s]
Mw	Molecular weight of gas through PRD [grams/mol]

ACRONYMS

AIP	Acoustic-induced pulsation
AIV	Acoustic-induced vibration
EI AVIFF	Energy Institute Guideline for the Avoidance of Vibration Induced Fatigue Failure in Process Pipework
FE	Finite element
FF	Fatigue failure
FIP	Flow-induced pulsation
FIV	Flow-induced vibration
LOF	Likelihood of failure
MMscfd	Million standard cubic feet per day
PRD	Pressure reducing device
PSV	Pressure safety valve
RO	Restrictive orifice plate
SBC	Small-bore branch connection
WD	Welded discontinuity

INTRODUCTION

The operator of an Alberta (Canada) gas plant contacted BETA Machinery Analysis (BETA) to evaluate a restrictive orifice plate (RO). The RO was located upstream of a separator (V-140), control valves, and many small-bore connections (Figure 1). The operator was concerned about the potential for noise and vibration created during the high flow relieving operating case.

BETA evaluated the risk of high vibration in this area by conducting an acoustic-induced vibration (AIV) study. The risk was found to be low. The operator wanted a follow-up field investigation, so BETA visited the site in August 2015. The field visit found some interesting pulsation results which indicated the potential for flow-induced vibration (FIV) issues.

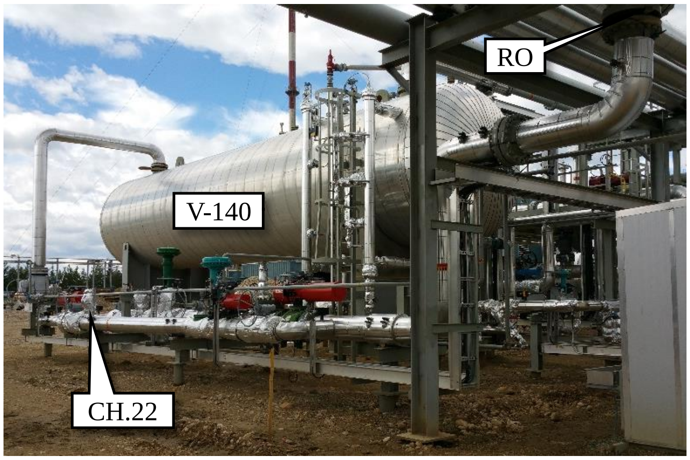


Figure 1. Piping downstream of restrictive orifice plate

ACOUSTIC-INDUCED VIBRATION

In some cases, the gas in vessel V-140 needs to be sent to the flare; this is called the relieving case. In order to control the flow of gas to the flare, a restrictive orifice plate (RO) was installed upstream of vessel V-140 (Figure 1). The relieving case would see the gas flow through the RO increase to 18.9E6 sm³/day [668 MMscfd] from the design flow of 4.2E6 sm³/day [150 MMscfd]. This will create significant noise downstream of the RO. This sound energy can also create unwanted vibrations of the pipe wall, and potentially cause fatigue failure of small-bore connections on the pipe.

An acoustic-induced vibration (AIV) audit was done using the procedure outlined in the Energy Institute “Guideline for the Avoidance of Vibration Induced Fatigue Failure in Process Pipework” [1], also referred to as EI AVIFF. The risk posed by AIV is typically to downstream welds that are not circumferential, like stub-in branches, small-bore connections, and supports that are welded directly to the pipe. These are called welded discontinuities (WD). Axisymmetric welds, like the circumferential welds on pipe, rarely fail due to AIV.

The AIV study is broken down into two phases:

1. First, the sound power level (PWL) created by the pressure reducing device (eg, a pressure safety valve, a blowdown valve, or an orifice plate) is calculated by Eq. (1). If the sound power level is less than 155 dB, the system is considered acceptable, and no further investigation is required. Note: the equation assumes there is subsonic flow downstream of the pressure reducing device (PRD).

$$PWL = 10\log_{10}\left[\left(\frac{P_1 - P_2}{P_1}\right)^{3.6} W^2 \left(\frac{Te}{Mw}\right)^{1.2}\right] + 126.1 \tag{1}$$

2. Second, the effect this sound energy has at downstream welds is evaluated and a likelihood of failure (LOF) is calculated. The LOF depends on the piping geometry. In general, smaller diameter branch connections and thinner mainline piping tend to be more at risk of AIV related failures. An LOF ≥ 1.0 indicates that modifications should be made to reduce the risk of failure.

Phase 1 was conducted on the RO and found the sound power level was acceptable (<155 dB) for the normal operating case but high (174 dB) for the relieving case. Phase 2 was conducted and found the LOF was acceptable for all the branch connections downstream of the orifice plate.

Table 1. AIV solutions

Solution		Example and Comments
Lower the PWL of the PRD	Reduce the pressure drop across the PRD	• Increase the effective area of the PSV or RO
	Reduce the flow rate through the PRD	• Split flow between two PSVs • Blowdown over longer duration
	Use a low noise trim on the valve	• Typically only available on blowdown valves
	Stage the pressure drop	• Replace one RO with several ROs
Mitigate the WD	Remove the WD	• Remove unnecessary or redundant connections
	Move the WD further away from the PRD	• The PWL attenuates at locations further away from the PRD
	Increase the diameter of the WD	• Larger diameter connections have a lower risk of FF
	Replace the WD with a extruded (welding) tee	• Extruded tees have axisymmetric welds and therefore are not at risk
	Change the style of the WD	• Sweepolets are more robust than weldolet
	Increases the thickness of the mainline piping	• Thicker mainline piping can lower the risk of FF
	Reinforce mainline piping	• Repads, pipe wraps, and stiffening rings require advanced analysis (phase 3)

Notes:

FF	Fatigue failure	PWL	Sound power level
PRD	Pressure reducing device	RO	Restrictive orifice plate
PSV	Pressure safety valve	WD	Welded discontinuity

If the AIV study had found issues, the solutions could either focus on lowering the sound power level, or changing the design of the downstream welded discontinuity (Table 1 above).

During the field visit, pulsation measurements were taken downstream of the RO (see Ch.22 in Figure 1 and Figure 2). Acoustic induced pulsations (AIP) are typically high frequency, broadband, and low amplitude, which is exactly what was observed (Figure 3). The peak amplitude was very low (less than 0.05% of line pressure).

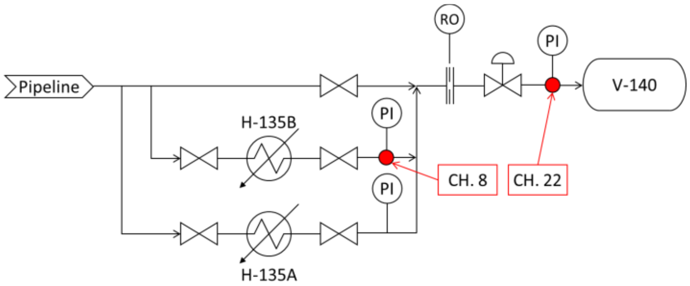
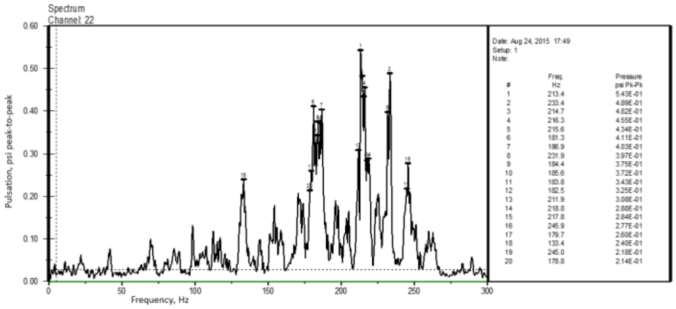


Figure 2. Layout of piping



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Note:

#	Freq. Hz	Pressure psi Pk-Pk
1	213.4	5.43E-01
2	233.4	4.89E-01
3	214.7	4.82E-01
4	216.3	4.55E-01
5	215.6	4.34E-01
6	181.3	4.11E-01
7	186.9	4.03E-01
8	231.9	3.97E-01
9	184.4	3.75E-01
10	185.6	3.72E-01
11	183.8	3.43E-01
12	182.5	3.25E-01
13	211.9	3.08E-01
14	218.8	2.88E-01
15	217.8	2.84E-01
16	245.9	2.77E-01
17	179.7	2.60E-01
18	133.4	2.40E-01
19	245.0	2.18E-01
20	178.8	2.14E-01

Figure 3. Downstream pulsation at 2100 e^{3}m^3/day (channel 22)

FLOW-INDUCED VIBRATIONS

Also during the field visit, pulsation measurements were taken near the line heaters (H-135A and H-135B) upstream of the restrictive orifice plate (see Ch. 8 in Figure 2 and Figure 7). The pulsations showed indications of FIV (Figure 5).

Pulsations can be created in high-velocity gas systems by flow past the mouth of branch connections that contain zero flow ("deadlegs"). These pulsations are created by the interaction between vortices and acoustic resonances. An illustration of this scenario is shown in Figure 4.

The vortices are created when the gas flows past the mouth of a deadleg. The vortices are created at a specific frequency based on Eq. (2). These vortices are amplified by the acoustic resonances of the deadleg, which are defined by Eq. (3). When there is coincidence between these two frequencies, flow-induced pulsations (FIP) are created in the piping system.

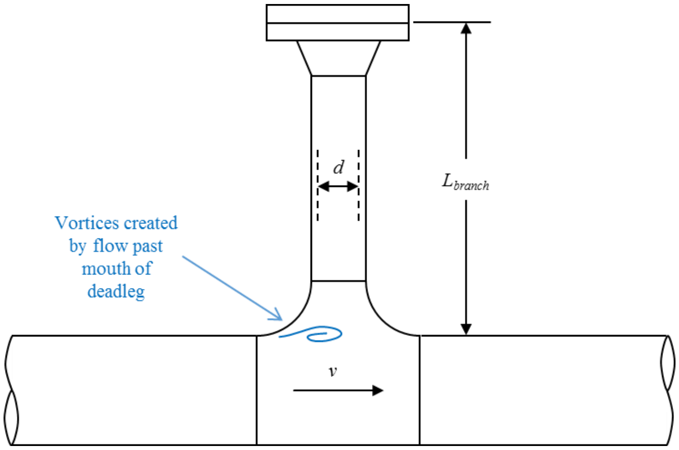


Figure 4. Flow-induced vibration illustration

$$F_V = \frac{Sv}{d} \tag{2}$$

$$F_S = \frac{(2n-1)}{4}\frac{c}{L_{branch}} \tag{3}$$

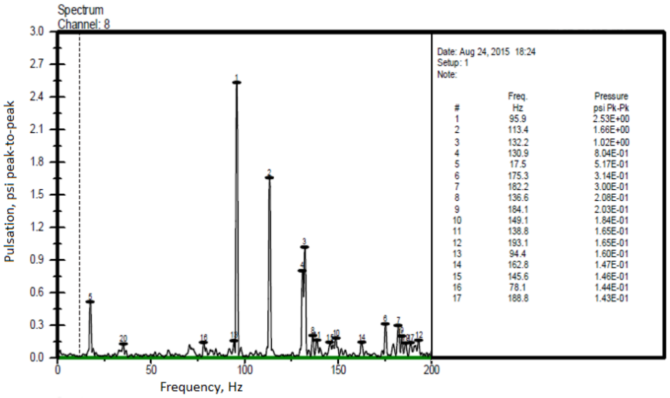
When taking measurements in the field, it can be difficult to do these calculations and determine the source of the pulsations. Piping systems typically have many deadlegs, any of which may potentially cause FIP. It can be useful to calculate the length of the deadleg while in the field, in order to start investigating the source of the pulsations. There tend to be multiple peaks (harmonics) created by FIP, and the difference in frequency between adjacent harmonics can be used to estimate the deadleg length. For example, from the pulsation measurement shown in Figure 5, the top two adjacent harmonics occur at 95.9 Hz and 113.4 Hz. Reformatting Eq. (3) allows the calculation of the deadleg length:

$$L_{branch} = \frac{c}{2 * \left(F_{S,n+1} - F_{S,n}\right)} \tag{4}$$

Assuming a speed of sound in the gas of 396 m/s [1300 ft/s], the deadleg length can be calculated from Eq. (4) to be 11.3 m [37.1 ft]. The field analyst can now begin investigating the piping system to identify potential sources of the pulsations.

Typical solutions to FIV problems are listed below:

- Change the length of the deadleg (typically shorten it)
- Avoid certain flowrates of gas
- Allow some flow through the deadleg (typically a temporary solution while permanent solutions are developed and installed)
- Add spoilers to the mouth of the deadleg to eliminate the creation of vortices
- Add additional supports and bracing to reduce vibrations



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Setup: 1
Note:

#	Freq. Hz	Pressure psi Pk-Pk
1	95.9	2.53E+00
2	113.4	1.66E+00
3	132.2	1.02E+00
4	130.9	8.04E-01
5	17.5	5.17E-01
6	175.3	3.14E-01
7	182.2	3.00E-01
8	136.6	2.08E-01
9	184.1	2.03E-01
10	149.1	1.84E-01
11	138.8	1.65E-01
12	193.1	1.65E-01
13	94.4	1.60E-01
14	162.8	1.47E-01
15	145.6	1.46E-01
16	78.1	1.44E-01
17	188.8	1.43E-01

Figure 5. Upstream pulsation at 1200 e^3m^3/day (channel 8)

In this particular case, the piping system was complex, and finding which deadleg was directly responsible for the flow-induced pulsations (FIP) was difficult. Further investigation indicated that there are potentially multiple deadlegs contributing to FIP.

The peak pulsations near the line heater were plotted over the entire flow range (Figure 6). The area of the circles in the plot correspond to the pulsation amplitude of the peak. The maximum pulsations measured were 76.5 kPa peak-to-peak [11.1 psi peak-to-peak]. There are no industry guidelines for FIP but keeping pulsations less than 3% of line pressure or 225 kPa peak-to-peak [32.6 psi peak-to-peak] in this case, is recommended. The pulsations measured were below guideline.

The potential forces created by the flow-induced pulsations can be estimated by assuming a worst case situation of the pulsations acting on the cross sectional inner area of the pipe (Table 2). In general, BETA recommends pulsation-induced shaking forces to be less than 4448 N peak-to-peak [1000 lb peak-to-peak]. The worst case forces are acceptable.

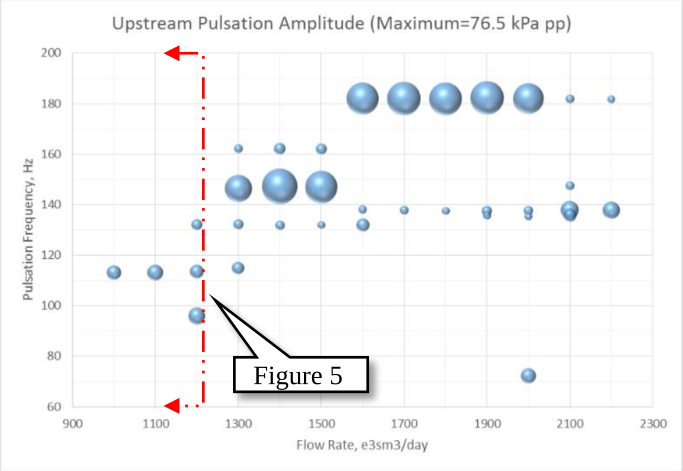

Figure 6. Pulsation amplitude versus gas flow rate (channel 8)

Table 2. Estimate of force due to 76.5 kPa peak-to-peak FIP

Pipe size	Pipe inner area, mm²	Pipe inner area, in²	Maximum force, N peak-to-peak	Maximum force, lb peak-to-peak
8” sch. 120	26188	40.6	2004	451
10” sch. 120	41629	64.5	3186	716
12” sch. 120	58556	96.8	4481	1007

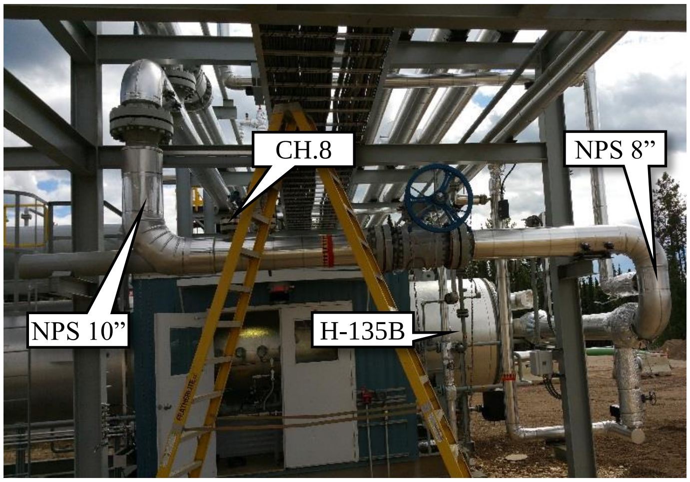

Figure 7. Piping upstream of orifice plate near line heater

In discussions with the owner, it was agreed that no modifications were required to deal with the flow-induced pulsations (FIP) that were measured. The reason was the pulsation and vibration levels were low and not predicted to get worse during the relieving case. Most gas piping system have deadlegs, and most piping systems with deadlegs will have FIPs at certain flow rates. Obviously not all piping systems have vibration problems, therefore some consideration of the pulsation levels should be included in the decision whether to make modifications.

SMALL-BORE CONNECTIONS

Vibration levels on the small-bore connections on the piping system were measured. The maximum vibration on the SBCs near the separator (V-140 in Figure 1) was 11.7 mm/s peak [0.46 in/s peak]. This is below BETA's vibration guideline of 25.4 mm/s peak [1 in/s peak] for small-bore connections and therefore acceptable.

The maximum vibration on the pressure sensor near the line heater (H-135B in Figure 7) was 4.1 mm/s peak [0.16 in/s peak] which is acceptable.

SUMMARY

Gas systems can have pulsations that are created by the piping system itself. These pulsations can cause vibrations and fatigue failure on the piping and small-bore branch connections. Acoustic-induced vibrations are created by pressure reducing devices like valves and restrictive orifice plates, and can cause failure on non-circumferential welds downstream. Flow-induced vibrations are created by deadlegs and can cause vibration of mainline and small-bore piping. A summary of these two phenomena is shown in Figure 8.

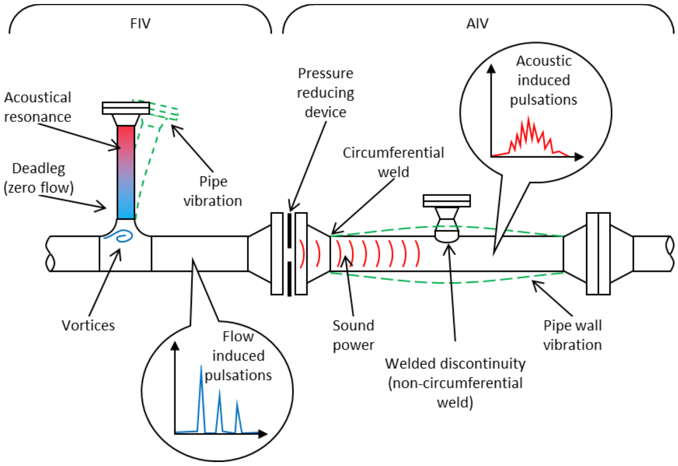

Figure 8. Summary of FIV and AIV in piping systems

ACKNOWLEDGMENTS

The author wishes to thank the gas plant owner who provided details about the piping system and operation conditions, which allowed further investigation to be carried out.

REFERENCES

[1] Energy Institute, Guidelines for the Avoidance of Vibration Induced Fatigue Failure in Process Pipework, 2nd ed., 2008.

[2] F. L. Eisinger, "Designing Piping Systems Against Acoustically Induced Structural Fatigue," *Journal of Pressure Vessel Technology*, vol. 119, pp. 379-383, August 1997.