

# Acoustic-Induced-Vibration Case Study for WDDM Onshore Facilities

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## Summary

In gas applications with high-pressure drops and/or high-velocity gas flow, acoustic-induced vibration (AIV) occurs when very high sound levels are propagated in piping. If the sound levels are high enough, they will excite the circumferential vibration modes of the pipe. This allows the pipe to vibrate in and out as the sound wave moves through the piping. Most often this occurs downstream of pressure-reducing valves or safety-relief valves, but AIV can occur at any location where the pressure drop or mass flow rate is sufficiently large. The level of pipe wall vibration is so high that it can induce fatigue cracking of the pipe and can potentially cause catastrophic pipe failure. The West Delta Deep Marine (WDDM) concession onshore of the slug catcher M9001 had a recent failure in the flare header as result of accumulating AIV effect. As a consequence of this failure Enppi/Burullus and Foster Wheeler have undertaken an engineering assessment study to investigate the risk of AIV for the plant and determine the corrective and engineering solutions to protect the plant from any failure that may occur as a result of AIV. This paper will present a case study as reference for gas-production facilities to consider the AIV application in regard to the design phase, and what might have prevented fatigue of pipes during the operation phase.

## Introduction

The Burullus Gas Company (Burullus) has developed the Scarab/Saffron, Simian/Sienna and Sapphire, and Sequoia and Serpent fields within the WDDM concession and plans to develop further fields there as well. The concession is located offshore Egypt in the eastern Mediterranean.

The WDDM development consists of a number of subsea wells, all of which have differing compositions. The product of these fields feeds three separate subsea tieback pipelines which deliver the three-phase fluid (gas, gas condensate, and water) to the onshore facilities for processing by three separate slug catchers (M-9000, 9001, and 9002).

During a controlled blowdown of the WDDM gas plant, fatigue failure has occurred on the flare header of a 20-in. × 16-in. unreinforced branch of the Slug Catcher 9001, as shown in **Fig. 1**.

A failure of the flare header is downstream of the blowdown valve, and associated restriction orifices during a blowdown are initiated in response to a uninterruptable-power-supply failure.

The company considers a number of actions to be short- and long-term solutions. The first such action was a planned shutdown from 8–13 November 2010 as a measurement investigation was conducted, and a long-term step is to start an engineering assessment

for the plant by Enppi and Foster Wheeler as independent verification bodies.

A forensic metallurgical examination of the failure was conducted and the conclusion was that the root cause of the failure was fatigue cracking, most likely caused by vibration during flare blowdown. The metallurgical report recommended that strain measurements should be undertaken during a plant planned shutdown.

The main effect of this failure was total plant shutdown and a resulting stoppage in production of 1.8 MMcf/d. Action was immediately taken to fabricate and weld another branch, as shown in **Fig. 2**. The failure occurred on 23 September 2010 at 5:30 PM, and production went back online the next day after at 3:30 PM.

## Background

**Acoustic Fatigue.** Experience in the gas production industry has demonstrated that acoustic energy in gas systems with large-volume flows and high-pressure drops can cause severe high-frequency vibrations in downstream pipelines. In some cases, these vibrations have led to fatigue failures after a few minutes or hours of operation. This is generally referred to as AIV.

Acoustic fatigue problems typically occur in the high-capacity safety relief or blowdown systems associated with metering stations, flare systems, and compressor recycle systems.

Design guidelines for the control of AIV have been available since 1985, after the publication of the CONCAWE 85/52 report. The Marine Technology Directive (MTD) published a set of comprehensive guidelines for the avoidance of vibration induced fatigue in process pipework in 1999, which has recently been revised and reissued by the Engineering Institute in 2008.

**Fatigue Failure Risk in Piping Systems.** High-frequency AIV of significant magnitude represents a fatigue failure risk in piping systems, especially those of large-bore piping with relatively large diameter-to-thickness ratios. Such piping systems are at potential risk for fatigue failure at the locations of asymmetric welded points. Symmetric welds represent geometric discontinuities, resulting in stress concentration regions and referred to here as “AIV-critical locations.” These include the following:

- Branch connections
- Small branch connections
- Welded pipe supports

It should be noted that technical research of the failures in pipe works caused by AIV have not recorded failures in straight pipes, considering that the welds are good (i.e., no misalignment, undercut, or other poor joint details). Therefore, straight pipes are not considered as AIV-critical locations, whatever the severity of the sound power level and/or their diameter-to-thickness ratio, as long as circumferential and longitudinal butt welds associated with that straight pipe are acceptable in terms of the criteria set by the applicable piping code.

The assessment also considers the piping integrity mitigation from the AIV and the anticipated fatigue failure for the piping-



**Fig. 1—20-in.×16-in. flare header unreinforced branch after failure.**

system downstream sound power source(s) associated with large pressure-drop devices such as pressure safety valves (PSVs) and restriction orifices (ROs).

The assessment includes the screening of the sound power level (SPL) and the calculation of the likelihood of failure (LOF) at all AIV-critical locations as mentioned previously.

Due to the nature of AIV, time consumed for fatigue failure can be relatively short. The Marine Technology and Energy Institute has

established a set of guidelines for the identification, analysis, and resolution of potential AIV problems in pressure-relief and depressurizing systems.

#### **System Description**

The blowdown system of the slug catcher 9001 comprises seven parallel BDVs and associated ROs which discharge through 16-in. tailpipes into a common 20-in. header, as shown in **Fig. 2**.



**Fig. 2—Seven blowdown 16-in. branches connected to 20-in. header.**

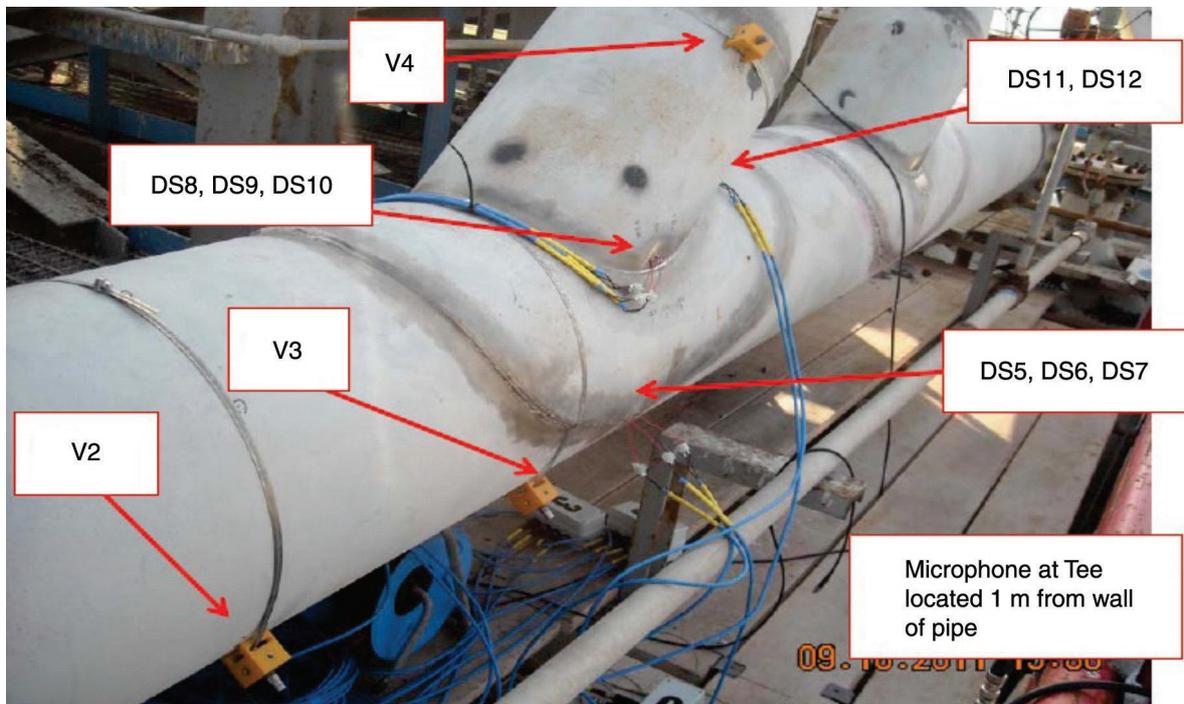


Fig. 3—Measurement survey during blowdown.

### Measurement Survey

Two sets of dynamic measurement were obtained by Veritas, as shown in Fig. 3 during the planned shutdown, and these included:

- Dynamic strain and vibration measurements during plant blowdown to determine the dynamic response of pipework under operating conditions.
- Experimental model measurement performed on the pipework after the blowdown to determine the dominated structural and associated frequencies, mode shapes, and damping.

### Measurement Locations

Two of the 16-in. × 20-in. branch connections were instrumented; at each branch, the following measurements were taken:

- Dynamic strain was measured using one strain gauge located above the weld between the 16-in. branch and the 20-in. header, and one strain gauge located below the weld between the reinforcing pad and the 20-in. header, which had previously failed. The other branch is similar.

### Experimental Model Tests

Experimental model tests were performed on both branches. The tests involved lightly impacting the pipework with an instrumented load hammer and measuring the vibrational response of pipework with triaxial accelerometer. The resulting frequency-response function (i.e., acceleration/force as a function of frequency) is then analyzed to obtain estimates of structural natural frequencies, mode shapes, and damping.

It was noticed that the radial direction of the 16-in. pipe above 500 Hz is approximately 10 times greater than the 20-in. pipe (i.e., 16-in. pipe will respond to a higher amplitude for the same level of applied force than 20: line).

On the basis of survey findings, the following conclusions are drawn:

- Before the commencement of blowdown, dynamic stress levels were low and well within the 35-MPa stress-range criterion.
- During the early stage of the blowdown, stress levels increased, with the majority of measurement locations remaining below the 35-MPa limit.

- After approximately 12 minutes, stress level increased significantly, most likely because of the BDV being fully open, with a maximum amplitude of approximately 150 MPa measured at the weld between the 16-in. branch and the 20-in. header, indicating a very high likelihood of the potential for fatigue failure at this location.
- Experimental model testing has indicated that there is a large model density with a large number of shell-flexural modes present. The 16-in. line appears to be more dynamically mobile above 500 Hz than the 20-in. line when exposed to the same level of excitation.
- The stress response is broadband in nature and indicates a multimodal structural response to broadband acoustic excitation. Local high-order acoustic modes may also play a part in the excitation of the pipe wall, particularly the 16-in. pipework.
- It may therefore be concluded that the failure of the 16-in. × 20-in. branch was caused by the high frequency of accumulated acoustic excitation generated by the RO located in the tailpipe branches.
- It can also therefore be confirmed that the excitation mechanism is broadband high-frequency acoustic excitation generated by high-mass flow rate and large pressure drop across the RO.
- Refer to **Table 1** for PSV tailpipe calculations.

### Surveying Screening Assessment

A screening assessment has been undertaken using the methods outlined in the Energy Institute Guidelines (Hart et al. 2008).

The methodology takes into account:

- The sound power level generated by each valve and the attenuation in sound power level caused by the distance run downstream of the valve.
- The types of connections on the main pipe run that give rise to a welded circumferential discontinuity in the pipe wall, where a fatigue failure will typically occur for high-frequency excitation.

The assessment methodology adopted is as follows:

**TABLE 1—AIV CALCULATION FOR PSV TAIL PIPES**

$P_1$ (bara)	$P_2$ (bara)	$\Delta P$ (bar)	$W$ (Kg)		$T_1$		MW (Kg/Kmol)	Di (in.)	Wt (in.)	PWL (dB)	Allowable PWL* (dB)
			Kg/hr	Kg/s	°C	K					
136	1	135	105880	29.4	30.0	303.0	17.6	12.39	0.18	170.2	170.0
143	1	142	105880	29.4	30.0	303.0	17.6	12.39	0.18	170.2	170.0
91	1	90	27295	7.6	125.0	398.0	17.5	8.325	0.147	159.8	171.5
91	1	90	27295	7.6	125.0	398.0	17.5	8.325	0.147	159.8	171.5
84	1	83	7222	2.0	185.0	458.0	16.43	6.395	0.133	149.3	172.6
84	1	83	6784	1.9	185.0	458.0	16.4	6.395	0.133	148.8	172.6
84	1	83	263182	73.1	50.0	323.0	16.4	12.39	0.18	178.7	170.0
88	1	87	263182	73.1	50.0	323.0	16.4	12.39	0.18	178.7	170.0

Key:  $P_1$ =Set pressure;  $P_2$ =Downstream pressure;  $\Delta P=P_1-P_2$ ;  $W$ =Rated flow rate;  $T_1$ =Discharge temperature; Di=inside pipe diameter; wt+wall thickness+CA (CA=corrosion allowance); MW=Molecular weight; PWL=Sound power level

\*Allowable PWL includes 3 dB. 5dB is added for intermittent operations such as PSVs and BDVs.

For each individual BDV/RO, the source of sound level has been calculated using

$$PWL = 10 \log \left[ \left( \frac{\Delta P}{P_1} \right)^{3.6} \times W^2 \times \left( \frac{T_1}{MW} \right)^{1.2} \right] + 126.1, \dots \dots \dots (1)$$

where  $P_1$  is set pressure,  $\Delta P$  is  $P_1-P_2$ ,  $W$  is rated flow rate,  $T_1$  is discharge temperature,  $MW$  is molecular weight, and  $PWL$  is sound power level.

The sound power level at the welded discontinuity (i.e., 16-in. × 20-in. tee) downstream of the respective BDV has been estimated based on the attenuation caused by the following:

1. Distance
2. Change in pipe cross section
3. The angle of the branch where it enters a header

(Note that attenuations 2 and 3 are not included in the standard Energy Institute method, but have been included here to reduce conservatism.)

Several valve sources are operating at the same time; the total sound power level has been calculated by using the logarithmic addition of individual sound power levels.

The sound power level at each discontinuity has been used to calculate the LOF score at each welded discontinuity; this takes into account the pipe diameter, wall thickness, branch diameter, and type of fitting.

On the basis of a single operational BDV/RO with a mass flow rate of 256 376 kg/hr and a pressure drop 45 bar across the RO, a source sound power level of 177.8 dB is predicted with high 176 dB at the 16-in. × 20-in. tee. The LOF score for the 16-in. × 20-in. tee is 1.45, indicating a high potential for an acoustically induced fatigue failure.

**Potential Modifications Required**

There are a number of potential modifications that could be considered to reduce the dynamic stress levels and hence increase the system-fatigue life.

Because of operational constraints, it is understood that reducing the flowrate through the ROs is not practical, and therefore a reduction in sound power level by this means is not feasible.

On the basis of the source of sound level for one BDV/RO (maximum PWL of 178 dB), the following piping modifications should be considered in addition to the immediate action that was taken to install another 16-in. × 20-in. branch:

- For the tailpipe and header, schedule 80 pipe should be used. This is predicted to reduce the LOF score to 0.72 for the same sound power level. Note the extent that the 20-in. header would need to be upgraded to schedule 80 will depend on what is further accomplished and which welds are required.

- For the 16-in. × 20-in. tee, use a one-piece forged 45° tee if possible; this will remove the weld line at the fatigue sensitive location so that only three circumferential welds are required.

**AIV Assessment Methods**

After site survey work, Enppi/Foster Wheeler began an AIV engineering assessment for the WDDM onshore slug catchers. This assessment consists of a number of steps for the calculation of sound power level and the determination of the LOF at the AIV-critical locations in the piping system. These steps are as follows:

- Calculate the sound power level at every noise source (PSV or RO) knowing the associated process conditions such as pressure drop and flow rate. If the sound power level at the noise source is less than 155 dB, then AIV mitigation is not considered necessary.
- Calculate the sound power level at each location in the piping system by considering sound power level attenuation caused by the flow in the downstream piping. Referenced guidelines are usually approximately 3 dB for every 50 diameters downstream of the sound power source.
- Calculate the sound power level owing to “addition” of two different sound power sources when they meet at branch connections.
- With the sound power levels at all AIV-critical locations in the piping system having been calculated, the LOF at those locations are then calculated based on the geometric parameter of the piping elements (diameter, thickness, branch connections, small Branch connections, and/or material) per the referenced guidelines.
- AIV screening of the existing piping system without any additional reinforcement has been checked for lower noise-restriction orifice. For a restriction orifice with a downstream maximum noise level of 156 dB when subjected to 133 bar upstream pressure, the LOF at all AIV-critical locations will be much less than 0.5. In this case, the existing piping system requires no further modification. Results of a survey of restriction-orifice vendors has demonstrated a positive answer for technically feasible multistage or multihole restriction orifices that can handle the 133-bar upstream process conditions while producing much lower noise levels than 156dB.

The AIV assessment described here produces quantitative evaluation of the piping-system integrity in terms of LOF. AIV calculations done on the piping systems are based on upset pressure, temperature, and flow rates.

**AIV Assessment Results**

The AIV assessment found the sound power levels are acceptable from some piping systems but are not acceptable for others in terms of the calculated LOF at each AIV-critical location in each piping.

The following technical solutions have been considered after investigation to reduce the risk of AIV:

- The use of conventional joint reinforcement can be used to greatly reduce the risk of AIV.
- The extent of reinforcement added could be reduced if a risk assessment is made against the likelihood of the release and the predicted number of acceptable cycles.
- If additional reinforcement is applied, a B31.3 analysis should be undertaken to ensure that no support modifications are required.
- The use of a multihole orifice plate has been proposed, which is intended to reduce the noise levels below the 156-dB AIV threshold.
- If low-noise ROs are used, the supplier must provide a guaranteed maximum noise limit for the RO and perform a shop test if at all possible. If this is not possible, it is recommended that noise-level measurements are taken onsite.

The following requirements are recommended to improve the blowdown piping integrity with respect to AIV:

- All branch connections on the main or subheaders downstream from the sound power sources should be fully reinforced.
- Special attention should be given to the lines downstream from the PSVs, where welding tees should be replaced by a minimum schedule 80 tees, and weldolets at nodes should be replaced with 6000# socket-welded couplings.
- For hydro test vent and drain connections, valves and nipples (if any) are to be removed and replaced with a seal-welded plug.
- All small-bore branch connections (1.5-in. NPS and smaller) should be 6000# socket-welded couplings.

All welds associated with the previously mentioned recommendations and requirements should be of a very good quality to avoid any source of stress concentration by considering contouring of fillet weld toes and avoiding any weld undercutting. Those corrective actions exhibit high LOFs for higher upstream pressures

of 133 and 68 bars. The associated number of cycles for failure is on the order of 1.5 and 15 million cycles for 133- and 68-bar upstream pressures, respectively.

For an average vibration frequency of 1,000 Hz during any probable blowdown, the time for failure can be estimated as 25 and 250 minutes for 133- and 68-bar pressures, respectively. Because the 133-bar pressure is not likely to occur, unless accidentally, and the 68-bar pressure is likely to occur during the next few months with the normal reasonable normal frequency, the previously mentioned corrective actions can survive for an accidental severe blowdown with 133-bar pressure and the frequent 68-bar pressure blowdown during the next few months.

## Conclusion

AIV assessment is highly recommended to be considered during design phase for the compressors' discharge lines, flare headers and flare tailpipes.

## References

- Hart, K., Brooks, S., Evans, G. et al. 2008. Guidelines for the Avoidance of Vibration Induced Fatigue Failure in Process Pipework, second edition. Technical Publication, Energy Institute, London (January 2008).
- Joint Industry Project. 2000. Guidelines for the Avoidance of Vibration Induced Fatigue in Process Pipework. Technical Publication No. 99/100, Marine Technology Directorate, London (April 2000).

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