ACOUSTIC AND TURBULENCE/FLOW INDUCED VIBRATION IN PIPING SYSTEMS

A REAL PROBLEM FOR LNG FACILITIES

Jim Cowling
Chief Technology Engineer – Noise & Vibration
KBR
Houston, Texas, USA
jim.cowling@kbr.com

ABSTRACT

Within the small community of flow and acoustic induced vibrations (FIV and AIV) subject matter experts, there is general awareness of FIV and AIV failures in LNG liquefaction plants that have had major safety and economic consequences. The challenge facing the LNG industry is that FIV and AIV do not receive a consistent and/or required level of attention during the design phase of projects to ensure both a safe and fit for purpose design.

FIV and AIV are known phenomena affecting piping systems in LNG facilities. These vibrations, driven by flow velocity and flow rate, can result in significant fatigue failures in piping systems. While safety concerns are obviously paramount whenever an LNG piping failure scenario is considered, the economic impact of lost production must be factored into the overall risk analysis.

This paper will provide a review of FIV and AIV design concepts relevant to the LNG industry, along with the screening tools and design options available. The paper will also discuss the recent efforts by API and the Energy Institute to establish design standards and requirements for FIV and AIV. In the context of an LNG project, options will also be discussed to find the sweet-spot in the schedule when the analysis and design modifications can be executed while minimizing impact to cost and schedule.

INTRODUCTION

Acoustic and flow, or turbulence, induced vibration (AIV & FIV) affecting process piping systems are phenomena that have been known to the general hydrocarbon process industry since the late 1970s. Certainly we have the landmark Carucci/Mueller AIV paper from 1983[1] that first introduced acoustic induced vibration to the industry. FIV has plenty of history affecting small bore connections, particularly on offshore projects but, FIV hasn’t necessarily been given the same systematic attention as AIV. Both AIV and FIV can be described and analyzed as different independent flow induced vibration phenomena. AIV is generated by turbulence and shock waves immediately downstream of a high flow rate, high pressure drop pressure reduction device and generates high frequency circumferential vibration in the piping. FIV is a nominally low frequency phenomena caused by high flow velocities and turbulence at branch connections, bends etc. that excites low frequency bending modes in the piping.
This paper is focused on AIV and the potential risk for LNG liquefaction facilities, but if the flow conditions at a pressure reduction device are right for AIV then the lower frequency FIV vibration can also be present and needs to be considered in the analysis and design. One of the clear lessons is that AIV modifications will also protect against FIV and optimization of AIV piping modifications and design which ignores FIV is putting the subject piping systems at risk.

Within the LNG industry there is little published documented history of piping failures due AIV/FIV. This is quite understandable; there isn’t a real incentive to publicize failures. But, particularly with in the relatively small group of AIV subject matter experts, there are known incidents of piping vibration in LNG piping that can be attributed to AIV that have resulted in failures with significant and far reaching operational and economic consequences.

The goal for this paper is to get the AIV message out to the broader LNG community and increase awareness of this important phenomenon with significant associated risks for LNG operators. Options for AIV screening and analysis will be considered from the engineering contractor’s perspective, with particular emphasis on the diameter to thickness ratio (D/t) of the piping and the selection of appropriate pipe connection fittings. Schedule issues associated with AIV analysis and their impact on AIV analysis and design decisions will also be discussed. The engineering contractor has to be able to identify systems at risk early in the project schedule and then have reliable analysis methods to decide on appropriate piping design modifications to deliver a robust, safe and fit for purpose final plant design. The engineering contractor must find the “sweet-spot” in the schedule when AIV can be effectively analyzed and the design optimized at minimum cost and schedule impact.

BACKGROUND – ACOUSTIC AND TURBULENCE/FLOW INDUCED VIBRATION IN PIPING SYSTEMS

Both AIV and FIV are flow induced vibration phenomena that can result in fatigue failures in piping systems.

ACOUSTIC INDUCED VIBRATION (AIV)

AIV is driven by flow rate and pressure drop and tends to affect large capacity relief, depressurizing and blow-down systems. The pressure restriction device, often with critical pressure drop, causes turbulent mixing and shock waves immediately downstream of device that tends to generates high frequency (500-2000 Hz) acoustic energy, which propagates down the pipe as an acoustic wave with higher order modes. This generates circumferential vibration in pipe wall with no visible pipe movement that can result in fatigue failures at asymmetric piping discontinuities (branch connects, welded pipe supports etc.) that act a points of stress concentration or intensification. Fig.1 shows a representation of the high frequency circumferential shell modes at a branch connection from KBR finite element analysis.

The pressure reduction device produces an area of turbulent mixing with shock waves immediately downstream of the device. As explained in much of the early experimental work by Norton and summarized in Norton’s excellent text book[2], the acoustic energy in this immediate area close to the pressure reduction device are due to an intense non-propagating sound field (turbulence and shock waves). This sound field decays with distance, nominally ten diameters,
and results in acoustic energy propagating down the piping as a plane wave together with higher order modes. This acoustic energy excites the high frequency circumferential mode vibration affecting asymmetric discontinuities in the piping (branch connections, small bore connections and welded pipe supports) at a distance from the pressure reduction device. These asymmetric discontinuities act as points of stress intensification for this shell mode vibration.

The important point with the higher energy levels in the area immediately downstream of the pressure reduction device (i.e. with ten diameters) is that this energy will also introduce circumferential vibration in the pipe wall that has the potential to propagate structurally within the piping itself and affect the first asymmetric connection in the system, typically the discharge lead connection to sub-header or header.

This effect can be further compounded by the potential for additional FIV excitation, discussed earlier, emphasizing the risk and importance of adequate reinforcement and modifications for this first branch connection in the system.

TURBULENCE/FLOW INDUCED VIBRATION (FIV)

FIV is driven by flow velocity ($\rho v^2$) and results from turbulent mixing with boundary layer separation and pressure pulsations at bends, tees, reducers etc. This results in shaking forces at the bend, or tee, that generates low frequency (<100 Hz), longitudinal beam mode vibration in the piping with visible pipe movement or shaking. FIV tends to affect smaller diameter low frequency vent systems.

AIV SCREENING OPTIONS

CARUCCI/MUELLER

The Carucci/Mueller[1] paper was based on field data for AIV fatigue failures in high capacity pressure reduction systems (relief systems, compressor recycle, depressuring systems etc.). Thirty six cases were considered for systems with high vibration that either failed, or did not fail,
together with comparable systems that had no abnormal experience. Using this data Carucci/Mueller produced a safe design curve shown in Fig. 2 that plotted calculated internal pipe sound power level against nominal pipe diameter for the range of the systems evaluated.

![Carucci/Mueller Safe Design Curve from 1985 ASME paper](image)

**Fig. 2 – Carucci/Mueller Safe Design Curve from 1985 ASME paper**

The Carucci/Mueller material was adopted and further publicized in 1985 by CONCAWE[3], the oil companies’ European organization for environment, health and safety. The CONCAWE publication also provided the equation below for the calculation of the internal pipe sound power level.

\[
L_w = 10 \log \left[ W^2 \left( \frac{\Delta P}{P_2} \right)^{3.6} \left( \frac{T}{MW} \right)^{1.2} \right] + 55
\]

Where: 
- \( L_w \) = Internal pipe sound power level (dB)
- \( P_2 \) = Downstream Pressure (Bar abs)
- \( W \) = Flow rate of the gas (kg/hr)
- \( T \) = Temperature of upstream gas (°K)
- \( \Delta P = P_1 - P_2 \) = Total pressure drop (Bar)
- \( MW \) = Molecular weight

Notes: 
1. Legend: ▲ Acoustically Induced Failures (Data From Table 1)  
   ▼ Severe Vibrations, But No Failures (Data From Table 1)  
   ○ No Abnormal Experience (Data From Table 2)
2. Point f Failure Attributed To Severe Weld Undercutting At A Small Connection. 
   No Abnormal Experience After Quality Welds Achieved.
3. All Data Points Are 6.0 mm (0.315") Or Less Wall Thickness, Except For Points B And 16 
   Which Are 9.5 mm (0.375") Wall Thickness, And 27 Which Is 11.0 mm (0.469") Wall Thickness.
\[ P_1 = \text{Upstream pressure (Bar abs)} \]

The Carucci/Mueller calculation methodology and design curve form the basis for most AIV screening methods in the industry today. For example, the API 521\(^4\) standard for pressure relieving and depressuring systems recently included a section on AIV and recommended screening methodology based on Carucci/Mueller. Also, the original Carucci/Mueller paper represents the only collated source of failure information on AIV. Other AIV induced piping failures have occurred, but this material has not been released in the public domain.

**ENERGY INSTITUTE**

In 1999 the Marine Technology Directorate (MTD) in the UK published Guidelines for Avoidance of Vibration Induced Fatigue in Process Pipework\(^5\). In 2008, the Energy Institute (EI)\(^6\) in the UK revised and reissued these guidelines. The EI screening procedures for AIV are again based primarily on the Carucci/Mueller internal pipe sound power level calculation and design curve. They expand the assessment to include consideration of fatigue life curves for a range of pipe fitting and piping material. Also, extending the application of EI screening to higher energy systems can lead to impractical or heavily over designed systems.

EI screening produces a likelihood-of-failure (LOF) number that defaults for 1 for any system screened at LOF of 1 or greater. Systems with an LOF=1 are deemed to be at risk and need to be redesigned. Tests of the EI LOF calculation for a range of pipe diameters with simple stub-in branch connections show that an LOF=0.5 closely following the basic Carucci/Mueller safe design curve and an LOF=1.0 follows the Carucci/Mueller curve plus approximately 7 dB.

The EI guidelines discuss all of the usual piping modification options for systems in AIV service; increased pipe wall thickness, using forged tees, sweepolets\(^\text{®}\) connections and full circumferential reinforcement of branch connections together with bracing for small-bore connections. But, the EI guidelines do not give guidance and direction when and how these piping modifications should be applied in systems identified at risk from AIV. It is important to remember that the EI guidelines are a screening tool and not a design tool.

**EISINGER**

Eisinger’s 1997\(^7\) and 1999\(^8\) papers looked at the original Carucci/Mueller data using a system energy assessment based on downstream Mach number and \( \Delta P \). Eisinger also considered the pipe diameter to wall thickness ratio (D/t) rather than the simple nominal pipe diameter used by Carucci/Mueller. Eisinger’s plots this as simple straight line, but the Eisinger material includes some discrepancies\(^9\) with some data point plotted incorrectly compared to Carucci/Mueller. The D/t versus sound power level plot with the points plotted at their correct sound power levels as reported by Carucci/Mueller is not a straight line and Eisinger’s straight line with a known failure point below the fatigue limit straight line cannot be accepted and used by the industry.

A further complication when considering the original Carucci/Mueller data are Points B1 and B2 that actually refer to only one failure\(^7\). This was a failure on a 10”x28” branch connection where there was a secondary choke at the branch connection. Carucci/Mueller plotted this same failure as two points plotting Point B1 against the 10” diameter discharge lead from the valve and Point B2 against the 28” diameter header. A convincing case can be developed to argue that the Point B1 should not be plotted and the Point B failure should be represented by only the adjusted
Point B2 sound power level to reflect the additional choke at the branch and then plotted against the 28” header diameter.

If the Point B1 is taken out of consideration then there is considerable doubt regarding how the D/t versus sound power level curve behaves for D/t ratios below 64. Carruci/Mueller report no failures for a D/t ratio below 64.

**FIV SCREENING**

The Energy Institute Guidelines\(^6\) provide the most useful source of screening options for FIV in the public domain. Energy Institute FIV screening is based on dynamic pressure \((\rho v^2)\) together with Energy Institute developed FIV factors that consider pipe diameter, wall thickness and a range of pipe flexibility. The Energy Institute FIV screening provides a likelihood-of-failure assessment that can then be used to consider piping design and flow/pressure control options for the identified piping systems at risk.

There are a number of issues to be considered when using the Energy Institute Guidelines because they are primarily a screening tool and not a design tool. Care must be taken when assessing a modified design in the context of the Energy Institute because full credit may not be given to increased mechanical integrity of a particular branch connection (e.g. reducing tee). KBR has direct experience\(^{10}\) where a modified piping design had been shown to be fit for purpose through detailed FEA yet the basic Energy Institute screening for FIV still showed a likelihood-of-failure exceeding one.

The Energy Institute FIV screening points towards increasing piping stiffness to reduce the likelihood-of-failure, but, again, care must be taken with this approach to ensure that the impact on thermal stresses is also considered.

KBR uses a similar proprietary \(\rho v^2\) based screening tool for FIV. KBR’s approach also includes a calculation of the predicted FIV shaking forces and hence predicted stress levels that can be factored in the assessment and design or required FIV piping modifications.

**AIV PIPING DESIGN OPTIONS**

Design options to improve a piping systems strength and integrity in the context of AIV excitation must focus on points of asymmetric discontinuity. As discussed earlier, these include branch connections, welded piping supports and small bore connections.

**STRESS INTENSIFICATION FACTORS**

In the context of both AIV and FIV excitation, the objective of piping design focuses on branch connections and especially at associated weld points which represent asymmetric discontinuities. The intention should be to reduce the stress intensification at these locations, thus improving the overall structural integrity of the piping system. Work by Karczub and Fagerlund\(^{11,12}\) has addressed dynamic stress prediction and fatigue life design factors for AIV in piping systems. KBR has also carried out extensive finite element analysis (FEA) on piping
connections\cite{13} assessing and ranking various piping connection options in the context AIV and resulting stress levels.

The normally accepted stress intensification factors taken from ASME codes are typically based on uniform loading. KBR FEA stress analysis considered a range of pipe fittings, while indicating similar trends to those reported by Karczub and Fagerlund, did also indicate that differences in stress intensification factors exist for uniform loading versus correlated loading, where the pressure distribution is proportional to the piping modal distribution. If AIV stress analysis is to be extended to meaningful fatigue life analysis in piping systems then research will be required to provide appropriate stress intensification factors for partial or fully correlated loading.

**PIPING DESIGN MODIFICATION OPTIONS**

KBR carried out FEA analysis to assess the effects of increasing the pipe wall thickness (i.e. reducing \(D/t\) ratio). This work produced similar proportional ratios and trends to those reported by Karczub and Fagerlund. The work also concluded that doubling the wall thickness decreased the stress by a nominal factor of two.

The stress reductions resulting from increasing the wall thickness and hence the \(D/t\) ratio are clear. However, there may be hesitancy to include the heavier walled pipe early in a project because of the increased cost. Balanced against this increase in cost, the following benefits should also be considered. Having pipe wall thickness already in place allows the use of swept and contoured fitting and avoids the late additional costs and field welding time/cost of adding locally heavier wall pipe to provide an adequate \(D/t\) ratio for the swept fitting or changing to wrought or forged tees.

The piping design modification options to improve the structural integrity of a piping system at the known asymmetric points of weakness would include; forged or wrought tees (Fig. 4), swept, or contoured connections (e.g. sweepolets\textsuperscript{\circledast}) (Fig. 5) and full-wrap reinforcement (Fig. 7). In addition all small bore (2” NPS and below) connections should have a contoured insert couplings and be braced in two perpendicular planes. Also, welded pipe support shoes should be replaced with clamped on shoes, or the shoes should be welded to a full encirclement band.
Fig. 4 – Forged, or Wrought Tee Connection

The benefits of the forged tee are straightforward; the forging wall thickness can match an acceptable D/t ratio, dependent on the AIV energy and all the welds are axisymmetric and full NDT can be performed.

Fig. 5 – Swept, or Contoured Pipe Connection (sweepleot®)

The stress intensification factors for a swept or contoured fitting are significantly reduced compared to a simple stub-in connection or a weldolet® connection. Other benefits include that the wall thickness will match the D/t ratio of the pipe, again determined based on the assessed AIV energy and the welds can be subjected too full NDT inspection. Another important benefit is that the swept nature of these connections means that the highest stress levels on this type of connections is remote from the welds. Fig. 6 shows stress plots for a sweepolet® connection in AIV service from KBR’s FEA analysis that shows the highest stress level well away from the connection welds.

Fig. 6 – Example Stress Plot for Sweepolet® in AIV Service
Fig. 7 –Pipe Connection with Full-Wrap Reinforcement

Full-wrap reinforcement at a stub-in connection increases the wall thickness locally resulting in a subsequent reduction in stress levels. Also, the full-wrap reinforcement changes the connection from the asymmetric connection to an axisymmetric connection. It should be noted that partial reinforcement pads would be considered asymmetric and not beneficial in AIV service unless the piping had an adequate D/t ratio for the AIV energy levels in play.

Weldolet® connections are not recommended for AIV service. The sharp angles between the pipe and weld, resulting from the weldolet® design (Fig. 8); result in high stress intensification factors. This renders branch connections using this type of fitting more susceptible to fatigue cracking in AIV service. Also, due to the fillet weld connections, as opposed to butt weld connections, the weldolets® cannot be fully inspected using ultrasonic or radiographic techniques.

Fig. 8 –Weldolet® Connection

For small bore connections, often with unsupported weight in the form of valves and flanges, protection from two sources or vibration must be considered; these will include the normal circumferential piping vibration associated with AIV together with cantilever vibration that can be generated by both AIV and FIV excitation. Therefore, in addition to considerations for D/t at the connection and the type of connection, with swept or contoured fitting being preferred, the small
bore connection must also be adequately braced in two perpendicular planes to protect against the cantilever vibration.

**KBR AIV SCREENING AND PROJECT SCHEDULE**

KBR’s approach to AIV screening is based on basic Carucci/Mueller screening leveraging our previous project experience applying AIV analysis and piping modifications since 1994. In addition, we also draw on finite element studies for piping systems and connection arrangements in AIV service. As discussed earlier, piping design modification will vary depending on system energy and piping configuration. KBR’s general approach is have a D/t<64 in the high energy systems and provide additional mechanical integrity by also using a combination of forged, or wrought tees together with the use of swept or contoured (e.g. sweepolet®) connections when appropriate. All small bore connections are also contoured fittings and fully braced in two perpendicular planes. When appropriate, all pipe supports are clamped, or welded to full circumferential bands.

LNG industry projects are, and will continue to be, under relentless pressure to reduce the schedule. For major LNG liquefaction projects, piping bulks are sourced worldwide, with multiple piping suppliers involved in staged delivery linked to construction schedules, lay-down availability and shipping schedules. The piping material purchase orders are evaluated and committed early in a project; coming back late in a project to change the wall thickness of a major flare header because of AIV analysis is not an option.

For effective implementation on an LNG project, KBR experience has shown that major AIV decisions, such as main flare header and sub-header wall thicknesses, must be made early during basic engineering. Therefore, this approach must include necessary conservative margins to ensure that early design decisions are thorough and robust. The reduced schedule risk in setting piping wall thickness and branch fitting requirements early outweighs the potential of specifying a few additional forged tees or reinforced branch connections or relatively small additional lengths of heavier wall header piping.

At KBR, we have seen FEED or basic engineering packages for major world scale LNG developments with no consideration at all for AIV. Thin walled flare headers and sub-headers from these packages become part of the material take-off and lump-sum pricing for the project and lead to serious consequences later in the project. At best, this results is rework and project change orders, but at worst there is the potential that these AIV issues are not adequately addressed during detailed engineering and the project moves to start up with a significant risk of AIV issues and potential pipe failure and loss of containment.

**ENERGY INSTITUTE JOINT INDUSTRY PRACTICE FOR ACOUSTIC INDUCED VIBRATION**

Following a very productive special one day technical session on AIV at the InterNoise 2012 conference in New York City, a Joint Industry Practice (JIP) committee was formed specifically to look at AIV for the process industry. The JIP is managed by the Energy Institute in the UK and members include significant players in LNG covering both plant owners and engineering contractors together with specialist consulting companies.
The main Phase 1 activity for the JIP has been setting up a test rig at the Emerson Innovation Center: Fisher Technology Flow Lab consisting of a relief valve discharging though a 12” diameter discharge lead in to a 20” header. This representative configuration can produce Carucci/Mueller sound power levels in the low 170’s dB at the relief valve discharge. Different connections in to the header (stub-in, stub-in with full wrap, weldolet® and sweepeolet®) together with different small bore connection and bracing options at various locations will be tested. Fig. 9 shows a photograph of an instrumented stub-in connection on the test rig with both strain gauges and accelerometers. In addition the test facilities include the capability of making internal pipe sound pressure level measurements to assess the internal sound field for the test conditions. In parallel to the testing effort several JIP members are conducting finite element analysis and computational fluid dynamic (CFD) analysis of the test rig for comparison with experimental data.

Any organizations involved in the LNG business, particularly plant owners, are encouraged to consider supporting the AIV JIP. Cameron Stewart (cstewart@t-eal.com) at the Energy Institute can assist with any questions relating to the JIP.

![Fig. 9 – Instrumented tee connection on JIP test rig at Emerson Innovation Center: Fisher Technology Flow Lab](image)

**CONCLUSIONS**

AIV and FIV are significant issues for LNG projects. Anything that introduces a risk of piping failure and loss of containment has to be a major concern. An incident of this nature has far reaching and potentially disastrous implications affecting safety, plant operation and production and the overall economics of the project.

Screening tools are available, usually based on the original Carucci/Mueller work, and these are included in published guidelines and in some plant owner specification and standards. The problem is that screening methodologies have not been extended to design tools for the selection and deployment of piping design modifications for AIV.
There is a good body of published material addressing and ranking piping modifications that include increasing pipe wall thickness, connection modification, tees, swept or contoured fitting and local branch reinforcement together with contoured connections and branch reinforcement for small bore connections. For the actual implementation of these design options, when/where and how much, there are currently more questions than answers. The current JIP effort will hopefully advance the industries understanding and capabilities for AIV analysis and design and participation in the JIP is encouraged for players in the LNG business. In the meantime design must rely on the experience and capabilities of a relatively small group of subject matter experts spread across operating companies, engineering contractors and specialist consultants.

For many current LNG projects we see newer and smaller entities entering the LNG market that perhaps don't have the specifications and standards experience and resources of the traditional “major” oil/gas companies. For these projects the onus on addressing AIV/FIV falls on the engineering contractors and specialist consultants to step up and ensure that AIV/FIV is fully and correctly addressed. Also, based on KBR’s experience, the importance of addressing AIV/FIV at the right time, early in the project schedule, cannot be underestimated. KBR has performed FEED verification on a number of LNG projects for which the FEED contractor gave no consideration for AIV/FIV screening or mitigation; a potentially costly and significant omission.

REFERENCES

5. Marine Technology Directorate, "Guidelines for the Avoidance of Vibration Induced Fatigue in Process Pipework" 1999 (MTD Publication 99/100)