Better design, smarter monitoring – managing vibration induced fatigue

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Introduction

Though the incidence of pipework failure subsea is rare, the consequences can be catastrophic. Until a few years ago, vibration induced fatigue was not considered a major threat to the integrity of subsea systems, but as flow rates increase, and the need for flexibility and mobility in the piping to accommodate the impact of HPHT becomes a key design requirement, so vibration is now being carefully considered, with subsea engineers taking the dilemma back to the drawing board.

There are a number of different aspects and challenges associated with vibration induced fatigue as an integrity issue subsea. Assessment of subsea systems has largely been limited to vortex induced vibration (VIV) of riser systems and unsupported pipeline spans (i.e. vibration caused by environmental loading) due to flow past the outside of a riser, conductor or pipeline. Piping vibration due to process excitation has only now started to become a recognised issue on manifolds and jumpers, in part associated with increasing production rates leading to higher fluid velocities. As well as piping integrity issues, additional vibration related problems have also been experienced with valves and instrumentation.

Published data suggest around 20% of pipework failures (topsides) which lead to hydrocarbon release may be caused by vibration induced fatigue. To date, on subsea systems, the number of actual failures has been much lower, although there have been a number of instances of high levels of vibration being experienced which have resulted in a lowering of production rates until a fix was put in place. Though the likelihood of a failure is low, the consequences of a failure can be high, resulting in an unacceptable level of risk.

Internal flow induced excitation mechanisms

There are a number of different sources of 'process-driven' excitation and these will generally depend on the type of process fluid within the system. The most common mechanisms are:

Flow induced turbulence

This is caused by broad band low frequency energy, generated by 'single phase' turbulent flow through valves, expansions and bends – essentially anything that disturbs the flow. This can lead to excitation of the low frequency modes of the piping system by energy transfer from fluid momentum to the pipe, resulting in low frequency vibration (although 'low frequency' in this context can mean frequencies of up to perhaps 50 cycles per second). This type of excitation is widespread in most processes and the level of excitation will depend heavily on the velocity and density of the process fluid as well as the flow path.

Multiphase flow

This is an area with a degree of uncertainty due to the known complexities associated with multiphase flow (which encompasses slug, bubble, annular and churn flow). Generally the excitation contains broad band low frequency energy, the characteristics of which are heavily dependent on void fraction and flow regime.

Figure 1 shows typical empirical data for excitation due to multiphase flow (as derived by Riverin et al on a small scale test loop), and illustrates the different force spectrum characteristics and how they vary as a function of void fraction, flow regime and (non-dimensional) frequency.

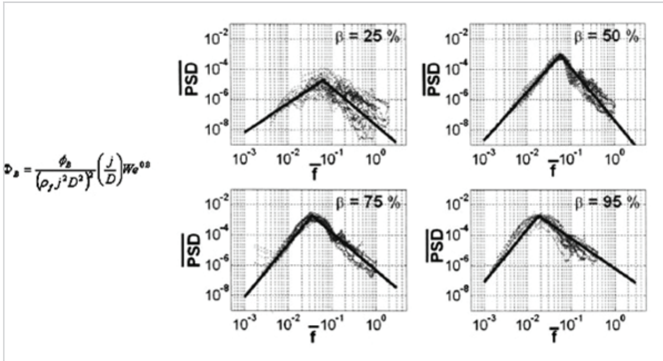

Figure 1 – Empirically derived forcing spectra for multiphase flow.

Flow induced pulsation

This is linked to gas flow through a flexible riser or jumper, and is sometimes known as the 'singing riser'. This is where gas flow across the internal corrugated geometry within the flexible causes vortex generation; this causes a pressure fluctuation (or pulsation) with a frequency and amplitude which are dependent on the gas velocity. This pulsation can then drive the piping systems at either end of the flexible at very high frequencies – in some situations up to 1000 Hz, meaning that fatigue damage can accrue very quickly. The phenomenon is typically only experienced on dry gas systems, so it can be an issue on gas export, gas injection and gas lift systems ▸

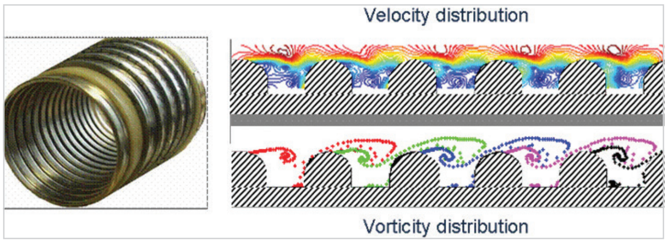

Figure 2 – Vorticity generation due to flow across a corrugated liner.

The hidden threat

Piping design and construction can present a number of unique challenges in the subsea environment given its remoteness and complexity to access; a vibration issue may occur subsea without any obvious sign topsides.

One of the key challenges is the practical difficulty of obtaining measurements on existing equipment which is on the seabed. This can be very expensive, usually requiring a dive support vessel to be on station to deploy and recover the monitoring instrumentation. For fatigue assessment, direct strain measurement would usually be preferred, but this is often impossible on subsea equipment (e.g. manifolds, FTAs and PLEMs) that has already been deployed. In practice, subsea engineers often have to rely on the measurement of vibration accelerations at non-ideal locations and infer the fatigue damage of the system by linking the measurement data with a suitable simulation.

Figure 3 – Accelerometer attached to a subsea piping system.

Another challenge relates to the often limited real-time capability of the measurement instrumentation. Fatigue damage can be accrued relatively quickly given the relatively high response frequencies, and the delay which often occurs between a measurement being taken and the subsequent recovery and analysis of the vibration data – in some cases perhaps days, or even weeks after the measurements have been obtained – can build in an unacceptable level of risk.

New industry guidance

To counter some of these problems, international energy consultancy Xodus Group has acted as the technical author of a new Energy Institute document due to be published shortly, which has also included input from a wide variety of operators, equipment designers and consultants. The purpose of this initiative was to build on the topsides version of the Energy Institute guidelines for piping vibration – which already provides a risk based methodology and good design practice – and tailor an approach specifically geared to subsea equipment. The latest Energy Institute guidance, which is due to be published this summer, is focussed solely on subsea equipment. In order to achieve a fatigue resistant design, there is a step-by-step approach (Figure 4) to identify and address potential issues early in the design cycle.

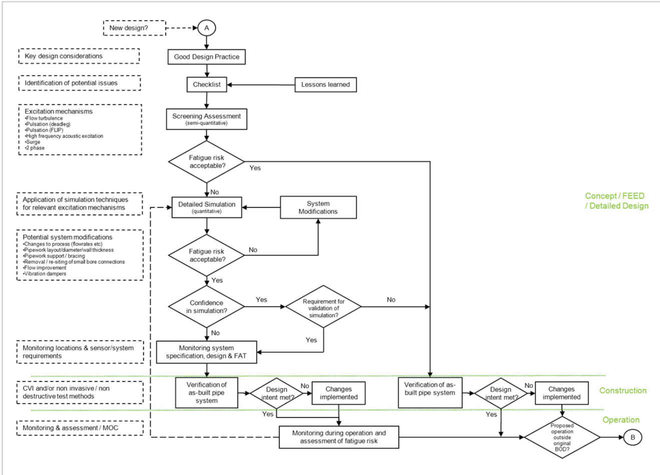

Figure 4 – Design stage assessment process.

The key elements are as follows:

Definition of good design practice

This includes guidance on the design, layout and support of the process piping, the type of fittings to be used and how branch connections should be made, as well as advice around the specification and selection of rough bore flexibles.

Initial risk assessment

For the initial risk assessment a series of screening methods are used. These screening methods, using information from P&IDs, process flow diagrams and in some cases piping isometrics, take each of the common excitation mechanisms and identify whether there are any hot spots on the build being assessed, taking into account how the piping will respond dynamically, not just statically. The methodology essentially uses a series of algorithms and process and piping information to ascertain a Likelihood of Failure (LOF) score for each excitation mechanism and then actions are determined depending on the LOF score. The methods can be used to check the sensitivity to changes in the process conditions and/or gross structural parameters (pipe diameter, wall thickness, degree of support etc).

Detailed simulation

If the fatigue risk is not acceptable, then guidance is provided on how to perform a detailed fatigue simulation for a variety of excitation mechanisms. Once the level of excitation is predicted (using empirical, analytical or CFD techniques), a finite element model is then created to assess the response of the piping in terms of the vibration acceleration and dynamic stress across the structure. This requires knowledge of the piping system layout, supports, process conditions and structural boundary conditions. The results not only provide an assessment of the fatigue life under certain operating conditions (and also the effect of varying those operating conditions), it also helps identify the most suitable measurement locations for the placement of vibration measurement sensors for any subsequent monitoring activities. However, across the oil and gas industry, better validation data is required to ensure that simulation methods are accurate, particularly when the excitation is generated by multiphase flow.

Monitoring system specification

There are some key considerations when specifying the monitoring system to ensure that useful data is captured. These include the frequency bandwidth that is required and instrumentation dynamic range, as well as the phase relationship between sensor pods and how transducers will be installed and mounted to various parts of the structure. Most importantly, how the data will be recovered and used.

One of the recurring problems is the issue of 'sparse data' – in other words not being able to install a large number of sensors as perhaps would be feasible on topsides facilities. Therefore the usual approach is to use this limited data, combined with the simulation, to predict the overall response to the structure in terms of the stresses at locations where it is difficult to obtain measurements. This is a complicated subject which requires further development, although analytical methods do exist to (i) help identify the optimum sensor fit and (ii) provide a means of using this 'sparse' data to obtain a pseudo stress time history anywhere on the structure.

Verification

The new Energy Institute guidance also identifies the verification steps required at the construction stage to ensure that what is built correlates with the original design intent, particularly aspects such as piping supports which have an important bearing on the vibrational response of the system. Verification may also include non-intrusive modal testing of the piping systems and associated support structures; this will help provide validation data for any previous simulations. If used with temporarily installed strain gauges, this type of testing in the construction yard can also provide useful information about the relationship between the vibration acceleration at locations where measurements will be made subsea, and the dynamic stresses at potential fatigue hot spots which could not be monitored subsea due to access restraints.

Figure 5 – Testing in a construction yard.

Monitoring during operation

This includes checking of the raw data (signal statistics, including kurtosis), data interpretation and interfacing with a suitable simulation to provide an assessment of the fatigue performance of the equipment under different operating conditions.

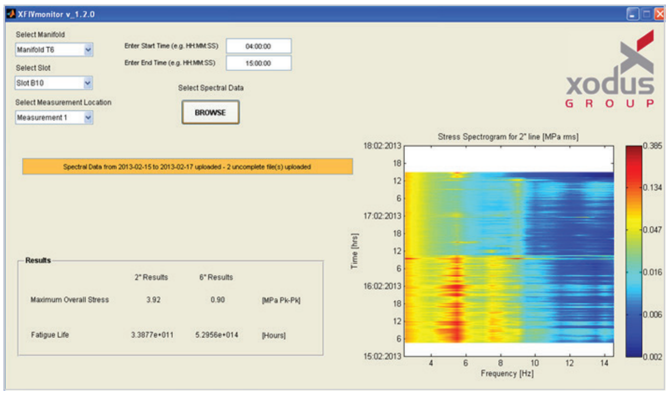

Figure 6 – Analysis of measured data.

Further investigation

As flow rates increase, there is a need to better understand the types of dynamic forces which are generated by multiphase flow in piping systems, as little work has been done in this area. A new Joint Industry Project (JIP) is being project managed by Xodus to address this area of uncertainty, with support drawn from key industry operators and equipment vendors.

This initiative will derive, from a series of 'industrial scale' tests, the power spectral density (PSD) of the forces acting on a bend under a variety of void fractions and superficial velocities, designed to include the most common flow regimes.

This will act as validation data for CFD predictions and could also provide an empirical means of determining the force PSD acting on a pipe bend given basic flow parameters. It is also intended that this new JIP will provide a series of benchmarks for the use of CFD to predict two phase flow forcing functions.

Conclusion

Following the Macondo incident three years ago, the integrity of subsea systems is receiving increased attention. Research into vibration induced fatigue, and its management in the subsea environment, is attracting greater emphasis and commitment. As flow rates increase and E&P goes deeper and into more harsh environments, subsea equipment is becoming more complex to improve production performance – new developments in subsea processing and separation are also on the horizon. Finding the balance between design, simulation and monitoring is crucial to maintain integrity of equipment and push ahead to recover more reserves.

The devil is in the detail and good design at the early stages can alleviate bigger problems later on. There is a way to go before subsea systems can be robust to all excitation challenges, but removing common pitfalls and help in identifying and preparing for potential vibration issues will shortly be available with the new Energy Institute guidelines ■

This paper was first presented at the Subsea Australasian Oil & Gas Conference which took place in Perth, Australia from 20–22 February 2013