Vibration fatigue in process pipework: A risk based assessment methodology

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ABSTRACT: Risk Based Inspection (RBI) has been used for some time to optimise inspection schedules based on assessing the risk of various corrosion related degradation mechanisms. However, one degradation mechanism that has been traditionally overlooked is that of vibration induced fatigue. A proactive methodology for assessment of vibration induced fatigue was published in 2000 as part of a Joint Industry Project to identify, using a risk based approach, which systems would be at risk from vibration induced fatigue. This paper describes the use of the overall risk based methodology and the key learning points in its application over the last 6 years.

1 INTRODUCTION

Vibration induced fatigue has always been recognised as a potential failure mode of process pipework, although the problem has usually been addressed on a reactive, or ‘fix-as-fail’, basis – the only exception being the guidance given in API618 and API674 (American Petroleum Institute 1995a, 1995b) for reciprocating compressors and pumps.

In the early 1990’s a sudden increase in pipework failure due to vibration induced fatigue was noted in the North Sea, especially on new offshore installations where extensive use had been made of duplex alloys. This resulted in thinner walled and lighter weight piping systems which were more susceptible to vibration related fatigue problems.

More recently there has also been an increasing trend of vibration related problems on existing or mature assets (both onshore and offshore) where process or operational changes have been made. Typical examples where problems have been experienced include:

- During commissioning of a new plant
- When changing the operating conditions on an existing plant (e.g. debottlenecking)
- Transient events over an extended period

In the UK, the Health and Safety Executive has collated data on reported hydrocarbon leaks on offshore installations. The results have been published for the period April 2000 to March 2001 (Health and Safety Executive 2002), and the results, in terms of ‘the immediate causes of releases’ are summarised in Table 1.

Table 1. Causes of failure offshore (from Health and Safety Executive 2002a).

<table>
<thead>
<tr>
<th>Description</th>
<th>Total reported failures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degradation of material properties*</td>
<td>28</td>
</tr>
<tr>
<td>Incorrect installation</td>
<td>21</td>
</tr>
<tr>
<td>Fatigue/vibration</td>
<td>21</td>
</tr>
<tr>
<td>Corrosion/erosion</td>
<td>13</td>
</tr>
</tbody>
</table>

*E.g. loss of flexibility in flange gaskets and valve stem packing.

In addition, it was found that ‘... the majority of releases involved gas, and occurred during normal production. Pipework was the main release site, with small bore piping a significant contributor’. (Health and Safety Executive 2002).

One North Sea operator has quantified the cost of a ‘typical’ failure to be approximately €0.1M, based on lost production and subsequent repair costs.

2 FACTORS INFLUENCING VIBRATION INDUCED FATIGUE

For a vibration problem to occur, there must be (a) some form of excitation, (b) response of the main line to that excitation, causing either fatigue damage to the main line itself, or (c) damage to small bore connections (SBC’s) on that main line. This ‘failure chain’ is shown in Figure 1.
2.1 Excitation mechanisms

The most common excitation mechanisms can be subdivided into two main categories – those occurring under ‘steady state’ operation, and those which are experienced under transient conditions (e.g. plant start-up or shutdown).

The majority of these mechanisms are sensitive to process and operational changes – for example, increasing the flow velocity in a line by 20% will increase the level of turbulent energy by between 40% and 50%.

In addition, key aspects associated with the geometry of each main line and small bore connection influences the level of fatigue damage that will occur for a given level of excitation; these are shown in Figures 2 and 3.

3 STRATEGIES FOR DEALING WITH VIBRATION INDUCED FATIGUE

Historically, there are three common strategies which have been adopted in an attempt to overcome the issue of vibration induced fatigue of process pipework. Each has advantages and disadvantages.

3.1 Bracing of all small bore connections

The principal advantage of bracing all small bore connections is that it is a ‘one off’ exercise. However, if undertaken retrospectively (i.e. on an operational asset) then the cost can be high, especially when access and insulation removal and reinstatement costs are included.

In addition, the long term maintenance issues associated with bolted braces need to be taken into account.
Finally, this approach does not address main line integrity problems (i.e. fatigue damage at main girth welds).

3.2 Visual survey

A visual survey on an existing plant has the key advantage that it captures the true ‘as built’ condition of the pipework. This is the only way that potential problems associated with local construction issues can be identified (for example, bracing of a connection to the neighbouring deck structure rather than the parent pipework).

However, a visual survey can be very subjective. It also cannot identify potential issues at the design stage of a new plant.

3.3 Vibration measurement survey

Another approach has been to identify problems using some form of vibration measurement survey. Whilst this approach can yield useful information and can identify any ‘immediate’ fatigue issues, it only provides a ‘snapshot’ of the health of the process plant for the process and operational conditions experienced at the time of the survey.

Unfortunately, vibration of process pipework is very dependent on a variety of process parameters (e.g. flow velocity, density, gas molecular weight etc) and how the plant is being operated.

4 OVERVIEW OF A RISK BASED APPROACH

Risk Based Inspection (RBI) has been used for some time to optimise inspection schedules based on assessing the risk of various corrosion related degradation mechanisms. For example, API581 (American Petroleum Institute 2000) provides a risk based methodology for corrosion mechanisms in refinery services. It is interesting to note that API581 states that ‘... fatigue failures of piping systems present a very real hazard under certain conditions...’

Following a similar logic, a proactive approach has now been developed which identifies systems will be at risk from vibration induced fatigue. The method can be applied at the design stage, or prior to commissioning, or when changes are being contemplated for an operational asset (e.g. debottlenecking).

The risk based approach draws on a Joint Industry Project (Marine Technology Directorate 1999) (the ‘MTD Guidelines’) completed in the UK in 2000 for ‘steady state’ excitation mechanisms, and also specific contract work undertaken for the UK’s Health & Safety Executive (Health and Safety Executive 2002) for ‘transient’ excitation mechanisms. Both of these documents are in the public domain.

The risk based methodology uses a 3 stage screening technique to identify whether any vibration related problems will occur, and where in the process system they will be experienced (see Figure 4 for a simplified schematic).

The 3 stage approach is built on the principle that in order for a small bore connection to fail due to vibration there must be:

1. some form of excitation (addressed in Stage 1),
2. vibration response of the main line (addressed in Stage 2), causing either a main line fatigue issue, or
3. vibration of the small bore connections on that line (addressed in Stage 3).

The data required for an assessment is very similar to the information required to implement RBI, although the output results largely in a modification strategy rather than an inspection strategy as shown in Figure 5.

The information required can be obtained from Process Flow Diagrams (fluid densities, pressures and flow rates) and P&IDs (pipe diameters and wall thicknesses). The assessment process identifies which main lines and associated small bore connections (defined as any connection less than 2” NB) are at risk of failure for the complete operational and process envelope, and what remedial actions (either in terms of modification or inspection) need to be undertaken.

The Likelihood of Failure (LOF) rating is a semi-quantitative value that represents the probability of a certain failure occurring. To obtain a true ‘risk’ assessment, the consequence
5 CASE STUDIES

5.1 Case Study 1: New offshore installation

The risk assessment was applied at the end of the detailed design stage, during construction. The complete hydrocarbon system was assessed, as well as several process and safety critical systems. The results indicated that 3 additional main line supports were required, and that 38 small bore connections (out of a total of 990) required modification. These modifications were implemented, and the installation successfully commenced production in early 2002, achieving its design throughput with no vibration related issues.

5.2 Case Study 2: Existing offshore installation

In this case, the risk assessment was applied to a mature asset where a number of problems had been experienced previously. A bottom up approach was adopted, with the small bore connection assessment being undertaken first. This identified 261 small bore connections of poor geometry, with an average modification cost of €4500 per connection (based on the mantime, material, insulation removal/reinstatement and access costs). A Stage 1 and 2 assessment was subsequently undertaken to identify which of these connections were located on lines which would have potentially sufficient excitation to cause a fatigue problem. The results (shown in Figure 6) showed that modifications to only 29 connections were required.

5.3 Case Study 3: Existing onshore gas plant

A risk assessment was undertaken for a gas plant where debottlenecking was being considered. The scope of the study encompassed 2 modules, each with 171 main lines which would be subjected to increased throughput. The results of the assessment indicated that 48 small bore connections per module required modification. The plant subsequently achieved its higher throughput with no vibration fatigue issues. Further details of this particular example are given in Martin & Swindell et al 2002.

6 COST BENEFIT ANALYSIS

A cost benefit analysis has been conducted for two projects – a refinery and an offshore installation. See Table 3.

The assumptions made in this analysis relate to the rate of return used (3%), and that a 90% success rate is achieved through the application of the methodology (this is based on the findings of a ‘blind’ assessment conducted for Shell in the UK).

The final NPV calculation takes account of the costs associated with the risk assessment and the subsequent modification costs.

7 KEY LEARNING POINTS

Since publication the methodology given in the MTD Guidelines has been applied to over 60 process plants and has played a significant role in helping to reduce pipework failures:

– 40 offshore installations (United Kingdom Continental Shelf)
– 8 offshore installations (non-UKCS)
– 8 downstream plants (gas plants and refineries)
– 6 petrochemical/chemical plants
Table 3. Cost benefit examples.

<table>
<thead>
<tr>
<th>Project</th>
<th>Average cost of failures €/y</th>
<th>No of failures</th>
<th>Cost of assessment €/y</th>
<th>Estimated saving based on 90% success rate €</th>
<th>Cost of risk assessment project €</th>
<th>Cost of modifications €</th>
<th>NPV (over 3 years) €</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refinery</td>
<td>55,000</td>
<td>3</td>
<td>165,000</td>
<td>148,500</td>
<td>148,500</td>
<td>100,000</td>
<td>153,000</td>
</tr>
<tr>
<td>Offshore install.</td>
<td>100,000</td>
<td>2</td>
<td>200,000</td>
<td>180,000</td>
<td>180,000</td>
<td>110,000</td>
<td>145,000</td>
</tr>
</tbody>
</table>

It was always the intention that the original MTD Guidelines would be reviewed after a period of usage and update as necessary. During the last 6 years, very useful experience has been gained in the practical application of the guidelines and associated methodologies. Constructive comments have also been received regarding aspects for improvement, principally:

– Procedural aspects – improving the overall usability of the guidelines to provide a clear holistic approach to the ‘through life’ management of vibration induced fatigue in process pipework.
– Technical aspects – inclusion of excitation mechanisms not covered previously and extending the scope of the assessment methods. In addition, it was identified that the Guidelines could be overly conservative in certain situations, and possibly not conservative in others.

In 2005 a new Joint Industry Project was therefore initiated by the Energy Institute (which had acquired the copyright to all MTD documents) with a number of sponsors including Shell, BP, Total, ChevronTexaco, ConocoPhillips and the UK’s Health & Safety Executive.

The revised Guidelines, due to be published in March 2007, include a number of excitation mechanisms not previously addressed including transient events and intrusive elements (e.g. thermowells). In addition, the new Guidelines include a new qualitative (“simplified”) screening assessment that can be used by a non-specialist, as well as the updated quantitative methods for more detailed assessments, thus mirroring the approach adopted in API581. The Guidelines now explicitly address the issue of how to apply the various techniques in different scenarios (i.e. a new design, for plant change and for troubleshooting existing vibration issues).

8 CONCLUSIONS

Vibration induced fatigue of process piping systems has been shown to be a tangible threat, accounting for approximately 21% of failures of pipework offshore. A risk based approach to addressing the problem of vibration induced fatigue has been described, including its integration with other risk based approaches to integrity management (e.g. RBI).

The key benefits of adopting the risk based approach are:

– The risk of failure is determined for the complete operational and process envelope of the plant.
– The effect of plant changes can be established well in advance.
– By identifying the high risk areas, modification and inspection effort is targeted – resulting in economic benefits.
– A full audit trail is established.

To date, the risk based approach has been used on over 60 different assets, ranging from offshore installations to refineries and onshore gas plants. Significant cost savings (in the region of €0.8M per asset) have been achieved as the result of using the approach to rationalise modifications and target inspection effort. The updated methodology will be available from the Energy Institute from March 2007.

REFERENCES
