Reducing Uncertainty Through The Use Of Mooring Line Monitoring
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Abstract

The offshore oil and gas industry is continuing to push into deeper water and more onerous environments, using increasingly bigger vessels and equipment. This, combined with more erratic and unpredictable global weather patterns has increased uncertainty in offshore production operations.

Monitoring mooring lines can help reduce this uncertainty by providing tools to calculate fatigue accumulation, based on tension measurement, during major storm events. This greater understanding helps to optimise inspection and maintenance schedules and assess the likelihood of future mooring line failures.

A popular technique for monitoring mooring systems is to measure mooring line angle (using accelerometer based inclinometers), and use this measurement to infer theoretical mooring line tension. Whilst these systems are effective at alerting operators to a line failure, the fact that tension must be inferred requires a certain amount of uncertainty in the calculation. This uncertainty is difficult to quantify and thus has been little understood. Also, the use of shackle load cells can give varying results depending on where the chain is sitting on the load shackle. These often fail in service due to the dynamic nature of the mooring line and the typical shackle location within it. This paper documents the sea trial of a new mooring line technology capable of measuring both mooring line angle and direct line tension. The improved accuracy associated with direct monitoring of line tension can help reduce levels of uncertainty in offshore operations and thus reduce future levels of conservatism in design and analysis models. This can help save costs and increase efficiency for future operations, whilst also helping support safety strategies.

INTRODUCTION

The number of Floating Production Systems (FPS) in operation has increased rapidly over recent decades, and with exploration and production (E&P) activities moving into deeper and more isolated locations this growth is expected to continue over the coming years. The past decade saw the number of permanently moored FPSs (including FPSO, FSO, Semi-submersible, Spar and offloading buoys) double to around 400 installed facilities [1]. Over the next 5 years this number is expected to grow by a further 50% [2].

Because floating installations are moored to the seabed and usually cannot move off station, they are subject to whatever weather comes their way. Environmental conditions offshore can lead to deterioration of mooring lines over time, increasing the likelihood of failures. There are various sources of potential breakages in mooring lines, a selection of which are listed in Table 1. Although failures can occur at any point along a mooring line the majority of failures occur at an interface or discontinuity [1]. These include:

- Between the mooring line and vessel- either at the fairlead or in the hawse pipe;
- At connections between two types of line- including shackles and H-links;
- Where buoys, clamp weights or tri-plates are attached to the line;
- In the thrash zone- where the line dynamically contacts the seabed;
- Where the line descends into the seabed to connect with the anchor pile.

The past decade has seen 21 mooring issues reported on FSUs. 8 of these can be classed as system failures (with multiple line failures sustained), with 4 of these incidents (Gryphon Alpha, Nan Hai Fa Xian, Hai Yang Shi You and Liuhua) leading to vessel drift and rupture of the risers. However, even incidents with a single line breakage led to damage being sustained on additional lines which may have led to further premature failures if undetected [1]. 3 mooring incidents involving two vessels (Fluminese FPSO and Jubarte FPSO) were reported in Brazil between 2001 and 2011. The details of these incidents are found in Figure 1 and summarized below:

- P-34 FPSO: Parted in the lower chain segments
- Fluminese FPSO: Damage to top chain and connector
<table>
<thead>
<tr>
<th>Mechanism Contributing to Mooring Line Failure</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wear</td>
<td>Due to rubbing on adjacent line components at connecting links, fairleads etc.</td>
</tr>
<tr>
<td>Fatigue</td>
<td>Due to crack initiation and propagation from axial and bending stresses. The combined effect of tension and out of plane bending of links drives fatigue failure.</td>
</tr>
<tr>
<td>Abrasion</td>
<td>From contact with seabed sediments, especially if the lower end of mid-water wire rope makes contact with seabed.</td>
</tr>
<tr>
<td>Corrosion (general and pitting)</td>
<td>Due to chemical reactions between the material and the surrounding environment- a major cause of several incidents. Particularly common in the splash zone (due to oxygenated water) and the thrash zone.</td>
</tr>
<tr>
<td>Damage during transport/ installation</td>
<td>Uncontrolled welding heat into a chain whilst an AHV causing high residual stresses, local damage caused by rough handling, local damage twisting to line during installation.</td>
</tr>
<tr>
<td>Strength</td>
<td>Flawed materials resulting from impurities, improper heat treatment, improper assembly or poor coating have resulted in failures due to under-strength mooring components.</td>
</tr>
<tr>
<td>Excessive tension</td>
<td>During severe environmental conditions and exposure to extreme loads.</td>
</tr>
<tr>
<td>Operational</td>
<td>Various other problems can arise during operation, such as a failure to disconnect in time during a sudden severe weather event or a reliance on active heading control thrusters to maintain heading control.</td>
</tr>
</tbody>
</table>

Table 1- Summary of Mechanisms Contributing to Mooring Line Failures

![Mooring Incidents in Brazil between 2001 & 2011](image)

Figure 1- Mooring Incidents in Brazil between 2001 & 2011 [1]
Mooring systems on FPSs are category 1 safety critical systems [5], and there are a number of potentially severe human, environmental and economic consequences of a mooring system failure. These include:

- Vessel drift;
- Riser rupture;
- Production shutdown;
- Hydrocarbon release;
- Repairing of damaged lines.

It is estimated that the financial cost of a single mooring failure could be anywhere between £2 million and £10.4 million depending on size of facility and location [5]. However, the cost of a system failure could be many times this. For example, the Gryphon Alpha has only recently resumed production in the North Sea 27 months after breaking free from some of its mooring chains and causing significant damage to subsea infrastructure [6]. The cost of this is expected to reach an estimated $1.8 billion [7].

MOORING LINE MONITORING

As the severe consequences of mooring line failure becomes better understood, more focus is placed on mooring line integrity management systems as a means to maintain system condition and operational integrity. Historically mooring line integrity management practices have focused mainly on inspection and maintenance, with a focus on limiting interruption to production [3]. These included visual, ROV and 3D camera inspections to identify changes in geometry, damage and line length. However, non-invasive inspection methods cannot provide a thorough understanding of the complete mooring system condition for 3 primary reasons:

1. Visual inspection is often impossible since mooring lined become coated with marine growth. This is rarely removed since the oxygenated water used in the cleaning process exposes the line to increased corrosion. Figure 2 shows marine growth on a mooring chain.

2. Visual inspection cannot see mooring line components below the mudline, one of the key areas of concern

3. Gaining a thorough understanding of the entire mooring system would require disconnecting recovering, inspecting, testing, replacing and reinstalling at least some parts of the system, resulting in high levels of cost and risk [4]

![Figure 2- Marine Growth on a Mooring Chain](image)

Since FPUs are increasingly expected to remain on location for longer periods (often longer than those specified in the design of various subcomponents), accurate fatigue assessments are increasingly being seen as beneficial for operators. Monitoring systems have become increasingly popular to this end, and provide two primary benefits:

- **Record of tension history**: monitoring can help derive the range of loads imposed on to the mooring line, together with their frequencies. Long term, averaged, tensions can be compared to initial mooring line pre-tensions to indicate any system deterioration (chain wear, weight increase due to marine growth, fibre rope stretching etc)

- **Instant warning of line failure**: allows any failure to mooring line components to be identified almost immediately, without awaiting the results of planned inspection activities. This early warning reduces the risk of component breakage turning into a system failure, as explained in Figure 3.
Figure 3- Advantage of Early Detection of Mooring Line Failure [5]

ANCHOR LEG LOAD MONITORING SYSTEMS (ALLMS)

Historically most mooring line monitoring systems have either used load cells to directly monitor tension or have used inclinometers to measure line angle and use this to infer tension using lookup tables. This paper will look in more detail at inclinometer based monitoring systems, and will also introduce a new technology for in-line direct tension monitoring. This system offers an alternative to load cells for direct tension monitoring of mooring lines.

Mooring Line Inclination Monitoring

In order to address reliability issues associated with load cell and shear pin based monitoring systems, some ALLMS use inclinometers to measure mooring line angle and convert to a calculated tension using look-up tables.

Case Study- Espirito Santo FPSO

Pulse Structural Monitoring provided an ALLMS for the BC10 FPSO deployed in the BC-10 field in the Campos basin, Brazil. The mooring system comprises of 9 mooring lines bundled in 3 sets of 3, 120° from each other around a turret chaintable. Pulse supplied an inclinometer based system, with the inclinometers attached to the chain hawse of each mooring leg. This meant that the sensor was outside the load path allowing straightforward maintenance of the equipment, and also allowing each chain to be pulled through the hawse for re-tensioning without affecting inclinometer operation. Acoustic communication was used to relay data to the control room to avoid the used of cables which can become trapped and severed during subsea intervention [8].

Equipment

Motion Data Loggers

The main components of the system were Pulse’s INTEGRipod motion data loggers and the system comprises:

- 9 acoustic loggers were deployed- one on each mooring line
- Communication with each of the 3 acoustic receivers installed underneath the turret chaintable
- Mounted to the chain hawse of each leg using a robust metal interface
  - Special coating on interfaces to resist marine growth
  - Interfaces allow easy removal & deployment of logger throughout operational lifetime

Figure 4 shows one data logger installed on a chain hawse.
Acoustic Receivers

3 acoustic receivers mounted on the chaintable using similar holders to those used for the INTEGRipods. Armour plated cabled connect the receivers to the control room through the electro-optical swivel. In order to ensure that communication can be achieved with the INTEGRipods regardless of turret orientation and position, 3 receivers are installed in the turret, shown in Figure 5.

Software

Data is transferred to a standard PC in the control room running Pulse’s MoorASSURE mooring line monitoring software, where:

- Angle data is converted into tensions using a software model of each of the mooring lines;
- Conversion of the angles to tensions is completed using lookup tables developed during system installation, see Figure 6;
- The software presents historical tension and angle data, enabling operations to make informed decisions about mooring system performance.

Downsides to Inclination Monitoring

Anchor leg load monitoring systems have generally proved a reliable method for mooring line monitoring over recent years, becoming increasingly popular as mooring integrity concerns have risen. However, although these systems offer a reliable warning in the case of a line failure, the conversion of angles into tensions must still be done using estimated lookup tables. This means that some accuracy will be lost as tension is inferred.

Inline Direct Tension Monitoring

The next generation in mooring line monitoring technology is thus being designed to remove this concern. Direct inline tension monitoring can be installed on mooring lines to more accurately track in situ tension performance over time. The Inter-M Pulse (IMP) is an instrumented H-Link, jointly developed between Pulse Structural Monitoring and InterMoor, which is capable of direct tension measurement and wireless communication with the platform. The IMP measures both mooring line inclination and tension, raising an alarm if either one exceeds pre-defined levels. Imbedding the sensing element in the centre of an H-Link and not within the connection of a mooring line (as in the case of load pins) makes the IMP inherently consistent in its long term performance. This also makes the IMP insensitive as to how it is connected to rest of the mooring system. By sensing steel forging with a large cross sectional area which is not subjected to wear over the measured area adds to the consistent performance of IMP for extended periods subsea. This is considerably different to a load pin which would be more susceptible to effects of corrosion and wear due to the smaller area under strain.

Figure 5- Installed Acoustic Receiver in Holder

Figure 6- Angle to tension lookup table for one mooring line
Components

The system main components are presented in Table 2 and a picture of the instrumented H-Link is shown in Figure 7.

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-Link</td>
<td>Industry standard H-link used to connect chains/ropes of different sizes together. The link is made from forged steel proof load tested to the chain grade loads. Certification is issued by either DNV or ABS.</td>
</tr>
<tr>
<td>Shroud</td>
<td>Made from a highly durable, marine grade polymer, the shroud houses the 2 motion data loggers in order to protect the electronic modems. This also allows the link to be deployed/recovered over a stern roller.</td>
</tr>
<tr>
<td>Strain Gauges</td>
<td>Two sets of tension/compression set strain gauges are supplied (4 in total) providing redundancy. These are located on opposite sides of the H-link and are linked to the data loggers. A proprietary coating provides water ingress protection at up to 1500m water depth.</td>
</tr>
<tr>
<td>Inclinometers</td>
<td>Proven MEMS (Miniature Electro-Mechanical Sensor) inclinometers are mounted securely and aligned within the H-link. 1 set of inclinometers (3 per set) on each side to provide redundancy.</td>
</tr>
<tr>
<td>Data Loggers</td>
<td>2 acoustically linked INTEGRIpod data loggers are housed in the Inter-M Pulse shroud. Accurate motion sensors record movement of the structure over time, with data transmitted to the surface via acoustic link.</td>
</tr>
<tr>
<td>Acoustic Modem &amp; Receiver</td>
<td>Proven acoustic technology is provided, with noise rejection capabilities a basic feature. Two modems are located on the Inter-M Pulse (1 on each INTEGRIpod) with 3 receiving modems located on the platform.</td>
</tr>
<tr>
<td>Batteries</td>
<td>28 standard non-rechargeable batteries are supplied per logger. Battery life will vary between 17 days and 7 years depending on logging &amp; communication settings.</td>
</tr>
</tbody>
</table>

Table 2- Inter-M Pulse Components

Figure 7- Inter-M Pulse Instrumented H-link for Direct Tension Monitoring of Mooring Lines
CALIBRATION TEST

The first calibration of the Inter-M-Pulse was conducted at QED in Huntly, Aberdeen, in 2012. The process was carried out using a calibrated rig, the same format by which all H-Links are now tested. During the test the device was brought from 0 Te tension up to 400 Te tension. The calibration curves in Figure 9 were determined based on the voltage produced by each strain gauge for each given tension. From the graphs it is possible to conclude that:

- Error can be seen at low tension level;
- Good agreement above 50 Te of tension.

Figure 8- Calibration of the Inter-M Pulse

Figure 9- Calibration Curves from Inter-M-Pulse test
Sea Trial

A sea trial was conducted during 2011 and 2012 in order to check deployment and recovery of the Inter-M Pulse over the back of a stern roller, as shown in Figure 11. The system has proven the capability of the system to communicate in an offshore environment. Details of the sea trial campaign are presented in Table 3.

The system was installed on 22\textsuperscript{th} December 2011 in mooring line #8 of the Ocean Nomad semisubmersible, operating in the UK continental shelf (UKCS). The Inter-M-Pulse is designed to be easily made up on an anchor handler and simple to install over the back of a stern roller. Although the system was designed to be installed 50 ft below the water surface, problems during mooring line deployment left the IMP on the seabed at around 290 ft. Despite this, the system communicated well throughout the sea trial. Due to the short term nature of the communications trial, a dunking modem was used for the acoustic receivers (rather than installing the receivers on the chain stopper).

Online Data Communication

Table 3- Inter-M Pulse Sea Trial Statistics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vessel</td>
<td>Ocean Nomad semisubmersible</td>
</tr>
<tr>
<td>Mooring System</td>
<td>Chain/ fibre makeup</td>
</tr>
<tr>
<td>Chain Diameter</td>
<td>76 mm</td>
</tr>
<tr>
<td>Water Depth</td>
<td>289.7 ft</td>
</tr>
<tr>
<td>IMP position</td>
<td>Installed at fibre/ shackle connection</td>
</tr>
<tr>
<td></td>
<td>Distance from rig- 1150 ft</td>
</tr>
<tr>
<td></td>
<td>Water depth- 289.7 ft</td>
</tr>
<tr>
<td>Max Sea State</td>
<td>7.8m</td>
</tr>
<tr>
<td>Significant Wave Height</td>
<td>5.1 m</td>
</tr>
<tr>
<td>Typical Signal Quality</td>
<td>10</td>
</tr>
</tbody>
</table>

Online logging was largely successful, and communication was generally reliable and did not cause any crashes. However, when the sea state became more extreme the communications did become more difficult, but this was expected giving the set up of the dunking modem described above.

Figure 10 shows measured tension data for July 2012, up until the Inter-M Pulse was retrieved on 27\textsuperscript{th} July 2012. The graph shows that the measured tension consistently lay within the calibrated range of the device (in this instance between 10 and 600 Te), helping to confirm the accuracy of the data to within ±2 Te. The graph also shows that there was no noise for this logging period since no unexpected spikes can be seen in the tension data. Finally, this graph shows that no sensor drift occurred during this period, with the sensor remaining stable for the length of the monitoring campaign.

Figure 10 – Tension Data for the Final 30 days of the Sea Trial
CONCLUSION

The complexity and variance of failure mechanisms makes mooring system integrity management an intimidating challenge, however the severity of failure makes it a necessary one. Designing an appropriate integrity management system requires careful understanding of mooring system integrity in terms of strength and motion extremes [3].

The threats from a mooring system failure are well documented, with vessel drift potentially causing riser rupture and hydrocarbon release. However, recent studies have shown that even in cases of a single line failure, extra loading applied to adjacent lines greatly increases the probability of further line failures if the breakage is not detected in time [1]. This evidence further supports calls for monitoring systems to improve early warning capabilities in cases of mooring line breakages. Monitoring systems also provide a record of line tension history, helping to plan inspection and maintenance activities as well as helping to justify system life extension further down the line.

Although anchor leg load monitoring systems have become the industry standard for mooring line monitoring over recent years, historically there have been some reliability issues with certain elements of these systems:

- **Load cells** - Not only have load cells been traditionally unreliable, but because they are mounted in the load path this raises difficulties with maintenance
- **Shear pins** - These require modifications to the chain itself, potentially affecting mooring line integrity
- **Strain gauges** - These have suffered issues with water leakage

Even systems using inclinometer based technology, like the case study covered in this paper, have downsides. The main issue is that tension has to be inferred from the measured angles using a pre-calculated lookup table. This leads to an inherent inaccuracy in tension measurements, depending on the precision of the lookup tables themselves.

The next generation of mooring line monitoring technology has thus set out to remove this problem from future monitoring systems. Direct tension monitoring systems can provide accurate input data for in-depth mooring line analysis. This data can be used to confirm whether actual behaviour is consistent with design, or used as a direct input into a fatigue analysis [4].

NOMENCLATURE

- **ALLMS** Anchor Leg Load Monitoring System
- **AHV** Anchor Handling Vessel
- **FSU** Floating Storage Unit
- **FPSO** Floating Production, Storage and Offloading
- **FSO** Floating storage and Offloading
- **IMP** Inter-M Pulse
- **UKCS** United Kingdom Continental Shelf

REFERENCES


[2] [IMA. 2012. “Floating Production Systems- assessment of the outlook for FPSOs, Semis, TLPs, Spars, FLNGs, FSRUs and FSUs”, International Maritime Associates, Inc., Washington DC, USA](#)


