Four mooring incidents were reported in Asia Pacific between 2001 and 2011. The details of these incidents are found in Figure 1 and summarized below:

- Gryphon Alpha: Seven legs parted from FPSO mooring turret;
- Nan Hai Fa Xian: Four lines parted in bottom end of upper wire segments;
- Hai Yang Shi You: Collapse of yoke tower;
- Liuhua FPSO: Seven legs parted from FPSO mooring turret;
- FPSO Kikeh: One line parted in shackle on anchor;
- Nan Hai Fa Xian FPSO: Four lines parted in bottom end of upper wire segments;
- Hai Yang Shi You 113: Collapse of yoke tower.

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, clump weights or tri-plates are attached to the line;
In the thrash zone—where the line dynamically contacts the seabed;
The line descends into the seabed to connect with the anchor pile.

The past decade has seen 21 mooring issues reported on Floating Storage Units (FSU). Eight 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].

Four mooring incidents were reported in Asia Pacific between 2001 and 2011. The details of these incidents are found in Figure 1 and summarized below:

- Liuhua FPSO: Seven legs parted from FPSO mooring turret;
- FPSO Kikeh: One line parted in shackle on anchor;
- Nan Hai Fa Xian FPSO: Four lines parted in bottom end of upper wire segments;
- Hai Yang Shi You 113: Collapse of yoke tower.

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 means that it is impossible to know for certain whether all mooring lines are in place.

Added to this, most FPSOs are only designed to cope with the failure of a single line. If this is not detected then increasing loads on the remaining lines may result in additional failures. This is regarded as a system failure and could lead to the FPSO breaking away from its moorings and drifting off station. This can have consequences for both well control and riser integrity, resulting in huge costs for operators. Unless the operator inspects on a regular basis or monitors in real time it is impossible to know for certain whether all mooring lines are in place.

A greater understanding helps to optimise inspection and maintenance schedules and assess the likelihood of future mooring line failures. 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. Increased 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 [3]. Over the next five years this number is expected to grow by a further 50% [2].

Because floating installations are moored to the seabed and often cannot move off station, they are subject to a variety of extreme weather conditions. South East Asia is subjected to a regular typhoon season between May and November. Forming in the Pacific Ocean or South China Sea, these storms gather force as they head towards the southern and eastern coast of China. Severe 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 [3]. These include:
<table>
<thead>
<tr>
<th>Vessel Name</th>
<th>Vessel Type</th>
<th>Year Installed</th>
<th>Water Depth (m)</th>
<th>Mooring System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hai Yang Shi You 113</td>
<td>FPSO</td>
<td>2004</td>
<td>18</td>
<td>Tower yoke mooring system</td>
</tr>
</tbody>
</table>

### Incident

2009: Yoke tower collapsed. Vessel drifted a distance causing risers to break.

### Cause

Fatigue crack in the base of the yoke column failed during strong winds.

<table>
<thead>
<tr>
<th>Vessel Name</th>
<th>Vessel Type</th>
<th>Year Installed</th>
<th>Water Depth (m)</th>
<th>Mooring System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liuhua (Nan Hai Sheng Li)</td>
<td>FPSO</td>
<td>2007</td>
<td>305</td>
<td>Internal turret mooring system; 10 composite mooring legs</td>
</tr>
</tbody>
</table>

### Incident

2006: Struck by typhoon Chanchu causing damage to all 10 mooring legs. 7 legs and all 3 flexible risers broke away from FPSO mooring turret causing damage to subsea infrastructure and a halt in production for over 12 months.

### Cause

100 year return period typhoon exceeded the design limit of the mooring system. This caused degradation of the wire ropes.

<table>
<thead>
<tr>
<th>Vessel Name</th>
<th>Vessel Type</th>
<th>Year Installed</th>
<th>Water Depth (m)</th>
<th>Mooring System</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPSO Kikeh</td>
<td>FPSO</td>
<td>2007</td>
<td>1,340</td>
<td>External turret mooring system</td>
</tr>
</tbody>
</table>

### Incident

2007: 1 line parted in shackle on anchor. Other shackles from the same batch showed low toughness

### Cause

Low fracture toughness.

---

Figure 1: Mooring Incidents in Asia Pacific between 2001 & 2011 [3]
Figure 2- Marine Growth on a Mooring Chain

Mooring systems on FPSOs are category 1 safety critical systems [6] 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 $3 million and $17 million depending on size of facility and location [6]. 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 [7]. The cost of this is expected to reach an estimated $1.8 billion [8].

MOORING LINE MONITORING

As the severe consequences of mooring line failure become 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 [4]. 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 lines 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 [5].

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 can answer these requirements, and provide two primary benefits:

Table 1- Summary of mechanisms contributing to mooring line failure

<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 on 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>
- **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)

- **Warning of line failure** - allows any failure of mooring line components to be identified within a few seconds (using hardwired communication) to a few hours (using acoustic communication), 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 [6]](image)

**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 these monitoring technologies, and will also introduce a new technology offering an alternative to load cells for direct in-line tension monitoring of mooring lines.

**Mooring Line Tension Monitoring Using Load Cells**

Real time monitoring of tensions in mooring lines can be provided by using systems based on load cell, load pin or load shackle technology. These systems have been installed on numerous floating production units and CALM buoys and can provide very useful data on mooring integrity to vessel operators.

**Case Study- FPSO in Australia**

Pulse Structural Monitoring is currently delivering an ALLMS using load cell technology for an FPSO planned to be installed off the north-west coast of Western Australia in 2015. The FPSO will be moored using a non-disconnectable turret mooring system designed to maintain the FPSO on station up to and including the 10,000-year survival cyclonic storm condition. The purpose of the ALLMS will be to measure direct tension of the mooring lines, detect line failures and maintain the integrity of the turret mooring system by detecting overloading.

**Equipment:**

![Figure 4- Load cell based ALLMS system overview](image)
Component Description

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load Cells</td>
<td>84 load cells (4 per chain connector), each with dual redundant set and diver-mate connectors, 4,300kN operating load and 8,750kN design load</td>
</tr>
<tr>
<td>Subsea Cables</td>
<td>Multi-pair cable, length 60m, to link topside junction box and load cells</td>
</tr>
<tr>
<td>Topside Junction Box</td>
<td>1 Exx 'e' junction box per mooring bundle, rated IP66, on riser/winch deck.</td>
</tr>
<tr>
<td>Control Panel</td>
<td>Housing PLC, with software</td>
</tr>
</tbody>
</table>

Table 2- Equipment supplied

All system components are either designed or selected to meet a target monitoring system design life of 40 years. Cables can often be a failure point of subsea installations and were highlighted as a potential weak spot for this system. In order to address this, all unsupported cables were given protection to maximize robustness. In order to minimize the impact of a sensor failure, 4 load cells (each with a redundant sensor) will be installed on each mooring line (surpassing the DNV requirement of 3) to provide increased redundancy. DNV also require all load cells to be certified to 70% of the maximum break load (MBL). In order to further improve reliability, all load cells supplied for this system are certifiable to 100% of MBL.

The advantage of such a system is that direct tension is measured with high sampling rates (no battery power limitations) and is displayed on screen immediately (Figure 6). Therefore full tension history is obtained, detailed fatigue analysis possible and immediate alarm is given in case of failure.

**Limitations of Load Cell Monitoring Systems:**

Despite being used for a number of years, there are still a number of issues relating to load cell based ALLMS. The nature of load cells means they need to be mounted in the load path resulting in difficulties with maintaining and replacing equipment. Shear load pins require modifications to the chain itself which can affect the integrity of the mooring system. On top of this, the cables used to connect the sensors to topside data gathering systems are areas of particular weakness when exposed to long term offshore loading conditions. Operational factors may also cause issues with the possibility of cables getting trapped and severed during subsea intervention activities such as riser pull-in [6].
Mooring Line Angle Monitoring Using Inclinometers

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. The main advantage of this method is that it requires less or possibly no design requirements and constraints for the FPSOs mooring system (turret, chain connectors…) and can be retrofittable to existing FPSOs already on station.

Case Study- FPSO in South China Sea

In 2013 Pulse Structural Monitoring provided an inclinometer based ALLMS for an FPSO deployed in the South China Sea. As Figure 1 shows, this is a region where typhoons are frequent, leading to a number of mooring failures in the past. The mooring system comprises of nine mooring lines bundled in three sets of 3, 120° from each other around a Single Point Mooring (SPM) buoy. Pulse supplied a fully diver installable mooring monitoring system using inclination measurement, the first of its kind. Acoustic communication was used to relay data to the control room to avoid the use of cables on the risers which can become trapped and severed during subsea intervention [9].

Equipment:

Motion Data Loggers- The main components of the system were Pulse’s INTEGRIpod motion data loggers:
- Nine acoustic INTEGRIpod data loggers deployed- one on each mooring line (Figure 7)
- Communicating to two acoustic receivers, installed underneath the FPSO hull using magnetic holders
- The INTEGRIpods are attached to the mooring lines using diver installable holders
  - Special coating on interfaces to resist marine growth
  - Interfaces allow easy diver removal & deployment of logger throughout operational lifetime

Acoustic Receivers- Two acoustic receivers were mounted on the underside of the FPSO hull using specially designed magnetic holders (Figure 8). This ensured that communication can be achieved with the INTEGRIpods regardless of FPSO orientation and position. Magnetic clamps were also used to attach the cables along the vessel hull (Figure 9), creating a fully diver installable and retrievable system and allowing communication between the subsea equipment and realtime mooring software installed in the control room.

Figure 8- Installed Acoustic Receiver in Magnetic Holder

Figure 9- Magnetic clamps attach the cable to the FPSO hull
Software: Data is transferred to a standard PC in the control room running Pulse’s 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;
- The software presents historical tension and angle data, enabling operations to make informed decisions about mooring system performance (Figure 10).

Limitations of Inclination Monitoring Systems

Inclination based 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 and is not directly measured.

NEXT GENERATION INLINE DIRECT TENSION AND INCLINATION MONITORING

The next generation in mooring line monitoring technology is thus being designed to both improve reliability and accuracy of mooring line monitoring systems. 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 (both part of the Acteon Group), which is capable of direct tension measurement and wireless communication with the vessel. The IMP measures both mooring line inclination and tension, raising an alarm if either one exceeds pre-defined levels. Embedding the sensing element in the body 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 the rest of the mooring system. Sensing steel forging with a large cross sectional area, which is not subjected to wear, 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, more concentrated area under strain.

Components

The main components of the IMP are presented in Table 3 and a picture of the instrumented H-Link is shown in Figure 11.

<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 a few days to several years depending on logging &amp; communication settings.</td>
</tr>
</tbody>
</table>

Table 3- Inter-M Pulse Components
Calibration Test

The first calibration of the IMP 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 (Figure 12). During the test the device was brought from 0 Te tension up to 400 Te tension. The calibration curves in Figure 13 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.
Sea Trial

A sea trial was conducted during 2011 and 2012 in order to verify performance of the IMP. The trial was designed to verify measurement accuracy, robustness of the subsea communication and the operational deployment and recovery of the IMP over the back of a stern roller, as shown in Figure 15. The sea trial proved the capability of the IMP to operate measure and communicate in an offshore environment. Details of the sea trial campaign are presented in Table 3.

The Inter-M Pulse was installed on 22nd December 2011 in mooring line #8 of the Ocean Nomad semisubmersible, operating in the UK continental shelf (UKCS). The IMP is designed to be easily assembled on an anchor handler and simple to deploy over the back of a stern roller. Although the system was designed to be installed 50ft below the water surface, issues during mooring line deployment left the IMP on the seabed at around 290ft. Despite this (wider acoustic communication angle and distance), 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 permanently installed receivers).

Online Data Communication

Online logging was largely successful, and communication was mostly reliable and did not cause any crashes. However, when the sea state became more extreme the communications did deteriorate. This was expected however, given the set up of the dunking modem and IMP described above.

Figure 14 shows measured tension data for July 2012, up until the IMP was retrieved on 27th July 2012. The graph shows that the measured tension consistently remained within the calibrated range of the device (in this instance between 10 and 600 Tc), helping to confirm the accuracy of the data to within ±2 Tc. The graph also shows that there was no noise for this logging period since no unexpected spikes can be seen in the tension data. The graph shows that no sensor drift occurred during this period, with the sensor remaining stable for the length of the monitoring campaign.

Table 4- 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>Vessel Contractor</td>
<td>Diamond Offshore</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>Inter-M Pulse 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>5.1m</td>
</tr>
<tr>
<td>Typical Signal Quality (10)</td>
<td>10</td>
</tr>
</tbody>
</table>
Figure 14 – Tension Data for the Final 30 days of the Sea Trial

Start of mooring line retrieval

Inter-M Pulse on vessel

Figure 15 – Inter-M Pulse recovered using a stern roller
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 [4].

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 [3]. This evidence further supports the need 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 issues with certain elements of these systems:

- Load cells- Not only have load cells had issues with reliability, but because they are mounted in the load path this raises difficulties with maintenance
- Inclinometers- Because tension must be inferred, accuracy may be lower than direct tension measurement

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 [5].

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
MBL Maximum Break Load
SPM Single Point Mooring
UKCS United Kingdom Continental Shelf

REFERENCES