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# MOORING SYSTEM MONITORING USING DGPS

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## ABSTRACT

Over the recent years, the need for active monitoring of offshore production facilities has increased. Due to significant amount of mooring line failures in the recent past, permanent mooring systems for Floating Production Units such as FPSO's, FSO's and future FLNG's are typically required to have active monitoring systems to provide feedback of the mooring system's status, performance and integrity.

This paper will address some of the offered solutions with regards to active mooring system monitoring. Some pros and cons are given for several techniques within the industry currently available, and then a simple but elegant alternative is proposed. With the use of position monitoring, for instance with GPS signals, qualitative and quantitative feedback can be provided on the status of the permanent mooring system. A detailed explanation is given backed up by a few real life examples in which such a system was used to quickly assess the status of the mooring system.

## INTRODUCTION

While the number of permanently moored floating production facilities has increased steadily over the last decade, the number of mooring line failures has increased as well, as observed by Kai-tung et al. [1] and Maslin [2]. Even though permanent mooring systems are designed for at least a 1-leg disconnected condition, the safety factors are reduced and the potential of progressive failure of other mooring lines may have severe consequences. It is important to determine instantly if a mooring line failure has occurred so that the missing mooring leg can be repaired and production can proceed with high confidence of safety.

As indicated in many previous studies (for instance [5], [6] and [7]), there is a growing need for monitoring the performance, status and integrity of a mooring system for floating production facilities, such as FPSOs.

Theoretically, real time monitoring of the mooring loads in all of the mooring lines could provide valuable information. In combination with the monitoring of the environmental conditions it provides instant feedback on the performance of the mooring system, and a verification of the numerical analyses that lead to the design. In the long run, it can give an insight into the accumulated cyclic loading, providing quantitative input to assessing the remaining fatigue-life expectancy, which is a contributing factor into life-extension decisions.

Even though several options are available within the industry, obtaining reliable, accurate and real-time mooring loads is not as straight forward as one may think.

## DIRECT TENSION MEASUREMENTS

Direct tension measurements are possible and have been applied on floating platforms.

Systems which use fixed chainstoppers have been outfitted with load cells underneath their base, as for instance shown in Irani et al. [5]. Fixed chainstoppers can be used in systems where the chain is fed into the stopper in a constant orientation, which is often achieved by the use of fairleads. Friction in these fairleads can however take up a significant portion of the line tension, which the load cells don't take into account. The measured loads at the chainstopper are therefore highly inaccurate. In case of a single- or dual-axis chainstopper, load cells would make these moving parts overly complicated and therefore less robust.

 

A new development in recent years is the use of in-line load cells, which are now being developed and tested, as for instance showcased in Elman et al. [4]. This system, called the Inter-M Pulse, is an instrumented H-link, with a load cell housed in a protective casing, making it better suited for offshore installation. Data transfer is conducted via an acoustic transmitter.

A fundamental issue with any direct tension monitoring is the trade-off between accuracy and range of the load cells. No monitoring system to date is capable of handling extremely high loads, while providing significant accuracy in the range of loads which the mooring line will experience the vast majority of the time, as is illustrated in Figure 1. Even more often, the load cells or strain gauges are not mounted on the chain itself (due to -among others- installation difficulties and out-of-reach for maintenance reasons), but on support structures. As those structures are typically designed to be stronger than the mooring lines they support, the strain for a given load is going to be extremely small. An operator requesting mooring line monitoring should ask itself what it is interested in, the integrity of the mooring system in extreme cases (i.e. knowing if the mooring lines stay intact during a severe storm), or for instance the monitoring of fatigue loads. Having both is an illusion, at least with current state direct tension monitoring.

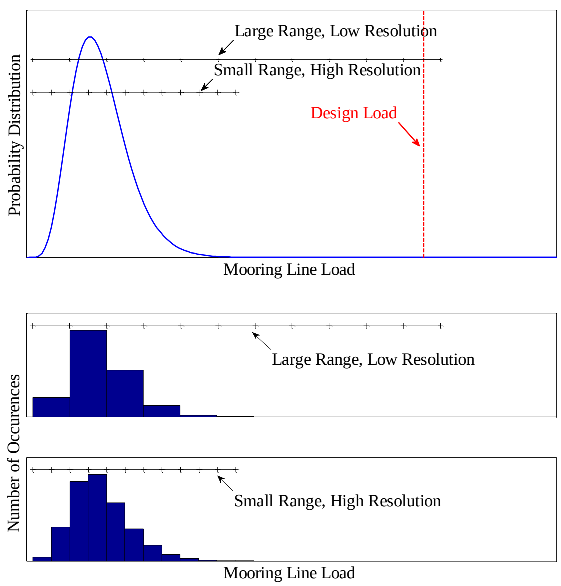


**Figure 1. Measurement discretization versus range**

Another issue that can come up with direct tension measurements is showcased in the following anecdote: One of the more recent FPSOs installed in the West-Africa region (permanently moored an external turret) has been outfitted with strain gages on the above water part of the chains, close to the chainstoppers, so to derive the tension in each of the mooring lines. After about one year in service the feedback from the operators on board was that the system performed very well. Not necessarily in providing accurate mooring line loads, but it was very capable of precisely indicating if it was night or day. It turned out that under sunlight (prevailing in that region), the thermal expansion of the steel on which the strain gauges were placed was many times larger than the strain caused by the mooring loads. The “mooring loads” had a nice 24-hour period loading cycle, while the fluctuating mooring loads (even the long period second order ones) were hardly distinguishable.

## INDIRECT TENSION MEASUREMENTS

A method which is applied commonly already is the use of inclinometers, which, for catenary systems at least, can derive an approximation of the mooring line tension by measuring the angle of the mooring line at or near the top connection to the platform [3]. Inclinometers also make for excellent aids for installation purposes, when mooring line angle changes significantly with applied pre-tension when the catenary is tightened. As pointed out by Elman et al. [4], tension can be derived from the mooring line angle (either from catenary calculations or look-up tables), but this introduces uncertainty. This is due to not including dynamic effects (calculated tension from angle is derived from a static equilibrium only) as well as to highly non-linear behavior. When the line is very slack, small changes in tension will introduce significant angle variations, while the tighter the line gets, the less significant the angle changes. However, inclinometers have the same accuracy over the entire range of fairlead angle and with an accuracy better than 0.1 degree can still be used to resolve the fairlead angle and thus the quasi-static tension.

## ROBUSTNESS AND RELIABILITY

Alongside the accuracy issues related to tension monitoring, a major concern with all this equipment (either direct or indirect) is the reliability and the robustness of the equipment itself, as is pointed out by Van den Boom et al. [6]. Equipment for sensitive measurements is often fragile, while the environment in which it is placed is harsh and non-forgiving. Especially in case of monitoring equipment positioned under water (for instance on an internal turret mooring system) access is not possible, so therefore the equipment has to be very robust to withstand many years of operation without failure. Under water cabling for data transfer from the sensors is in such cases hardly feasible. Just imagine how to handle such delicate cables during the installation of the mooring system, a process not known for its “silk glove” approach.

Even though nowadays remote data transfer is getting more viable and common, as for instance on the in-line tension monitoring systems discussed earlier, retrieval of equipment or replacement of batteries still requires diver or ROV intervention, a costly operation. Besides, putting in-line tension monitoring systems in a mooring line adds more components and hence more connectors, which in itself could reduce the reliability of the mooring lines. Kai-tung Ma et al. [1] have shown that close to 25% of the investigated mooring line incidents are due to failures at connector interfaces.

So, while there are multiple monitoring systems available, with all the issues that have not been resolved one should reconsidered what really matters when it comes to assessing the real time status and condition of a permanent mooring system.

The crucial parameter to monitor at all times is if all mooring lines are still intact. On an external turret mooring system -or on some of the spread moored vessels- that can be easily checked by visual observation. If a mooring line is broken, it will hang straight down, or at least at a much steeper angle than when connected. On systems where visual observations of the mooring system cannot be directly performed (internal turrets or spread moored vessels with below water fairleads) this is much harder to determine.

In some cases simple inclinometers can be used to check if a mooring line is connected or not. The inclinometers don't need to be accurate or very sensitive (only need to detect a large deviation in mooring line angle, i.e. hanging vertically), and can therefore be built quite rigidly. However, this would still require equipment in hard to reach places, which could potentially suffer during for instance mooring line installation.

## POSITION MONITORING

A reliable and cost effective alternative to monitor the performance of a mooring system is to observe the platform's position over time, as has already been indicated by Brown et al. [7] some years ago. In combination with monitoring the environmental conditions on site, the measured offset and bearing from equilibrium position and the vessel heading can provide instant feedback on the mooring systems effectiveness.

Position monitoring can be achieved by installing a Position Monitoring System (PMS) on board the vessel based on differential navigation systems. While navigation systems are easily and widely available, the position accuracy is in the order of 10 meters. This accuracy is improved significantly by adding differential corrections to the system's receiver onboard the vessel from reference stations. Often the differential corrections are provided by satellite based differential navigation systems. The most well-known satellite based differential navigation systems are GPS (Global Positioning System US), WAAS (service area North America) and EGNOS (service area Europe). With corrections from satellite based navigation systems, the position accuracy is about 3 meters. Horizontal positioning accuracy is increased to 0.1m (rms) with a Precise Point Positioning Service. Precise Point Positioning (PPP) solutions compute individual satellite clock and orbit corrections separately, free of ionospheric and tropospheric effects.

Locations which are of interest to monitor the offset are the COG for spread moored FPSO's and the turret for turret moored FPSO's. To obtain the maximum accuracy of 0.1 meter at these locations of interest, the antennas of the Position Monitoring System shall be installed at these locations. Both locations are located in hazardous areas though. MARIN's approach is to use a highly accurate long base dual antenna system and install it on the wheelhouse outside the hazardous production area. The antennas can be placed on the bridge wings at portside and starboard side. With readings of both position and heading the position can be determined at any location of the FPSO. With a Position Monitoring System installed in the wheelhouse, the accuracy of the position calculated at the turret center of a 300 meter FPSO in moderate seas is less than 0.4 m (rms) which is sufficient to detect line failure. In order to obtain a similar accuracy in higher sea states, the offset position shall be corrected with the wave frequency motions of the FPSO.

The benefits of this approach are:

- No sensors or any other equipment in hazardous areas;
- All equipment on FPSO bridge;
- No wireless transmissions of signals;
- No connection to other sensors such as gyro compass;
- Minimum of hardware, cabling and installation costs;
- Less components; higher reliability.

**Figure 2. A Position Monitoring System (PMS) installed on the on wheelhouse of an FPSO**

The Position Monitoring System includes a laptop on the bridge which acquires, visualizes and stores the measurements. The differential navigation system provides the longitude coordinate (deg and min), the latitude coordinate (deg and min), the heading (deg), the rate of turn (deg/s) and quality indices with an update rate of 1 Hz. Also the time is provided by the navigation system which allows for synchronization with data from other onboard systems (e.g. mooring angle monitoring system, loadmaster system, environmental monitoring system, etc.). It is noted that a Position Monitoring System could interface with these systems which ensures that all measurements are synchronized.

The Position Monitoring System calculates from the signals received from the navigation system, in real time with an update rate of 10 Hz, the excursions of the turret's center (or any other specified location) with respect to the reference position. The PMS visualizes the actual position of turret's center with respect to her reference position on a screen figure where also the reference position and the offset limits are shown. The vessel's heading is visualized in the same figure as well. Furthermore the actual excursion is presented relative to the maximum allowable excursion in a bar type figure. In case the actual excursion exceeds the anticipated excursion or in case a rapid transient behavior of the excursion occurs an alarm is given. This alarm is visualized in the GUI by changing the colors of typical GUI parts in red. An alarm signal can also be made available to any other system of the FPSO.

**Figure 3. Laptop with visualization software**

Future developments:
Following feedback from the industry, the Position Monitoring System will be extended with various features which are addressed shortly below:

In the aftermath of a line breakage a clear overview of the FPSO and tug positions is desirable. The PMS can be extended with the positions and heading of the tugs. The tug positions including lines to the vessel/FPSO bollard will be drawn to indicate line direction.

The system shows the offset of the FPSO with respect to her reference position and provides an alarm based on the anticipated offset and transient behavior of the offset. The PMS can be extended with the calculation of the real-time offset based on the actual measured environmental conditions. A mooring line failure does not always result in a pronounced offset (e.g. shallow water applications). By comparing the measured and calculated offset, failure of the mooring line can also be detected for applications with a minimum offset as a result of line breakage.

The above scope will be addressed in a new Joint Industry Project (LineSense JIP) which is currently being initiated.

## DETECTING MOORING LINE FAILURE

With a Position Monitoring System as described above, a mooring line failure can be easily detected.

Statically, the absence of a single mooring leg will result in the absence of a force vector, and the loads in the remaining legs will have to rebalance to a new force equilibrium, which results in a shift of static equilibrium position, as shown in Figure 4. A mooring system is of course never exactly in its equilibrium position, there will always be some environment acting on the floating platform. Therefore, it is essential to have a feedback on the in-situ environments as well. Note that for spread moored vessels a change of mean heading will occur as well, in addition to the shift in equilibrium position.

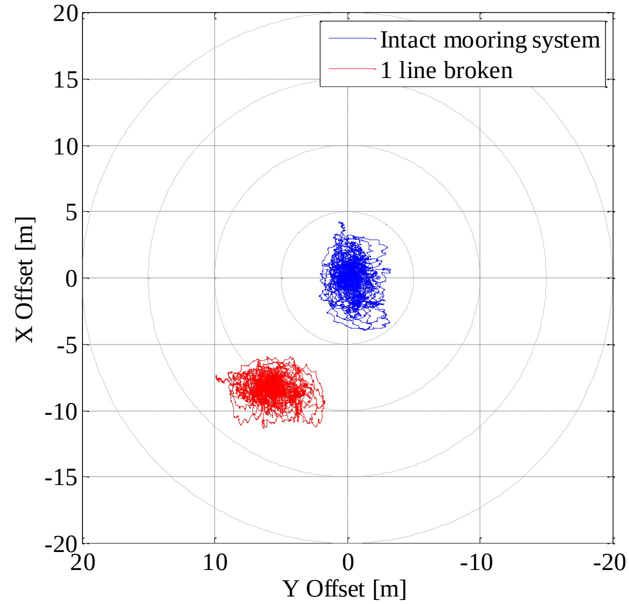


**Figure 4. Mean offset due to a single broken mooring line**

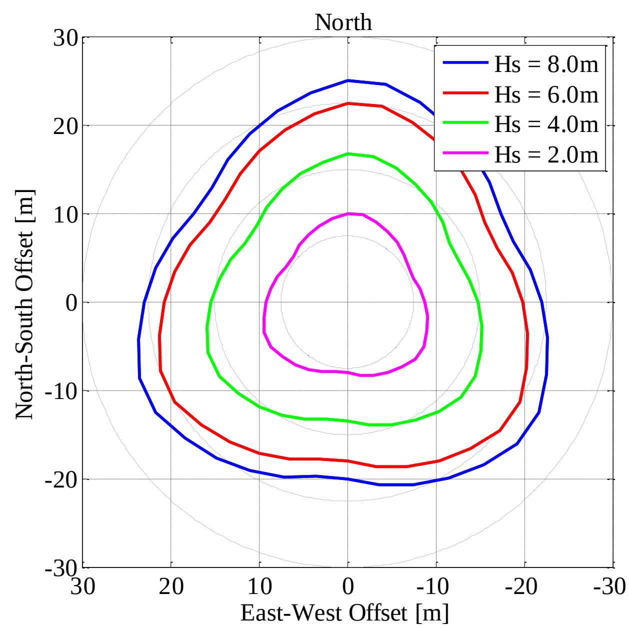


**Figure 5. Offset capacity plot for selected seastates**

Based on the as-installed mooring system information, a mooring offset capacity plot can be generated. An example for a 3-grouped single point mooring system is shown in Figure 5. This plot shows what offsets can be anticipated for the intact mooring system for certain environmental conditions. Similar capacity plots can also be generated for the effect of wind and currents, or combinations of those. If for some reason a steady offset is observed beyond the anticipated offsets for the given seastate, an alarm will go off. This situation can than quickly be analyzed by numerical simulation to see if this unusual offset could indeed be caused by a failed mooring line. In case this would be suspected, an underwater inspection can then be scheduled and performed to confirm.

A mooring line failure is in itself a rapid event, and the transition from the intact force and position equilibrium to the damaged equilibrium will be transient as well. An actual mooring line failure has recently occurred on an FPSO which was outfitted with a differential navigation system. Time traces of the statistics of the offset measurements recorded during the month in which the failure occurred can be seen in Figure 6. The statistics comprise the mean (blue), maximum (red) and minimum value (green) of the half hour measurements. During day number 17 the line failure occurred resulting in a shift of the offset of about 40 meters. A tug was afterwards hooked up to reduce maximum offsets.

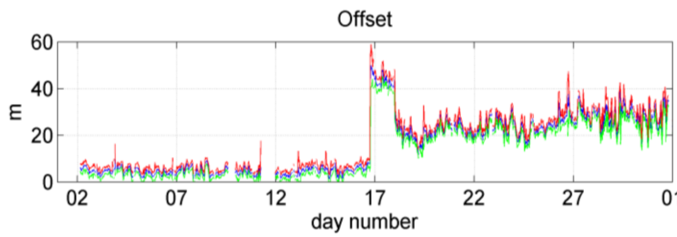


**Figure 6. FPSO turret offset over time**

This break occurred during relatively benign environments in approximately 1000m water depth. In this particular case it was an external turret, so the damage was instantly observed, but if this would have happened to an internal turret mooring system, the damage could have gone unnoticed. The monitoring software can be programmed such that this kind of transient behavior instantly triggers an alarm.

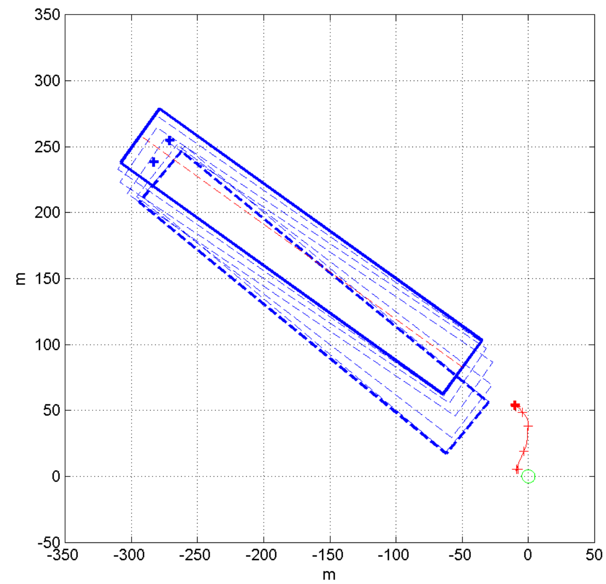


**Figure 7. FPSO positions immediately after line failure**

Figure 7 shows in steps of one minute the positions of the FPSO just before line failure and up to four minutes after the line failure. In red the corresponding positions of the external turret is shown. Figure 8 shows the East and North offset positions of the turret before and during the day of line failure.

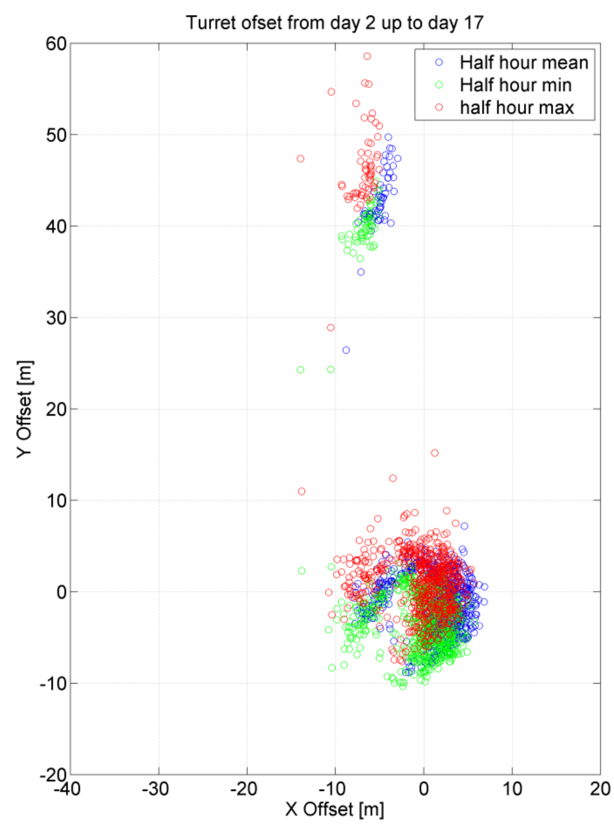


**Figure 8. FPSO offset (turret)**

## CREEP

It's not just mooring line failure that can be detected with the Position Monitoring System. Systems in ultra-deep water (for instance the spread moored vessels in Brazil's Santos Basin) use taut or semi-taut lines with long sections of polyester. Polyester lines tend to get a permanent elongation (creep) after being in use for some time, making the overall mooring system's force-deflection characteristics less stiff, in turn leading to larger excursions. Monitoring the mooring system over a prolonged time may provide insight in the amount of creep, as also indicated by Van den Boom et al. [6] and Viana et al. [8]. Using the Position Monitoring System, the vessel offsets and the instantaneous environments can be tracked over the course of months to years and the changes of offset from stiff to reduced stiffness can be observed. At that point an estimation can be made on the amount of creep that has set in and it can then for instance be decided to re-tension the mooring lines to retain the force-deflection characteristics of the original mooring system.

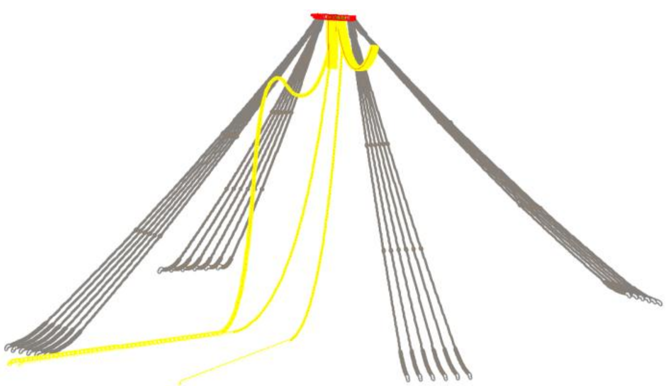

**Figure 9. Spread moored vessel in approx. 2000m water depth**

## SEASONAL VARIATIONS

Offshore Australia, on the North West shelf, one of the FPSO's has been outfitted with a DGPS system in late 2011. This particular FPSO has an internal, disconnectable turret, which obstructs visual observations to be made of the mooring system. After several months of monitoring, the crew onboard noticed that the offsets observed were consistently larger than what had been observed some months before, questioning whether or not one of the mooring lines would have failed.

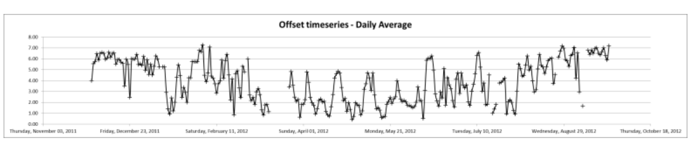


**Figure 10. Observed offsets**

The obtained data from that FPSO was sent over to SOFEC and was analyzed. The data available consists of instantaneous measurements of turret offset, vessel bearing, wind speed and significant wave height, taken twice a day. The total duration of this measurement series is 300 days, with a total of 280 days of measurements. On each of these 280 days, a measurement was taken at 7AM and 6PM and for comparison these measurements have been averaged on a daily basis.

The observed data has been compared to the metocean report, which gives insight into the governing environmental conditions at the location of this FPSO. In general, the trends observed correspond to the trends in the metocean report.

In the summer months (October to March), wind and waves tend to come from the South West, while currents are predominantly heading towards the North West. Therefore, the vessels heading is (roughly) anticipated to be around 180 degrees (Clockwise from North). The general intensity of the wind, waves and current is qualified as "strong", hence higher offsets can be anticipated.

In the winter months (April to September) the wind and waves tend to come from East, while currents are predominantly heading towards the West. Therefore, the vessels heading is (roughly) anticipated to be around 90 degrees (Clockwise from North). The general intensity of the wind, waves and current is qualified as "moderate", hence lower offsets can be anticipated.

Plotting the measured vessel bearing and the corresponding offset shows a relationship where the larger offsets are around 160 degrees vessel bearing, and the lower offsets are around 110 degree vessel bearing, close to the roughly predicted 180 and 90 degrees.

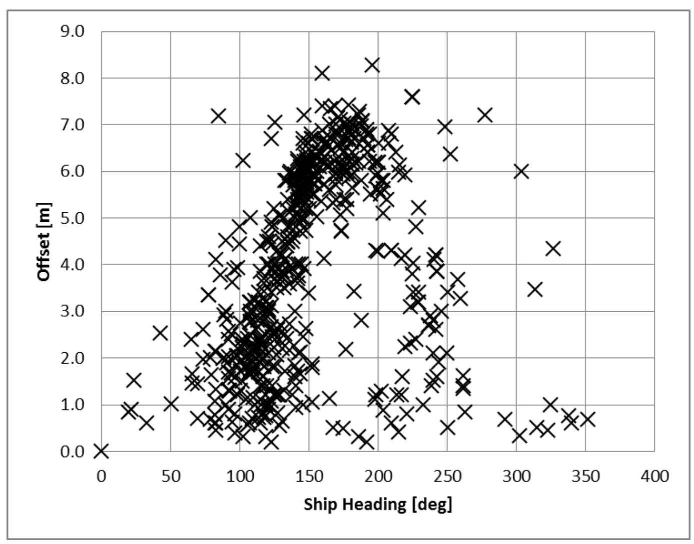


**Figure 11. Relationship between vessel heading and turret offset.**

When these anticipated headings and weather intensities are plotted on top of the measured, chronological data, the seasonal trends can be observed. Indeed the vessel generally had some larger offsets and in a different heading than a few months earlier, but there was no reason to assume a mooring line had broken. The regular UWILD (Under Water In-Lieu of Dry-docking) survey held about 6 months later confirmed this.

| | WIND | | WAVES | | CURRENT | | | ANTICIPATED VESSEL HEADING | General |
|---|---|---|---|---|---|---|---|---|---|
| | Direction (from) | Intensity | Direction (from) | Intensity | Direction (to) | Intensity | | [DEG] (CW from N) | Intensity |
| JAN | W-SW | strong | SW | strong | NW | strong | JAN | 180 | strong |
| FEB | W-SW | moderate | W-SW | moderate | NW | strong | FEB | 180 | moderate |
| MAR | SW | moderate | SW | strong | W-NW | strong | MAR | 180 | strong |
| APR | - | weak | SW | moderate | W | strong | APR | 135 | moderate |
| MAY | E | moderate | E | weak | W | strong | MAY | 90 | moderate |
| JUN | E | strong | E | moderate | W | moderate | JUN | 90 | moderate |
| JUL | E | moderate | E | moderate | - | weak | JUL | 90 | moderate |
| AUG | - | weak | - | weak | - | weak | AUG | - | weak |
| SEP | SW | moderate | SW | strong | - | weak | SEP | 225 | moderate |
| OCT | SW | strong | SW | strong | NW | moderate | OCT | 180 | strong |
| NOV | SW | strong | SW | strong | NW | moderate | NOV | 180 | strong |
| DEC | SW | strong | SW | strong | NW | strong | DEC | 180 | strong |

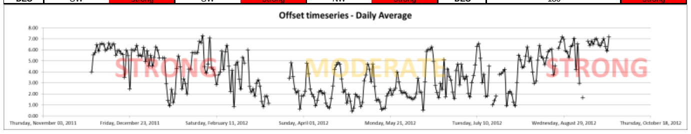


**Figure 12. Rough metocean analysis**

This shows that using position monitoring can quickly assist in analyzing the performance of the mooring system, which showed to be performing as expected in this case.

## CONCLUSIONS

With an increase in mooring line failures over the last decade, monitoring of the mooring system has become a much wanted and needed aspect of the integrity management of floating production systems.

While theoretically direct tension measurement of mooring line loads can offer useful feedback of the mooring systems' performance, integrity and effectiveness, practical experience has shown these systems to be inherently inaccurate and unreliable, with the net result that they are ignored by the operators. Many existing methods suffer from issues related to accuracy, reliability and robustness. The few systems that are overcoming these issues often turn out to be very expensive, either from an initial investment or from an operational perspective.

An alternative and cost-effective solution is proposed by means of an accurate Position Monitoring System, based on signals received by a Differential Navigational System, such as the well-known GPS. With such a system, the heading of the vessel and its position (COG or any specific point on board, like the turret center) can be accurately known to within 0.5m, or better based on the location of the receivers. The system is relatively inexpensive, and it is robust and reliable. A DGPS system with the appropriate software and data analysis can provide information on mooring performance in terms of stationkeeping as a function of environment, line break detection, and along with inclinometers can provide a good estimate of the individual leg performance.

Mooring line failure can then be detected based on transient position variation, as the loss of a mooring line will result in a sudden change of vessel position, and in case of spread moored vessels also heading. If the break would happen during harsh weather, and the transient behavior is less pronounced, the Position Monitoring System can be programmed such that a sustained offset outside of an anticipated envelope will trigger an alarm. It can then be analyzed (numerically) if this observed offset can be attributed to a mooring line failure or if other circumstances play a role in an observed unusual offset.

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