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A Critical Review on Permanent Catenary Mooring Health Monitoring and Evaluation Technologies

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Abstract

Recent times have seen the proliferation of Oil and Activities in increasing deeper waters. In such context, fixed structures are no longer a viable option. Floating structures applied for deepwater developments comprise of several major floater concepts that are either moored in position or employ dynamic positioning. For permanently anchored Floating Production Systems, the vessel and mooring systems are expected to withstand up to 10,000 years return period storms. Permanent catenary moorings have been known to fail prematurely due to various interconnected factors at the manufacturing, installation and operation stages. Such failures have led to serious aftermaths with consequences to human safety, environment and incurred costs. Catenary mooring integrity monitoring technologies to date are mainly focused on predicting line failure and are based either on geometric or tension based monitoring solutions. This paper presents a review of mooring line-based failure and the current integrity technologies in the market. The existing technologies are either geometrical or tension based, with latest systems being a combination of the two. A holistic review on wire-chain mooring line deterioration is discussed alongside challenges facing the industry. An overview of a proposed alternative methodology for mooring integrity is presented based on vessel-mooring dynamicity.

Keywords: *Deepwater, floating structures, mooring line integrity, monitoring technologies*

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INTRODUCTION

The age of easy large shallow water Oil and Gas resources are dawning to an end. This is dotted with ever increasing ventures into deepwater exploration and production. In water depths exceeding 300 m, conventional fixed steel jacket platforms become unfeasible. Exploration and production today takes to depths well exceeding the 1000 m mark hence floating solutions are constantly being sought after to develop deepwater and ultra-deepwater reserves. As the previously unexplored offshore blocks are opened, developers today face numerous engineering challenges both in terms of novel platform solutions and more isolated regions of the oceans with severe weather conditions. Present day deepwater floater concepts utilize two main types of station keeping methods; via mooring lines or dynamic positioning. By industrial norm, mooring lines are frequently employed as the main on-station restraint while dynamic positioning, if available, functions primarily as an auxiliary to the mooring system. There are of course exceptions to this such as seen in the newer generations of Mobile Offshore Drilling Units (MODU) which can rely completely on their Dynamic Global Positioning System (DGPS) coupled with azimuth thrusters to stay on station during drilling activities in deep water. Nonetheless, for the bulk of permanently moored production vessels, turret or spread mooring systems are employed to ensure that the floater offset is within acceptable limits. With the continual increase in demand for energy, the number of Floating Production Systems (FPS) has been on an upward trend. In 2013, this number was approximated at 400 installations and is anticipated to increase by up to 50% over the next 5 years [1]. Despite it's up front simplicity, the mooring systems used for FPS station keeping have been known to fail prematurely that which could potentially lead to serious consequences [2]. Examining historical incidents, this is most common in ship-shaped FPS such as Floating Production Storage and Offloading (FPSO) vessels. The long span beam of an FPSO would naturally subject it to high abeam metocean forces if not headed into the predominant wave direction. Even with weathervaning capabilities this can prove to be a challenge without active thrusters as the stochastic nature of metocean loads rarely occur concentrically, if ever. It is then prudent to note that to date, FPSOs are the most common type of floating production system with a market share of 65% of the available floaters [3]. Figure 1 showcases several FPSO projects in the making.

Examples of FPSO projects in the planning stage				
Discovery	Country	Field operator	Water depth (m)	Estimated production start
Africa				
Blk 32 -- Kaombo GG	Angola	Total	1,600	2016/17
Bonga Southwest	Nigeria	Shell	1,200	2017/18
Nsiko	Nigeria	Chevron	1,768	2018/20
Elephant	Congo	CNOOC	550	2020/25
Bobo	Nigeria	Shell	2,480	2020/25
Brazil				
Oliva/Atlanta BS-4	Brazil	Queiroz Galvao	1,560	2017/19
Carcara BM-S-8	Brazil	Petrobras	2,027	2018
Espadarte Module III	Brazil	Petrobras	750	2020
Libra Complex	Brazil	Petrobras	2,200	2020/30
Franco Leste	Brazil	Petrobras	1,800	2019
Other Regions				
Ayatsil/Tekel	Mexico	Pemex	120	2016/18
Maximino Cluster	Mexico	Pemex	2,500-3,000	2018/22
Gohta	Norway	Lundin	342	2020/25
Sea Lion	Falklands	Premier	415	2019/20
Belud	Malaysia	Hess	155	2015/16
Bunga Dahlia/Teratai	Malaysia	Petronas	65-70	2016/18
Ubah	Malaysia	Shell	1,430	2018/20
Ande Ande Lumut	Indonesia	Santos	73	2016-18

Fig. 1: *FPSO Projects in the Pipeline [3].*

With more FPS to join the fleet and the requirement of life extension in dealing with aging infrastructure, there is a pressing need for operators to ensure mooring integrity as evident from the case study in Ref. [4]. Today, the advent of high tech sensor systems has enabled the monitoring of dynamic response of the FPS alongside the stochastic environment in-situ, in real time. These readings can range from motions, loads, vessel response, wind, wave and current conditions at the platform. Such monitoring campaigns would typically involve detailed planning to ensure that its objectives are met [5]. This obviously has enormous potential, if executed correctly to streamline inspection and maintenance procedures as well as gauge the performance of the mooring system.

THE NEED FOR MOORING INTEGRITY

With an increasing number of FPS soon hitting the oceans in ever more isolated regions, it is crucial that operators and developers pool efforts into development of robust and reliable mooring system failure prediction or prevention mechanisms. FPS life extension due to improved oil recovery technologies requires the management of aging infrastructure. Such floating facilities are very unlike their counterparts in the marine sector because they are relatively complex and cannot easily be dry-docked for repairs [6]. These facilities are typically expected to maintain on-station for the entire operating duration. The Joint Industry Project on mooring integrity places mooring systems on FPSOs as Risk Category 1 safety critical systems, which is its highest risk rating [2]. There is a clear need to focus on mooring integrity backed by sound data, state of the art technologies and engineering [7]. A mooring system failure may potentially cause severe human, environmental and economic consequences [8]. Failure of a single line if undetected may cascade into failure of other lines which would lead to excessive vessel drift. This can cause the riser system to break, hence if pressurized, will lead to hydrocarbon release and production shutdown. Figure 2 [9] illustrates this. Mooring failure will also lead to incurred financial cost as evident from the Gryphon Alpha which resumed production in the North Sea only after 27 months from the event where it broke free from its mooring causing significant damage to subsea infrastructure. The cost incurred herein is expected up to $ 1.8 billion [8].

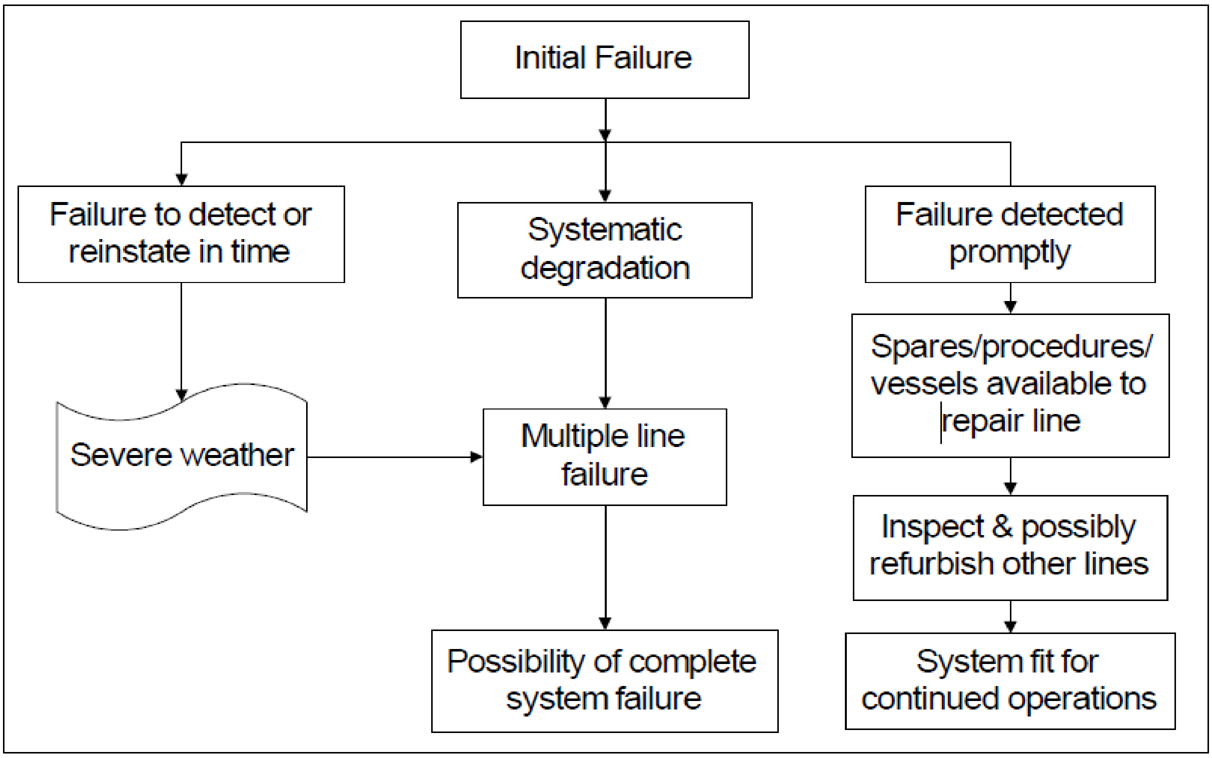

Fig. 2: *Possible Scenario Flow Diagram [9].*

Table 1: *Mooring Incidents from 2006 to 2014 in Asia Pacific [1].*

FPSO	Year	Description of Event	Consequence
Linhua FPSO	2006	Struck by Typhoon Chanchu causing damage to all 10 mooring legs	7 legs and all 3 flexible risers broke away from FPSO causing damage to subsea infrastructure. Production was halted for over one year
FPSO Kikeh	2007	One line parted at the shackle of an anchor, believed due to low fracture toughness	Other shackles from the same batch showed low toughness
Nan Hai Fa Xian FPSO	2009	Struck by Typhoon Koppu causing 4 of 8 lines parted in the bottom end of upper wire segments	Vessel drift caused pipeline to rupture and all risers to break
Hai Yang Shi You 113	2009	Yoke tower collapse	Vessel drift caused risers to break
Rubicon Vantage FPSO	2014	Bad weather conditions caused the vessel to drift into the exclusion zone	Mooring chains came into contact with production riser, resulting in a discharge of approximately 20 barrels of oil

Mooring Integrity is a highly specialized industry target sector which has only garnered credible attention within the past decade. To re-emphasize on the magnitude of the matter discussed herein, a summary of recent FPSO mooring incidents in the Asia Pacific Region between 2006 and 2014 are summarized in Table 1 [1]. In addressing this matter, several notable mooring system integrity management systems have been proposed to date. This ranges from simple visual inspection [6] to complex sonar systems [10, 11]. The effectiveness vary from one project to another and it can be inferred that there is not yet a single solution package that is capable to cover the entire spectrum of mooring systems.

It should be noted that mooring line incidents are not exclusive to FPSO vessels but have also been documented for other FPS such as semi submersibles. A case example would be to recall Argyll Transworld 58 which was a production semi-submersible that suffered complete break away in 1981 [9]. There was also a recorded series of semi-submersible multiple line failures during the storms of October 1991 and January 1992 [9].

A hypothetical mooring incident would typically be initiated by failure of a single mooring line which if undetected may result in multiple line failure. An exception would be to scrutinize Petrojarl 1, which in 1994, experienced concurrent failure of two lines after being battered by a 20 to 25 m wave.

This implied that a common degradation mechanism may result in simultaneous multiple line failure [9]. The obvious lack of documentation on historical mooring systems have spurred the industry to develop a better understanding on mooring deterioration and the reliable quantification of such risks.

MOORING LINE DETERIORATION MECHANISM

This paper discusses mainly chain and wire rope mooring lines as they are most common in offshore FPS industry today. However, it should be noted that polyester mooring system are gaining popularity, as evident from notable projects like that of the Mad Dog Spar but its discussion is beyond the scope of this paper. A generic failure model applicable to mooring systems is a well-known hypothetical reliability curve or 'Bathtub Curve' shown as Figure 3. As can be clearly deduced, the initial phases of a mooring program will experience high possibility of failure.

This is attributed to the initial commissioning and startup phase [6] where ill-organized installation and bad practices may lead to pre-mature unplanned damage. Once properly installed, the mooring system will experience a steady failure rate during the bulk of its operational lifespan, which is usually based on the accepted as-designed risk margin. Towards the end of its life, illustrated in Figure 3 as the wear out phase, the mooring system again experiences high risk of failure due to prevalent fatigue, wear, corrosion and accumulated damages.

This can also be linked to an interesting tenant of basic probability stated as such: the longer the vessel stays on station, the higher the probability that it will experience extreme storms. The EU Major Accident Hazards Bureau (MAHB) through its Major Accident Reporting System Database (MARS) approximates that 28% of all reported major accident loss of containment events are due to aging [6]. With a degraded mooring system and increased probability of seeing an extreme 100 year storm, this is a crucial stage for the FPS especially if life extension is being considered. To understand mooring integrity, the operator must first grasp the major common mooring failure mechanisms. This is summarized in Table 2.

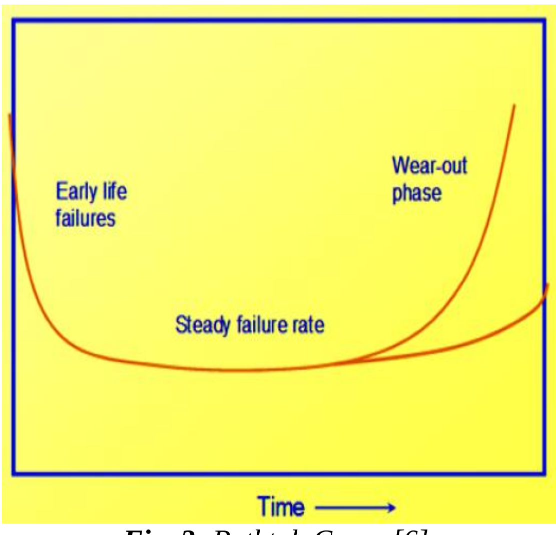

Fig. 3: *Bathtub Curve [6].*

It is also important to note the entire length of the mooring line is susceptible to failure but historical incidents have shown a trend that failures typically occur at interfaces or discontinuities. These include [8]:

- Between the mooring line and vessel (fairlead or in the hawse pipe)
- At connections between two types of line
- Where buoys, clump weights or tri-plates are attached to the line
- In the thrash zone (dynamic contact with seabed)
- Where the line descends into the seabed to connect with the anchor pile.

Table 2: *Mooring Line Deteriorative Mechanism.*

Deteriorative Mechanism	Reference
• Sea floor trenching • Wear • Fatigue • Turret Hawser Tube/Bending Shoe/Fairlead Issues • Out of Plane Bending • Differential Loading • Vortex Induced Vibration • Microbiologically Influenced Corrosion (MIC) • Sulphase Reducing Bacteria (SRB)	[6]
• Wear • Fatigue • Abrasion • Corrosion (general and piting) • Damage during transport/installation • Strength • Excessive tension • Operational	[8, 12]

The Health and Safety Executive (HSE) Joint Industry FPS Mooring Integrity report 444 [2] gives additional detailed guidelines and information on the mechanical and biological deterioration of a mooring line. The keen reader is referred therein. Several generic areas of interest in mooring degradation [9] are labeled in Figure 4. Interestingly, it is rather counterintuitive that the leeward lines are likely to have worst wear [2] as indicated by the red arrows in Figure 5. This can be reasoned by the fact that the slack leeward lines experience greater relative motion in their links and increased risk of kinking or harsh dynamic touchdown at the seabed.

Mooring Integrity Challenges

There is a pressing albeit difficult need to fully understand mooring failure mechanisms and manage such risks. Threats from mooring system failure are well documented and the industry is pushing towards new technological frontiers to manage its risks. To date, many, if not all technologies rely on either tension measurement or geometrical mapping methods, or both in tandem. Some of the better publicized technologies are discussed briefly in this paper. There is rarely a solution too, for detection of mooring failure beneath the mudline, which is a zone of constant dynamicity and possibly, micro-bio action.

It should also be observed there is not a single solution package that can address in general, the broad spectrum of mooring systems and their various applications in the FPS industry. If the same ideology is maintained, it is doubted that such a solution would ever be achieved. Many, if not all of the existing solutions are unable to predict mooring line failure, rather, they are focused on detecting when a failure has occurred. A good structural health monitoring system should be able to perform both functions.

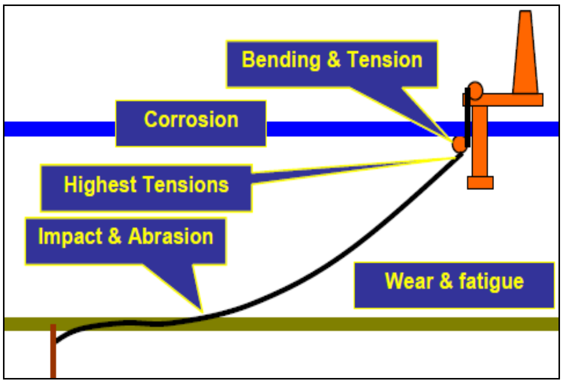

Fig. 4: *Key Areas to Inspect for Mooring Degradation [9].*

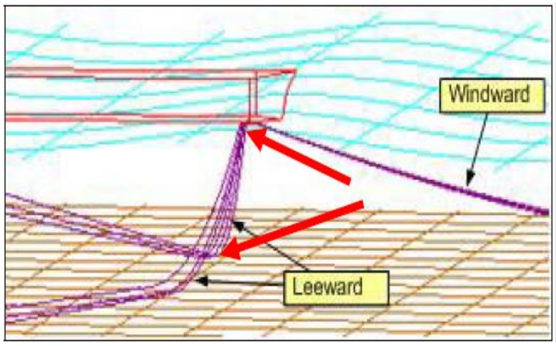

Fig. 5: *Key Areas (Red Arrows) Subject to Degradation [2].*

The ideology referred to is that of the mooring integrity solutions which usually consist solely of the aforementioned measurement of the mooring lines without regard to the vessel's motion and dynamicity. It is noted nonetheless that metocean measurement correlations are beginning to gain traction as a verification step to filter out anomalous readings from the mooring lines.

Most documented or commercialized strategies to date would typically require undersea installation of sensor arrays which would relay information back to the control room on deck. Data transmission can be performed via hardwired cable or more recently, by acoustics which is preferred due to avoidance of accidental cable snapping and knotting. Herein, a small later section of this paper is dedicated to a presentation of an alternative school of thought.

It is also worrying that many existing FPS facilities are ill-equipped in terms of mooring monitoring. The statistics of mooring monitoring capabilities are presented in the HSE's JIP Report on FPS Mooring Integrity are summarized for North Sea based FPSOs are as such [2]:

- 50% of units cannot monitor line tensions in real time
- 33% of units cannot measure offsets from the no-load equilibrium position
- 78% of units do not have line failure alarm
- 67% units do not have mooring line spares available
- 50% of units cannot adjust line lengths

The matter of estimating wear and corrosion rate of mooring lines is rather vague up till today despite intensive research. Reason being that the many cause of wear and corrosion can be intertwined in unforeseen combinations with project specific dependence. This is evident from [13] where a wide variation of chain link wear was measured, even for similar mooring system designs operating in the same region. More than often, the industry, through actual measurement of diameter loss has found that the design standards under compensates for the excessive rate of wear.

ISO 19901-7: 2005 provisions for wear and corrosion by an increase in diameter, further stating that typical values of allowances would lie within 0.2 mm to 0.8 mm per year [13]. Whereas information from a number of companies revealed that the wear may be up to 3 or 4 mm per year [2]. The lack of baseline dimension data complicates the computation of actual loss of thickness. It can be inferred that such ambiguity on a baseline benchmark would undermine the reliability of actual mooring dimensioning. The Mooring Integrity JIP has thus developed a more universal practical method for calculation chain wear using a modified form of Archard's Wear Equation [2, 13].

MOORING LINE MONITORING

Visual Inspection

General Visual Inspection (GVI) is probably the oldest and most established method to help operators collect meaningful information on the condition of a mooring system. It involves visual based underwater inspections which may not reveal in depth mooring flaws. Today, it exists in many upgraded variants and forms part of the set of subsea inspection technologies in aiding decision making. A well-known subset of this is the risk based inspections which must be planned and executed according to a class of defined objectives [6]. The frequency of inspection would determine largely on the client's requirements alongside relevant codes and standards. GVI is usually the initial stage of a mooring monitoring program followed by a Close Visual Inspection [6]. This is where a non-intrusive global survey of the mooring line is performed either with divers or Remotely Operated Vehicle (ROV). In this context, ROV is preferred over their human diver counterparts as the moving dynamics of mooring lines may pose a serious safety issue for divers.

This does not provide in depth information about the mooring condition as the length of the line would be covered in marine growth [14]. Forcefully removing marine growth is highly cumbersome and may expose the mooring links to accelerated corrosion. GVI does not provide quantitative measurements of the mooring line, hence will find limited use in the FPS scene today. One of the more established methods today is by having an 'optical caliper' shown in Figure 6, utilizing video cameras and lights to collect high resolution video footage of specific links [14]. The video frames are then analyzed by spatial analysis software. Chain dimensioning and in depth deterioration 3-dimensional models can then be re-created in a computer [6]. It should be noted that although visual inspections have improved tremendously, they are still unable to see lines below the mud line, which is usually a key area of concern [12].

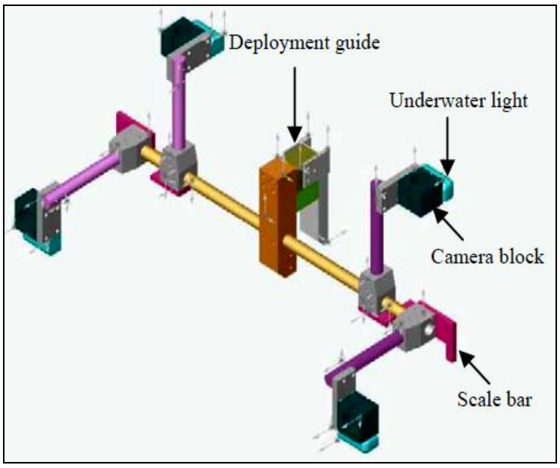

Fig. 6: *Optical Caliper Generic Components [14].*

Progressive Inspection Technique

The Progressive Inspection Technique is essentially a multi-tiered GVI-CVI with increasing depth of recorded details. Put in other words, the inspection progresses from gathering data of the entire system at a high level after which detailed inspections are performed at suspicious and high risk areas [6].

Examples of high risk areas are as labeled in Figure 4 through Figure 5, mainly at the dynamic thrash zone, splash zone, transitions and interfaces. After in depth subsea dimensioning and documenting have been performed the mooring links are then re-modeled in computer software or machined in its physical form by grinding a similar replica for testing of reserve strength.

This is a logical progression from a simple visual inspection where techno-economic considerations are being balanced. In this sense, the costly and cumbersome Close Visual Inspections utilizing specialized tools such as the aforementioned 'Optical Calipers' can be optimized by the prior GVI and knowledge on critical mooring areas.

This method is anticipated to be one that offers a balanced intelligence – cost relationship. The interested reader may consult Oil & Gas UK's Mooring Integrity Guidance [15] for an in depth discussion on practical mooring integrity fundamentals and best practices.

Sonar

With Sonar technology being constantly improved by the marine industry, it has now found application in mapping the geometric layout of a turret mooring system. One such technology is RAMSTM developed by Tritech International Limited [10]. RAMSTM is based on Tritech's proprietary multibeam sonar technology which enables the operator to visualize the area directly beneath the turret chain table in a 360 degree plane in real time [11], as shown in Figure 7. The technology is touted to be able to detect mooring failure and provide a riser integrity monitoring solution in one package. Its primary function is to provide crucial information to the crew on the risk exposure at a current point in time [11].

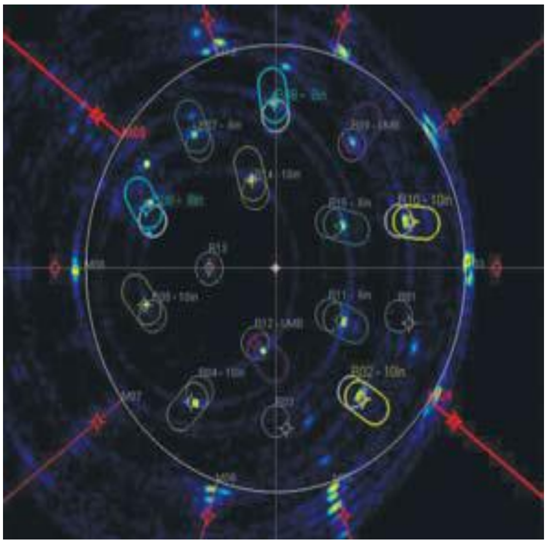

Fig. 7: *RAMS™ Software [10].*

Anchor Leg Load Monitoring System (ALLMS)

The limitations of inspection based routines were highlighted in a preceding section. Such non-invasive inspection methods would typically not be able to provide a detailed understanding of the complete mooring system [1]. Most mooring line monitoring systems of the past employ load cells for direct tension monitoring or inclinometers for line angle computation [7] which is then used to obtain line tension from catenary based lookup tables [12].

Load cells can be arranged on the chain table of a turret for direct monitoring of mooring tension [12] or alternatively, be attached in-line with the mooring line in the form of 'pin-like' load cells or shear pins. While measuring the tension on each mooring line is ideal, there are issues in dealing with load cell based ALLMS.

Such difficulties mainly stem from intensive maintenance, replacement or re-calibration issues for load cells placed in the load path (i.e., Chain table) and the fact that shear pins would require modifications to the chain link itself which may affect the integrity of the system [12]. Figure 8 through Figure 9 showcases load cell (turret chain table) and shear pin systems. Strain gauges on the other hand, are known to suffer issues with water leakage [8].

Inclinometer based ALLMS have also been used to monitor mooring line tension, indirectly. Unlike load cells or shear pins, ALLMS utilizing inclinometers measure mooring line angle that which is converted into tension via look up tables with fundamentals on catenary equations. The main benefit of this technology is that it requires relatively much less effort to retrofit into existing systems with possibly no design constraints for the FPS's mooring system [1].

However, despite gaining popularity, inclinometers are still approximately second order accurate due to the presence of a yet un-quantifiable error in the process of converting the recorded angles to tension via the look up table. This then banks questions as to its reliability in predicting line failure. Figure 10 showcases an acoustic based data logger for angle acquisition. The use of acoustic data logger would mean a slight delay in failure reporting during an event as compared to hardwired configuration. The INTEGRIpod loggers alongside the MOORASSURE software is an example of the implementation of traxial inclinometers with look up tables [16].

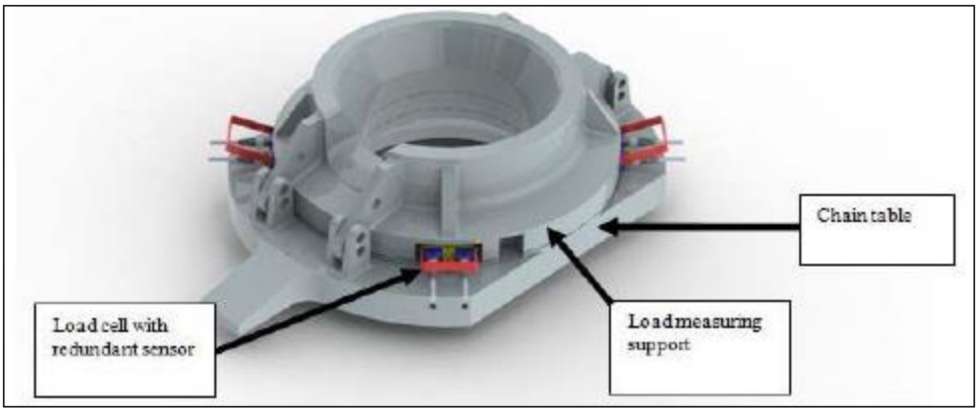

Fig. 8: *Illustration of a Chain Table Load Cell System [12].*

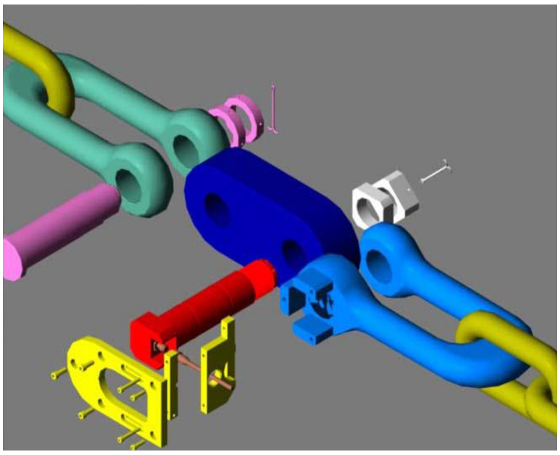

Fig. 9: *Illustration of a Load/Shear Pin System [2].*

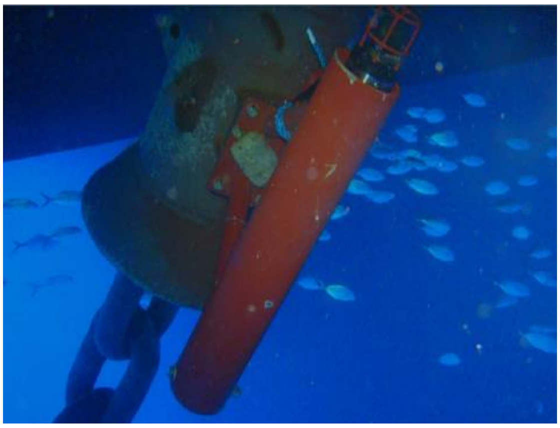

Fig. 10: *INTEGRIpod Installed on Chain Hawse [16].*

New Generation of Direct Tension Monitoring Systems

A recent development would be to scrutinize the Inter-M-Pulse system which combines both inclinometers and tension measuring methods. It is essentially an instrumented H-Link capable of measuring angles and tension, to be placed in line with the mooring components without the need to resort to load pins [8]. It should be noted that direct inline tension monitoring is able to more accurately track *in situ* tension performance. The Inter-M-Pulse is encased with a highly durable polymer shroud and houses acoustic transmission equipment to enable wireless communication with the vessel [8]. Although this integrated system is definitely an improvement over standalone modules, it would still be unable to detect mooring failure below the mudline unless moved by an extreme event. It is the purpose of the new proposal at the end of this paper that the alternative can be incorporated into existing technologies to provide detection of impending failure, beneath seabed failure and damage localization. A good structural health monitoring system should not only be able to tell the operator when failure has occurred but rather also, to pre-amp the degraded condition and gauge the risk at any point in time prior to failure.

Brief Conceptual Overview of Alternative Method

It was noted that the wide variations observed in mooring line wear can be attributed to the variations in the motion of the moored unit [13–15]. The difference in vessel response in return, would depend on the seakeeping capabilities of the unit, which is primarily a function of the environment and the inherent vessel characteristics (i.e., type of FPS, dimensions, loading, hull submerged shape, propulsion system).

This new ideology then addresses mooring integrity from a global dynamic standpoint: by utilizing the vessel-mooring system hydrodynamics and mechanical properties to gauge changes in the stiffness of the mooring lines. In principle, its implementation is misleadingly straightforward. A simplified algorithm pseudo chart is illustrated in Figure 11.

The method depends primarily on the intelligent detection of change in vessel hydrodynamic response given an input metocean spectra as measured from the metocean sensors on board the vessel. It is noted that no attempts to measure strain or the geometric position of a mooring line is made. Hypothetically, a damaged mooring line will result in a notable change picked up by sensitive sensors in vessel responses to the environment although these changes may not be obvious to a human being. Where possible, the accelerometers placed at pre-determined intervals along the mooring line will provide information on the dynamicity of the lines. Modal characteristics will be extracted therein to determine and identify damage using novel smart damage detection algorithms. The difference in mooring line drag contribution to the second order FPS oscillation which is quite substantial [17–33] may be used to infer mooring line damage from the aforementioned smart algorithm. It is anticipated, as done with fixed jacket platforms, that the type and extent of damage would be able to be captured via this new method. This new school of ideas has the potential to be integrated into existing technologies to provide added value and increase in reliability of failure predictions and detection.

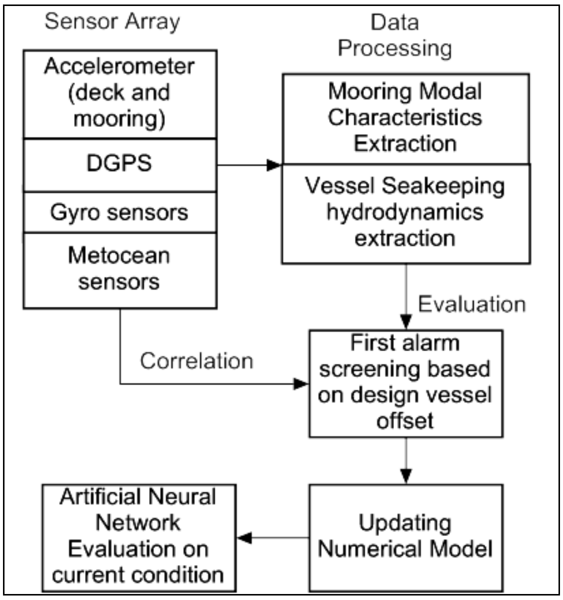

Fig. 11: *A New Ideology: Generic Overview.*

CONCLUSIONS

This paper presents an overview of mooring line integrity. It is clear herein that the soundness of a mooring system is crucial to the state of the entire production system. With increasing number of permanently moored production solutions coupled with heightened awareness, there is a viable need for reliable mooring monitoring solutions. Ship-shaped production vessels are particularly susceptible and sensitive to mooring line failure due to their inherent large length to breadth ratio and water plane area. Mooring line integrity monitoring technologies today are largely limited to detecting failure rather than predicting it. Such technologies typically utilize either tension or geometric monitoring, otherwise, both in tandem. Tension based monitoring technologies can be instrumented by direct inline load pins, customized links or by load cells. These solutions may pose a problem in undermining the integrity of the entire mooring line and pose maintenance or re-calibration difficulties. Geometric monitoring can be automated like that of sonar and inclinometer systems or they may be charted via visual inspections. The progressive inspection methodologies are an extended, streamlined version of typical 'classic' general and close visual inspection. These methods, whilst aptly employed in historical developments, are noted to have major room for accuracy and reliability improvements. A combination of both tension and geometric monitoring has been implemented successfully via the Inter-M-Pulse Integrated H-link system, although there is rarely a comparison made in the literature with standalone systems in terms of mooring line damage detection accuracy. An alternative method is proposed in the final discussion, utilizing vessel – mooring structural-hydro dynamic characteristics to predict impending failure and detect when failure has occurred. As the Offshore Oil and gas industry push for ever deeper waters in harsher environments with limited budgetary constraints, permanent mooring systems will have to be instrumented with the appropriate systems to ensure integrity and prevent unplanned mishaps which might result in unprecedented consequences.

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