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## Cost Effective Mooring Integrity Management

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### Abstract

This paper discusses data which indicate deteriorative trends in mooring chains on offshore floating production systems (FPS). A global data set collected from the measurements taken on chains on 29 FPS shows a clear trend towards increased elongation of mooring chains near the touch-down point at the seabed. Elongation also occurs in chains near the surface at the interface with the vessel and turret. At the midpoint there is less deterioration through elongation.

Data were collected using an optical caliper chain measuring system deployed by ROV to take measurements of chains while they are in the water. This *in situ* methodology is both cost- and time-efficient because it eliminates the need to recover chains for dry inspection. It also reduces the risk of mooring damage during the retrieval and reinstallation.

When used in combination with other tools that assess the looseness of chain link studs and that provide 3D video visual display, this inspection methodology can improve the management of mooring systems and reduce the risk of a moorings failure, thereby increasing the operational integrity of FPS.

### Introduction

The integrity of underwater moorings is critical to the viability of floating offshore production installations. Industry operators, regulators and certifiers have recognized that a failure of the moorings of a floating production system can have serious consequences for assets, production outputs, the environment and safety of crew.

The UK Health and Safety Executive ranks multiple mooring line failure of FPSO facilities as Risk Category 1, its highest hazard rating. A study by DNV found that the average failure rate for an FPSO moorings system in the UK is once every 5.4 years<sup>1</sup>. In addition to FPSOs, moorings failures also have serious implications for other floating installations such

as Spars, FPU's, MODUs and CALM Buoys. Certifying authorities such as DNV, Lloyds, ABS, and Bureau Veritas require periodic inspection of chains as a component of vessel reclassification. And an international Joint Industry Project that was convened in 2003 to study the issue has released recommendations on improving moorings integrity of floating production systems<sup>2</sup>.

The implications of failure are wide ranging. They include everything from reduced or suspended production to vessel damage through collision, oil spills and endangered safety of crew on board floating production installations and vessels in the vicinity. In order to avoid failure operators must verify the operational integrity, or condition, of mooring components. By doing this, ongoing deterioration can be identified and monitored to ensure that appropriate actions are taken before the condition becomes critical and failure imminent.

### Traditional approaches of moorings inspection

Dry inspections require the recovery of mooring chains from water for assessment on the deck or on shore. While chain recovery is a necessity for mobile drilling units (MODUs), this measure is neither cost-effective nor time-efficient as an inspection methodology for permanently and semi-permanently moored installations such as FPSOs. In some cases the recovery of mooring chains is not possible because of design limitations of turrets and the absence of in-built equipment that allows the moorings to be recovered.

When mooring recovery is possible, it is necessary to reduce or shut down completely the level of production as a safety measure. Recovery procedures usually require the use of large anchor-handling vessels and ROV support which add extra costs and time to inspection programs. There is also an element of risk associated with recovery and reinstallation because of the potential for damage to mooring chains and their components. The latter is particularly troublesome because if a mooring is damaged during reinstallation, damage is unlikely to be detected until a subsequent inspection.

Increasingly, operators are seeking to mitigate some of these risks and costs by avoiding dry moorings inspections and conducting programs underwater while mooring chains remain *in situ*. These in-water programs are rapidly becoming established as a standard component of operational inspections.

While in-water mooring surveys are undoubtedly time- and cost-efficient for operators, this inspection methodology is not without its limitations. Underwater mooring surveys alone

provide limited information because the surfaces of mooring components are obscured from view by marine organisms which become established on underwater components of offshore facilities. Unless this marine growth is removed, detailed inspection is not possible.

When marine growth is removed, in-water surveys conducted with video cameras provide evidence that moorings are in place and intact but they do not provide enough detail to quantify extent of deterioration and assess the fitness of moorings.

To address this limitation, a new generation of quantitative in-water inspection systems and techniques has been developed to identify and monitor deteriorative trends in moorings systems. This paper presents a summary of data collected on mooring chains on 29 floating production systems (FPS) world wide. It describes the nature of deterioration and its location on moorings arrays. It also describes the systems which have been used to collect data.

### Inspection of mooring chains

The chain components of FPS mooring systems are the subject of particular scrutiny because visual surveys have identified various features thought to be indicative of deterioration on chain links. These include shoulder wear and flattening of internal radii, particularly in the regions of the seabed touchdown (contact) and at the vessel interface. The presence of these seabed features is indicative of the dynamic condition of mooring systems, which are constantly moving in response to the dynamics of the FPS.

**In-water chain measurement.** There have been a number of in-water ROV-deployed mooring chain measurement systems developed, but the only established system is an 'optical caliper' that uses video cameras and lights on a deployment frame (Figure 1) to collect scaled, high-resolution video footage of specific links.

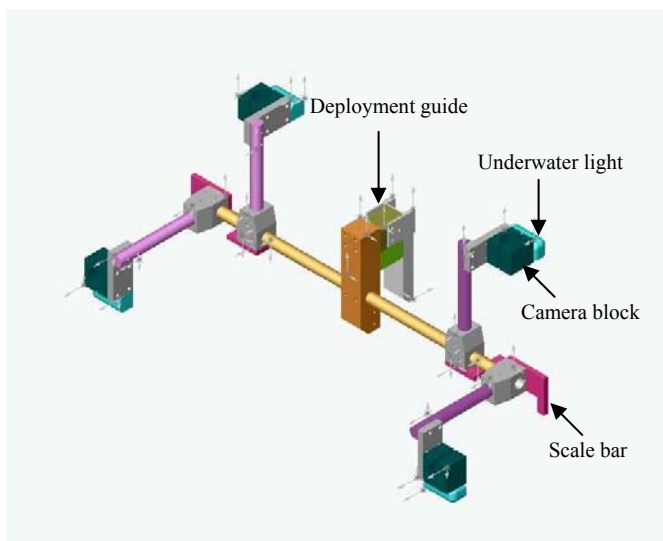


Figure 1 Illustration of 'optical caliper'- type mooring chain measurement system showing positions of cameras, lights and guides

The system is deployed by ROV (Figure 2) and measures the chain dimensions through software-based spatial analysis of synchronous video frame grabs from each of the cameras (Figure 3). The standard system measures two parameters, the length of specific numbers of chains, and the 'double diameter' at the contact point (grip zone) of adjacent links (Figure 3). Measurements are subsequently compared to established manufacturing and in-service chain standards<sup>3,4</sup> (Table 1). This type of system has no depth limitation except that of the onboard lights and cameras, and can be configured to measure difficult-to-access regions at the vessel interface and other types of mooring 'jewelry' such as connectors, shackles and kenter links.

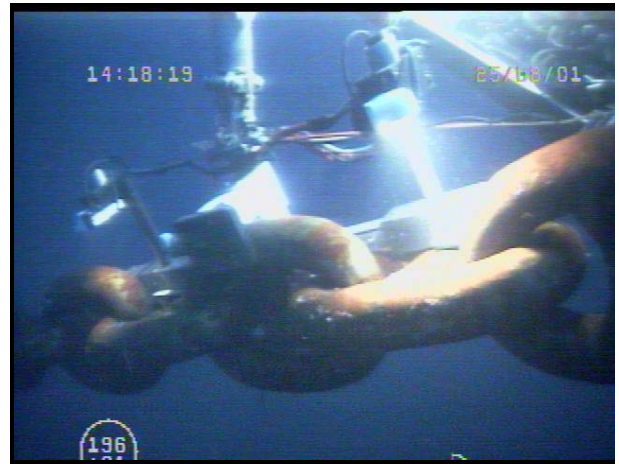


Figure 2 Video frame grab showing 'optical caliper'-type chain measurement system being deployed to a chain by ROV

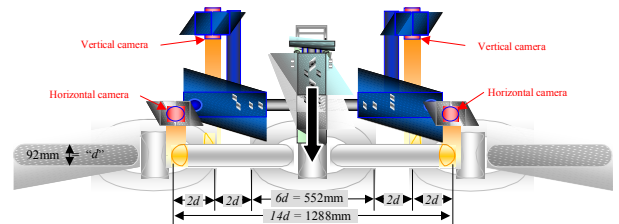


Figure 3 Illustration of orientation of 'optical caliper'-type chain measurement system to chain links during deployment, and chain parameters measured (in this case a 92mm studded chain)

Measurements are compared to established manufacturing and in-service chain standards<sup>3,4</sup> (Table 1) for corresponding chain sizes.

**Table 1 Summary of API<sup>3</sup> and DNV<sup>4</sup> dimensional specifications for standard studded and studless chain. All dimensions are expressed as numbers of nominal diameters (d)**

Type of chain		Studded	Studless
Single link	Length of one 1 link (d)	6	6
	Height of one 1 link (d)	3.6	3.4
Five link section	Minimum manufacturing specification (d)	22	22
	Maximum manufacturing specification (d)	22.55	22.55
	Maximum operational specification (d)	23.25	23.25

**Summary of global operational results.**

Since the first system was deployed in 1998, the ‘optical caliper’-type chain measurement systems have been used to measure the mooring chains of 29 floating production systems and peripheral installations (e.g. loading buoys, mid-depth riser support buoys). The measurement programs have been conducted for a range of operational reasons, including establishment of dimensional base-lines, the identification and monitoring of in-service deterioration, and an extension of an inspection period required for recertification of a semi-submersible to class. Each FPS has distinct parameters, such as age of moorings system, size of chain, grade of chain material, numbers of mooring legs, depth, numbers of locations of measurements, local sea conditions (dynamics), seabed materials etc. Each of these parameters may influence the nature and rate of operational deterioration.

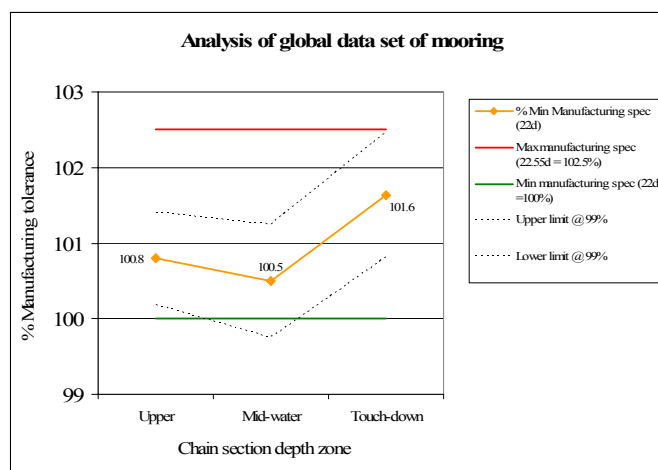
The unique combination of parameters that underlie each of the data sets and the relatively small size of each for statistical purposes mean that it is not possible to characterize the relative contribution of each parameter to any deterioration. However, although the characterization of cause and effect is elusive, there are patterns to the distribution of deterioration that are evident in most of the facilities that have been surveyed. Specifically, chain sections at the seabed touchdown – that point at which the chain comes into contact with the sea floor - tend to be elongated compared to mid-water sections and sections adjacent to the vessel in the upper water column.

**Chain measurement.** Table 2 and Figure 4 present the results of an analysis of the accumulated global data set that has been collected using the optical caliper-type chain measurement system. Because of the differences between installations, particularly chain size and water depth, data are presented as percentages of the API minimum and maximum manufacturing specifications<sup>3</sup> (Table 1), and are grouped according to their relative position between the surface and the seabed.

**Table 2 Results of ANOVA<sup>5</sup> of global data set for lengths of chain sections of floating production systems pooled according to depth zone**

Chain section	Upper	Mid	Seabed
Mean	100.8	100.5	101.6
Standard Deviation	1.10	1.17	1.62
Standard Error	0.22	0.26	0.30
95% Confidence Interval	0.45	0.55	0.61
99% Confidence Interval	0.61	0.75	0.83
# of facilities	25	20	29

The analysis shows a distinct trend to greater elongation at the seabed, followed by upper sections, and the mid-water sections. The seabed touchdown mean of 101.6% of the API minimum manufacturing specification, was 1.1% greater than the mid-water mean of 100.5% and 0.8% greater than the upper mean of 100.8%. This analysis is the first published evidence that there is a distinct correlation between depth zone and elongation of chain sections of the moorings of floating production systems.



**Figure 4 Results of analysis of the global data set for lengths of chain sections of floating production systems pooled according to depth zone**

Intuitively these results are not surprising. The seabed sections of moorings can be highly dynamic, and often there are trenches or lateral indentation in the seafloor material that have been caused by the motion of the chain. This action may increase wear, which may be enhanced by the ingress of material between the contact faces of adjacent links where it may act abrasively rather like a rubbing compound. Similarly, the upper sections are the most highly loaded and can be highly dynamic, depending on the type of facility and local sea condition.

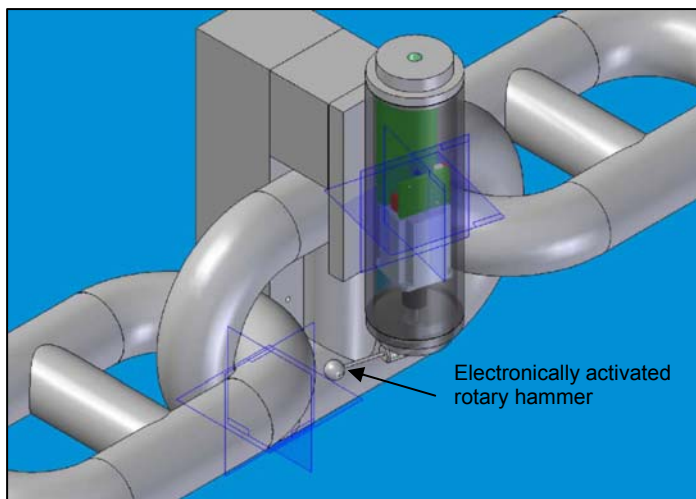
When viewing these results, it is important to realize that although the trend is clear, it is somewhat tempered by the nature of facilities from which the data were collected. A large number of programs were conducted on relatively new FPS systems, primarily to establish a base line data set from which future changes could be tracked. The chain sections of these moorings were basically new, and consequently had been exposed to minimal deteriorative forces and would not be

expected to have experienced in-service elongation.

**Loose stud detection.** As discussed in the preceding section on chain measurement, there are a range of reasons (e.g. cost, potential damage) why operators are disinclined to recover moorings for inspection, and that these have driven the development of ROV-deployable in-water inspection capabilities. One recently developed system is an ROV-deployed loose stud detection tool (Figure 5).

Loose chain studs are recognized to be involved in crack propagation and fatigue of link material<sup>3</sup>. Consequently, there are prescribed recertification protocols to determine the presence and the degree of ‘looseness’<sup>3,4</sup> of studs. Where moorings can be recovered, traditional loose stud detection programs are conducted manually, where a hammer is used to hit the studs to determine whether or not they are loose. Loose studs do not resonate, whereas ‘tight’ studs respond with a distinct ‘ring’.

The remote system stud measurement operates on the same principle. An electronically activated hammer is used to hit the stud and two sensors - a hydrophone and a micro-accelerometer - record the resonance response to the impact. A software program then distinguishes between ‘loose’ and ‘tight’ responses.



**Figure 5 Illustration of remote loose stud detection system showing orientation on chain, and the position of the rotary hammer**

Although the data set from this system is limited, it appears that there are higher numbers of loose studs in certain sections of chain, particularly in lower sections, adjacent to the seabed. Unfortunately it was not possible to determine whether this pattern was a direct result of the dynamics in this region, or whether it was an artifact of previous chain handling practices (i.e. recovery and reinstallation). This uncertainty highlights the importance of maintaining a full maintenance history for mooring systems.

**Component condition.** The visual assessment of the condition of mooring components is an important part of the underwater mooring integrity verification process, particularly because there are limited numbers of empirical systems with which to assess the operational fitness of components, or the

action of deteriorative processes. When moorings have been recovered for inspection, the value of a subjective assessment of the overall condition depends largely on the experience and visual acuity of inspection personnel.

Similarly, during underwater inspections the experience of the ROV operator or data recorder is important to the assessment of operational condition. However, ‘dry’ inspectors on deck have offered the advantage of being able to remove all marine growth from components, to inspect the surfaces of components from close range, and to have the ability to perceive geometry in three dimensions. The latter is particularly significant because the presence of surface features such as ‘scalloping’ or indentations, ‘anvil’ flattening, or pits give insights into the types of deteriorative processes that are at play. For example surface pitting may be indicative of pitting corrosion and unusual geometry may indicate wear, friction bending, or plastic deformation. The 2D video cameras that are used for the majority of underwater inspections are not particularly useful for this type of inspection because of the inherent ‘flatness’ of images.

This problem can be addressed by using 3D video systems. The value of 3D video in underwater inspection has long been recognized but until recently technical limitations have hindered wholesale adoption of the 3D video technologies for inspection. However with new designs of 3D cameras that include more user-friendly viewing systems, the benefits of 3D perception have proven very effective for the assessment of the surface condition and general geometry of mooring components.

During recent underwater inspection programs in the Norwegian sector of the North Sea, ROV crews reported improvements in task completion and task accuracy. It was also reported that it was easier to maintain the ROV position relative to the mooring legs. It was also reported by the reference engineering interests that a review of the 3D footage provided useful insights into the orientation and condition of the components, and assisted in identifying the presence and severity of anomalies. It is likely that as 3D systems become available in a wider range of configurations, sizes and weights, the use of these systems for condition monitoring of moorings will increase.

## Conclusions

The results of this paper demonstrate that when more comprehensive methodologies are used to assess the condition of *in situ* moorings on floating production systems, trends of deterioration become more evident. The results of an analysis of chain dimensions from a substantial global data set collected using an in-water chain measurement system shows a clear trend to increased length at the seabed touchdown and in upper sections, adjacent to the vessel. This study focused primarily on these results, however these results are also borne out through data collected by other systems designed to assess the condition of moorings. These include a loose stud detection system and underwater 3D video.

It is therefore reasonable to assume that these results are indicative of in-service deterioration of chain sections, and mooring integrity management programs should consider this

when assessing the necessary scope of condition monitoring activities.

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