Bringing the re-certification in motion

A study to explore how motion monitoring systems can be used in the re-certification process of existing offshore structures.

February 2017

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Preface

This paper is the result of a scientific research carried out to achieve a Master's degree in the track Construction Management & Engineering at the University of Twente. The research is executed at the company Siri Marine in Appingedam. The research explores how motion monitoring systems can be used in the re-certification process of existing offshore structure. I would like to take this opportunity to gratefully thank the director of Siri Marine, Albert Lenting for giving me the opportunity and trust to execute my graduation research in his company. Further, I also would like to thank all employees at Siri Marine with whom I have worked. Furthermore, I would like to thank Robin de Graaf and Irina Stipanovic, as supervisors of the university, for their guidance, substantive input and constructive criticism. Last, I would like to thank all case study participants, especially Jens Ulfkjær.

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***Abstract*— Oil and gas are sources that are widely used in modern life. The extraction of these sources from beneath the sea and ocean beds is done by offshore structures. While many offshore structures exceed their original design life, the safety of the operations on these structures needs to be guaranteed. This safety is warranted during the re-certification process. In this research is explored how motion monitoring systems can be used in the re-certification process of existing offshore structures. As methodology four case studies were investigated. All case studies exist of offshore structures on which motion monitoring systems are installed. The main source of data in these case studies are in-depth interviews, with experts in the field and relevant document analysis. Together with the standards applicable on offshore structures, sections of the standards which can be verified by motion monitoring systems are captured in a confrontation framework. For cases with fixed steel offshores structures ISO 19902 is used as reference standard and for concrete offshore structures DNV-OS-C502 is used. One of the frameworks is validated by an integrity engineering from one of the case studies. From this study two main conclusions can be drawn. First is that there are sections and clauses of the standards, which can be verified by motion monitoring systems. Second, that the installation of motion monitoring systems can be used for the re-certification process of existing offshore structures. However, not the entire re-certification program can be accomplished by motion monitoring systems. In this stage, current inspection techniques still need to be used and reference points for further research on motion monitoring are illustrated in this paper.**

***Index Terms* — DNV-OS-C502, ISO 19902, life-time extension, motion monitoring, offshore structures, re-certification, Structural Integrity Management.**

I. INTRODUCTION

OFFSHORE structures have been built in oceans and seas across the world for the primary support of the activities of petroleum industries. The first offshore structure was built in 1887 off the coast of southern California near Santa Barbara (Wilson, 2003) and nowadays, according to Statista (2015), there are 485 offshore structures worldwide. A worldwide well-known offshore structure incident was the Macondo blowout in the Gulf of Mexico, in 2010. Besides the thirteen people who were killed, the impact of the blowout was (Peres et al., 2016) and still is (Breyer et al. 2016) enormous. Studies underscored the unprecedented nature of the spill in terms of its magnitude, release at depth and impact to deep-water ecosystems (White et al. 2012). In response to the loss of life and environmental damage caused by the Macondo blowout, the European Commission issued Directive 2013/30/EU on the Safety of Offshore Oil and Gas Operations (the Directive) in June 2013.

The Directive has been designed to mitigate the risk of major offshore oil and gas incidents. It requires owners and operators of offshore structures to identify and manage major accident hazards and to put in place effective response strategies if an incident occurs. The Directive must be implemented from July 2018 by offshore operators of existing offshore structures. It demands a Risk Based Integrity Management approach from a ‘zero-defect’ philosophy. Intrinsically, by its principles, it includes challenging characteristics. These characteristics open the way to use more effective and efficient Structural Integrity Management (SIM) techniques, without doing concessions to safety, environmental and production loss risks.

The Macondo blowout was caused by inadequate SIM, due to a cut on maintenance budgets (Deepwater Horizon Study Group, 2011). Stacey, Birkinshaw & Sharp (2008) and Betti et al. (2015) concluded that current inspection and maintenance regimes are not generally designed to detect and manage the onset of accumulating and accelerating structural damage, which are necessary to know for comprehensive SIM. Moreover, Stacey, Birkinshaw & Sharp (2008) suggested that there is a need for the development of new inspection techniques. They are suggesting ongoing structural monitoring methods to enable continuous monitoring of the structural integrity of offshore structures. The assessment of a comprehensive SIM is done during a re-certification process of the offshore structure (May, 2009). The principles from the Directive in combination with the suggestions of ongoing monitoring for ensuring the structural integrity of offshore structures requires a research for the use of motion monitoring systems, especially in the re-certification process. The research question addressed in this research is: *How can motion monitoring systems be used in the re-certification process of existing offshore structures?*

In this research paper, a literature review is provided, in order to explore what is already described in previous studies about motion monitoring systems and its relation with SIM and re-certification. Third, the research design is described. The fourth section contains the case studies and provides the results of the study. The discussion part is treated in the fifth section of this research paper. The conclusion is provided in the last section and gives an answer to the research question.

Date of submission: 27.02.2017. This work was supported in part by Siri Marine B.V., Stationsweg 1, 9901 CP Appingedam, the Netherlands. The research is conducted in order to obtain a Master Degree in Construction, Management & Engineering.

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II. Literature review

Structural Integrity Management (SIM) can be defined as: '*The ongoing lifecycle process for ensuring the continued fitness-for-purpose of offshore structure'* (Westlake, Puskar, O'Connor, Bucknell & Defranco, 2005), wherein the 'fitness-for-purpose' is meeting the intent of an International Standard, such that failure will not cause unacceptable risk to life-safety or the environment (ISO 19902, 2007). The Health and Safety Executive (HSE) uses the following definition of SIM: '*The means of ensuring that the people, systems, processes and resources that deliver integrity are in place, in use and will perform when required over the whole lifecycle of the structure'* (May, 2009). Milne (1994) mentioned that the importance of the integrity of engineering structures is addressed from the viewpoint of its effect on the costs to the nation. Very large financial savings could be obtained by a more intensive application of current knowledge on how to manage the factors which contribute to structural failures. An example is provided by the Macondo blown out, which hit a total cost of $62 billon (Grandi, 2016). According to Narayanan & Mohammad (2009) SIM is important for the protection of offshore crew, environment, business assets, company and industry reputation. SIM can be seen as a broader term, which includes the safety of all aspects on an offshore structure. The safety can be defined as the absence of accidents or failures (Moan, 2017). In order to constitute good practice in SIM, together with an appropriate management and documentation structure, the UK Health and Safety Executive identifies a number of key processes and developed a comprehensive flowchart for SIM (May, 2009). This flowchart together with the interaction between the different parts is shown in Figure 1.

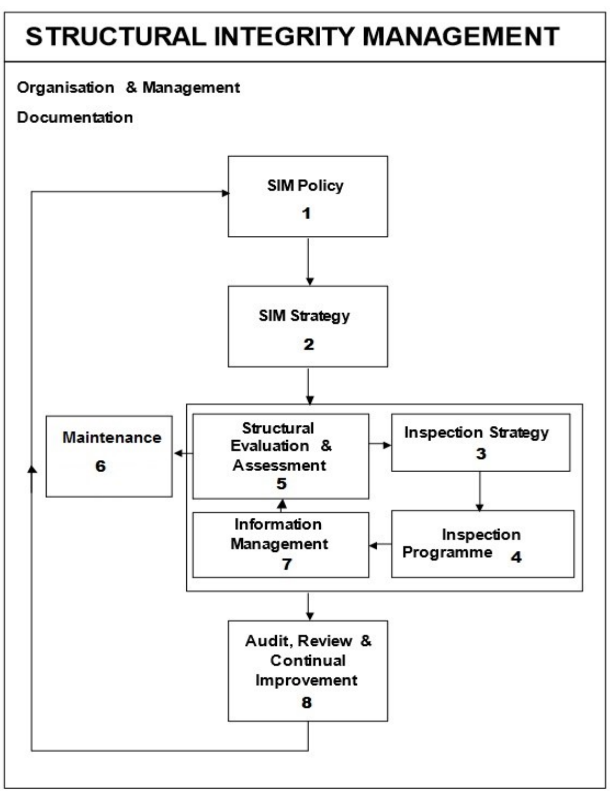

Figure 1. *SIM overview flowchart (HSE, 2009) (adopted by author).*

According to the HSE the SIM is carried out by the asset manager of the offshore structure. Guidance on setting a SIM Strategy (Figure 1, point 2), Inspection Strategy (Figure 1, point 3) and Inspection Programme (Figure 1, point 4) are given by ISO 19902 and API RP 2SIM (May, 2009). According to Moan (2017) the International Organization for Standardization (ISO) has developed a harmonized set of codes for offshore structures since the early 1990's, with contribution from all countries with major offshore operations. All ISO standards related towards offshore structures are shown in Figure 2.

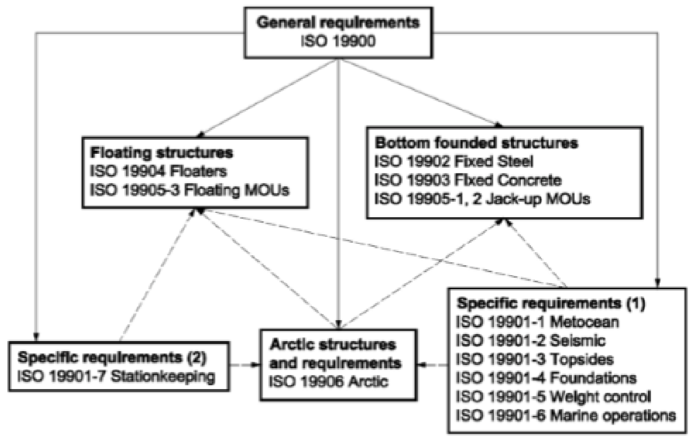

Figure 2. *ISO standards related towards offshore structures (International Association of Oil and Gas Producers (2014)).*

To assure that a SIM system is adequate it needs to be certified by a certification body. A certification body is a non-governmental organization which establishes and maintains technical rules and guidelines for the design, construction and operation of offshore structures (National Research Council (US), 2011). In practice the certification body validates the offshore structure according to the standards and carries out regular surveys in service to ensure compliance with the standards (IACS, 2011; Clark 1991). The certification body is on its duty bounded by two contracts (Lagoni, 2007). The first contract is with the flag state and is an agreement of delegation of power. The second contract is with the offshore owner of the offshore structure, for the performance of the obligation statutory surveys, this is a statutory survey contract. The statutory survey contract is drafted during the design of an offshore structure and valid during the design life. The design life is defined as *'the assumed period for which a structure is to be used for its intended purpose with anticipated maintenance but without substantial repair from ageing processes being necessary'* (International Standard Organizations, 1996 & 2007).

However, offshore structures have a finite design life and many are approaching that limit (Thompson, & Harper, 2004). Stacey, Birkinshaw and Sharp (2008) argued that over thirty years of oil and gas production in the UK sector of the North Sea, a significant number of offshore structures have exceeded their original design life. In their study they showed that approximately over 50% of the total population of 127 offshore structures are beyond their original design life. Because this is happening, there is a particular need to evaluate the approach of SIM by offshore operators. Ageing processes affect the structural integrity of the installation and the risk of failure increases with time, unless this is properly managed. The continued operation of an offshore structure beyond the design life, assumed at the time of design, followed by a reassessment, is the life time extension (Stacey, Birkinshaw & Sharp, 2008). This reassessment is a re-certification and provided by the certification body. In Figure 3 is shown when the re-certification arises at an offshore structure.

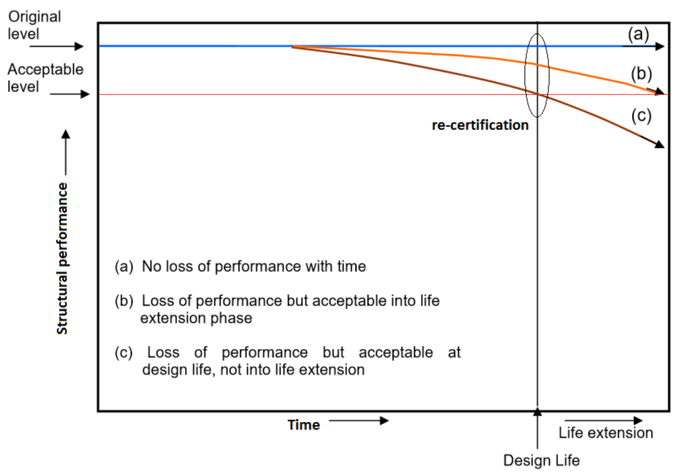

Figure 3. Re-certification moment in time at an offshore structure (based upon Stacey, Birkinshaw & Sharp, 2008).

Figure 3 shows three possible scenarios when the design life is exceeded. Line A represents no loss of structural performance within time and a straightforward re-certification, which is in practice rarely common. Line B shows loss of structural performance but this is acceptable for the life extension phase. Therefor a re-certification arises, whereby the SIM strategy for the upcoming years is in accordance with the standards in order to prevent any collapse and to guarantee the safety. Line C represents a structural performance loss on the structure that for any life time extensions the re-certification needs a comprehensive new SIM program. This in order to bring back the safety on the offshore structure.

Important in the re-certification process are inspections. Bruce et al. (2003) concluded that the inspections carried out on an offshore structure, which are under the inspection program (Figure 1, point 3) are the responsibility of the owner of the offshore structure and that the certification body checks the results of the inspections to verify the structure and if it meets the requirements. Moan (2005) described the objective of inspections on offshore structures to detect cracks, buckling, corrosion and other damages. Most typical inspections on offshore structures are carried out every four to five years. According to Moan (2005) an inspection plan for offshore structures involves the following components: a) prioritizing which locations need to be inspected, b) selecting inspection methods, depending upon the damage of concern, c) scheduling inspections and d) establishing a repair strategy. Inspections consist of periodic, scheduled checks of a structure to supply discrete measurements at points in time. Constant measuring or surveillance, to give actual time histories is mentioned as monitoring. The primary purpose of monitoring is to be aware of what is happening to an offshore structure in order to: a) assess structural degradation, b) verify design assumptions, c) assess potential failures due to gross errors in the design and fabrication and d) assist the operation of the structure.

Bruce et al. (2003) mentioned, the broader term of monitoring, which can be accomplished on all types of objects of an offshore structure. A particular form of monitoring is motion monitoring, motion monitoring is limited towards the registration of motions and vibrations. An offshore structure can undergo six kinds of motions (Han & Benaroya, 2013), which can be divided in translation motions and rotational motions. The three translation motions are heave, surge and sway. The rotational motions are yaw, roll and pitch. Figure 4 provides an impression of these motions on a structure.

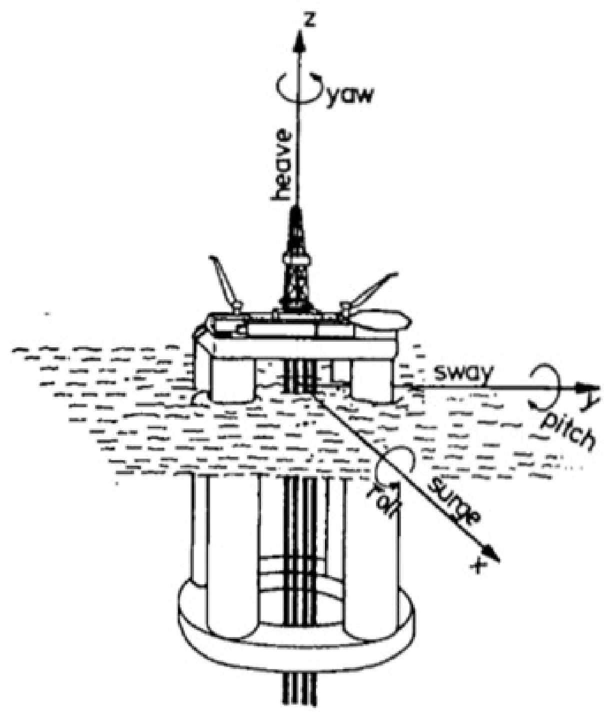

Figure 4. Motions on an offshore structure (Faltinsen, 1993).

Natural motions on offshore structures are mainly created by the environment, which can be wind and waves (Han & Benaroya, 2013). Other external factors which can create motions can be caused by the berthing of vessels on offshore structures or earthquakes. Motions are mainly expressed in periods, which are defined in seconds. The natural periods on an offshore structure are typically two till four seconds on both transversal and longitudinal periods, which makes them less than the most wave periods (Faltinsen, 1993). Studies on motion monitoring and offshore structures are scarce. Jimenez & Vargas (2004) concluded that motion monitoring is a tool to know the offshore structure's current, general behavior. In their research they made an evaluation through a monitoring campaign on a selected offshore structure in which a useful simple serviceability criterion was obtained. The study provided a reference that notes how simplified rules for the evaluation of the performance of a given offshore structure to an acceptable confident degree can be developed, without the need of complex computations. However, the study lacks a reference towards the standards which are used in SIM and re-certification. Sanderson et al. (2002) did a study on motion monitoring related towards offshore structures and they concluded that the implementation of an ongoing monitoring system allows for the immediate detection of member failures, thereby minimizing the time that a structure exists in a weakened condition. Ongoing monitoring can therefore have a significant improved effect on through-life structural reliabilities. However, they also concluded that sensors need to become more sensitive. Besides that, concrete suggestions were missing in their research and a confrontation with the standards was not made.

Concluded from this literature review; the SIM assures the offshore structure is safe. The certification body verifies the SIM against the standards and carries out regular surveys in service to ensure compliance with the standards. Despite the fact that some studies demonstrated that motion monitoring systems can improve the SIM, current studies lack the confrontation with the standards and therefore the implementation of motion monitoring systems in the re-certification process is subject to a number of caveats.

III. Empirical research design

An exploratory research with in total four case studies was chosen to answer the research question *'How can motion monitoring systems be used in the re-certification process of existing offshore structures'*. The case studies combine data collection methods, in order to understand a real life event. The reason for using case studies is because it is a suitable research method if deeper and more detailed insights are sought (Eisenhardt, 1989; Yin, 1994). Moreover, results of case studies are more likely to be accepted in the field (Verschuren & Doorewaard, 1997), because the study is placed in a less interventionist perspective than other research methods. The study focusses only on bottom-founded structures (fixed offshore structures). The research design for this study is shown in Figure 5.

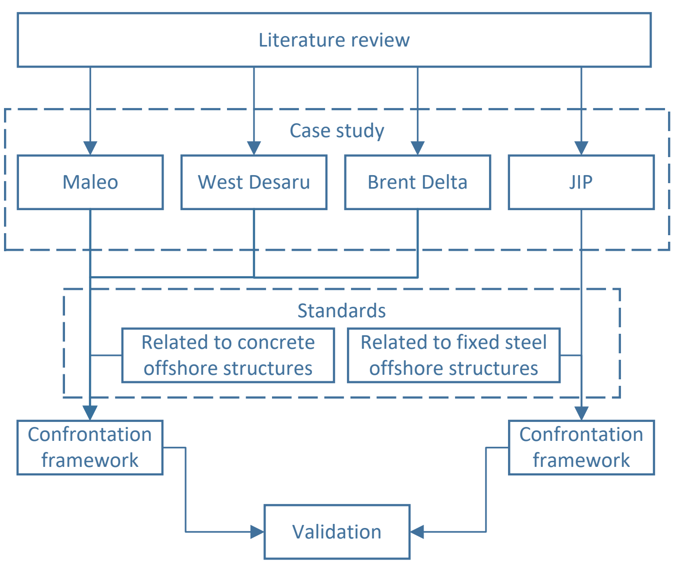

Figure 5. *Research design.*

First, four case studies are selected. Three of the case studies contain an offshore, which are currently equipped with motion monitoring systems. These offshore structures are the *Maleo Producer, the West Desaru* and the *Brent Delta.* Also all these case studies contain concrete fixed offshore structures. The aim of using these case studies is to understand how and why motion monitoring systems are used on an existing offshore structure. The *Maleo Producer* case study contains an in-depth interview with the former asset manager of the offshore structure, an interview with the supplier of the motion monitoring system and document analysis. The *West Desaru* case study and *Brent Delta* case study contain an interview with the supplier of the motion monitoring systems and document analysis. The last and fourth case study is a Joint Industry Program *(JIP)* among i.a. offshore operators, certification bodies and motion monitoring suppliers. Motion monitoring systems are installed on the offshore structure for executing this study in combination with an internal research of the offshore owner to explore how the motion monitoring systems could be used for replacing current inspection techniques. Therefore, it can have a contribution in the re-certification process. The advantages of this research is that it involves the offshore operator, a certification body and the motion monitoring supplier, which are all important stakeholders in the re-certification process. In total nine parties are cooperating in the *JIP*. From these nine parties there are four parties approach for participating in the *JIP* case study, these four parties are selected based on their experience in the field, their interest in the case study and their financial contribution in the case study. This case study contains in total seven in-depth interviews among the following four parties:

- Motion monitoring supplier
- Offshore operators (2x)
- Certification body

Besides that, the JIP case study contains the participation in two meetings, the participation of a conference presentation and the analysis of all relevant documentation. The aim of using this case study is three-fold, 1) checking the findings of the first three case studies, 2) a stronger focus on exploring how motion monitoring can be used to replace current inspection techniques, because all relevant parties are involved and 3) broadening the scope by including fixed steel offshore structure too.

The second step is in this research, is analyzing the standards related towards offshore structures. For the three concrete offshore structures, standards related towards concrete offshore structures are selected. For the fixed steel offshore structures, standards related to fixed steel offshore structures are selected.

Third, two confrontation frameworks are developed. Based on the analysis of the standards and the findings of the case studies, parts of the standards which can be validated by motion monitoring systems are clarified. The both frameworks are designed based upon the standards for concrete offshore structures and fixed steel offshore structures.

Fourth, both confrontation frameworks will be validated by the participants of the *JIP* case study and the findings will be discussed.

The outcome of this research is twofold. The confrontation frameworks indicate which sections of the standards can be verified by motion monitoring systems. And the discussion part of the study reflects on the outcomes with the literature and with experts in the field. In the last section the conclusion of this research is given.

IV. Results

This section contains the first part of the research, up until the confrontation framework as shown in the research design in Figure 5. The results of the four case studies are given and the standard applicable to these case studies are selected, standards are analyzed and based upon these two parts, a confrontation framework is developed.

A. Maleo Producer

The *Maleo Producer* is an offshore structure located in the Java Sea in the territorial waters of Indonesia and installed on its current location in 2006. It is a three-legged concrete offshore structure and has a mat foundation at a water depth of 60 meters. Before the *Maleo Producer* was installed in the Java Sea it was used as a Mobile Offshore Production Unit (MOPU) in bening conditions. Before it became a fixed offshore structure, the *Maleo Producer* was first used as a MOPU, therefor it was classified differently. The change towards a fixed offshore structure came along with a re-classification and therefore also a re-certification. The re-certification was done by a dry-docking project (whereby the structure was placed on the mainland) in order to ensure the structural integrity for the *Maleo Producer* until decommissioning. The dry-docking project made reinforcement by bringing the MOPU on the mainland. The re-certificate was granted by the American Bureau of Shipping (ABS) and is reviewed every five years. The decision for the installation of motion monitoring systems was under the responsibility of the asset manager of the *Maleo Producer.* In 2007 one sensor was installed in the control room of the offshore structure, it was placed at this location because of accessibility and the presence of a reliable power supply. The reason for the installation was to verify the tilt of the structure, because the structure is located on a soft soil. During the years, the motion monitoring system was used for a variety of verifications:

- Condition monitoring (results presented in Figure 6).
- Verification of the tilt (results presented in Figure 7).
- Back-up information of historical settlements.

From the total operational time of the motion monitoring system (2007 – present) it can be concluded that the change in the tilt is approximately 0.04 degrees increase in heel and 0.12 degrees decrease in trim (Figure 7). This means that the structure is not completely on horizontal level, but this will not be visual by the naked eye. For the condition, motion monitoring systems could be used to verify that an X-bracing has been installed on the legs of the *Maleo Producer* in 2012 (Figure 6, 1) and that some failure occurred in 2015 (Figure 6, 2). However, the results of the motion monitoring system are never used in the re-certification process of the offshore structure. The asset manager of the offshore structure stated that the motion monitoring system would only be useful for re-certification if it could measure any failure, therefore the system is used internally and not in cooperation with ABS. The offshore owner had the intention to use the system for further degradation estimations, but never came that far. Figure 6 indicates that motion monitoring is being able to detect longitudinal and transversal periods. Together with additional maintenance information, this can be verified by the motion monitoring system. Figure 6 point 1 indicates that the installation of the X-bracing decreased the periods. Point 2 indicated that some failure occurred. All standards related towards periods and maintenance verification are therefore appropriated to consider that they can be verified by the motion monitoring system.

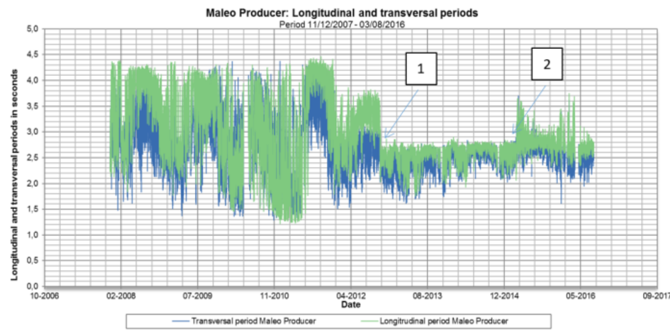

Figure 6. *Longitudinal and transversal periods of the Maleo Producer 1) installation X-bracing 2) some structural failure.*

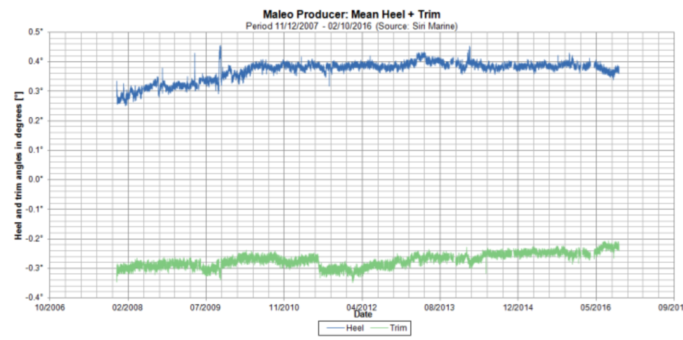

Figure 7. *Tilt (heel + trim) of the Maleo Producer during time.*

Figure 7 indicates that the tilt of the offshore structure can be measured by the motion monitoring systems. All standards related towards tilt are appropriated to consider that they can be verified by motion monitoring systems.

B. West Desaru

The *West Desaru* offshore structure is similar to the *Maleo Producer.* It is a three-leg concrete structure with a water depth of 65 meters. The structure is owned by Petrofac and situated in the Cendor field, offshore Terengganu on the Malay peninsula. In 2013 a total of five motion monitoring systems were installed on the structure. Three systems were installed on the legs (Figure 8) and two systems were installed on the free-standing Wellhead Support Structure (WSS) (Figure 9).

The purpose for the motion monitoring system of the offshore owner of the *West Desaru* is to safeguard the structural integrity of the structure, by setting a certain design value period and at the same time provide long term condition monitoring. Besides the operator collects data from the motion monitoring systems for a 'fatigue assessment' of the WSS. Because of confidentiality of information by the offshore owner in this case study, it is not possible to give results of the 'fatigue assessment'. However, in terms of safeguarding the structural integrity of the offshore structure, the owner of the *West Desaru* made a design criterion on the natural period of the WSS. Figure 10 shows the transversal and longitudinal periods of system 5 with the design value of the periods (which is 4 seconds).

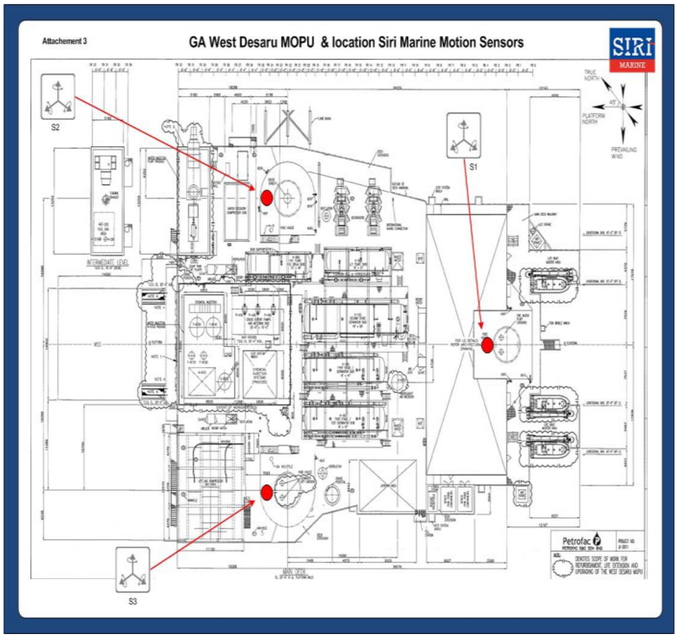

Figure 8. *Topview of the West Desaru with the location of the three motion monitoring systems.*

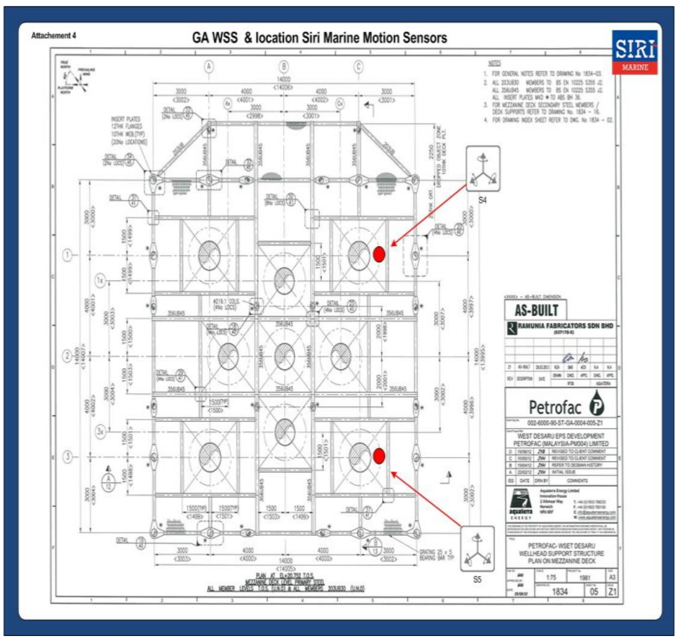

Figure 9. *Top view of the WSS with the location of the two motion monitoring sensors.*

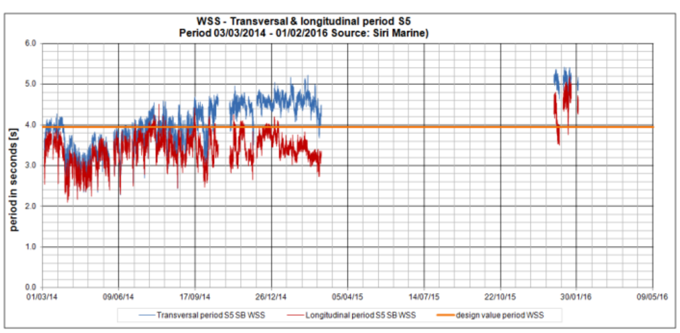

Figure 10. *Transversal & longitudinal periods (of sensor number 5) together with design value period.*

Figure 10 indicates that natural periods of offshore structures can be measured. It underpins the finding of Figure 6 that all standards in relation towards periods are appropriated to consider if they can be verified by the motion monitoring system. Beside that standards in relation towards design value periods are also appropriated to consider if they can be verified by the motion monitoring system.

From Figure 10 it can be noted that the period of the WSS sometimes exceeded the alleged design value period. According to the supplier of the motion monitoring systems, the period values above the design value period, are due to environmental impact and annual variations caused by monsoons. Referring to the condition monitoring system on the *Maleo Producer*, during 2012 additional support X-bracings were installed between the legs of the structure and immediately the dynamic motions decreased and the motion periods became more stable and shorter (i.e. the structure became stiffer after the support structure installation) and the influence of monsoon environmental impact became less (Figure 6).

Figure 11 and 12 shows the tilt of the *West Desaru* compared with the WSS. According to the autoreports of the supplier of the motion monitoring systems, small daily fluctuations in the heel and trim graphs are caused by the influence of temperature differences on the structure of the *West Desaru* and its WSS. Figure 11 and 12 both underpin the finding of Figure 7, which stated that all standards related towards tilt are appropriated to consider that they can be verified by the motion monitoring system.

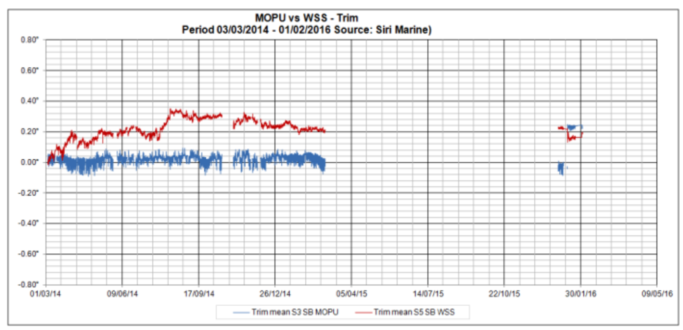

***Figure 11**. West Desaru trim vs. WSS trim.*

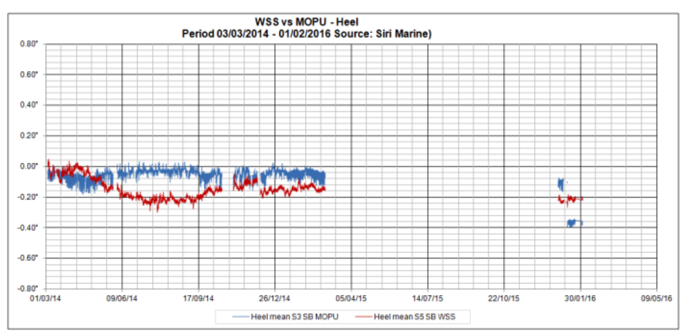

***Figure 12**. West Desaru heel vs. WSS heel.*

C. Brent Delta

The *Brent Delta* is a three-leg concrete offshore structure with a condeep foundation situated in the North Sea in the territorial waters of the United Kingdom. The structure is installed in 1979 and was in operation until 2012. Since 2013 the decommission of the *Brent Delta* started and in 2016 a motion monitoring system was installed. The offshore owner has identified the need to monitor the condition of the *Brent Delta* (motion frequencies, accelerations, inclination and dynamic behavior) of the structure during the period between the start of cutting of the legs until final removal of the complete topside, planned in 2017. The aim is to identify any abnormalities in tilt and period in the event of structural damage (e.g. storm damage, vessel collision, etc.). Because the structure is in decommission stage there is no need for any re-certification of the structure since operations are shut down. During the motion monitoring period no notorious results were measured in the autoreports of the supplier of the system and the inclination is 'steady as a rock'.

Figure 13 shows the tilt of the *Brent Delta* structure, both heel and trim. Figure 14 shows the longitudinal and transversal periods of the *Brent Delta*.

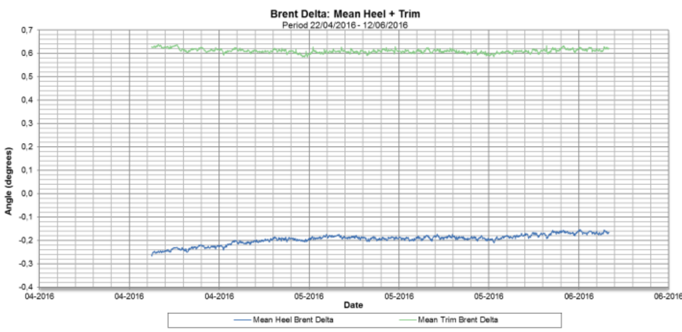

Figure 13. *Tilt (heel + trim) of the Brent Delta during time.*

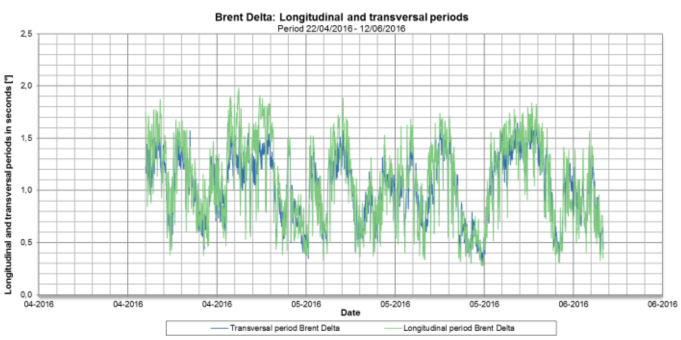

Figure 14. *Longitudinal and transversal periods of the Brent Delta.*

Figure 13 and 14 underpin the findings of the results of the motion monitoring system in the *Maleo Producer* and *West Desaru* case studies. Standards related towards tilt and periods are all appropriate to consider that they can be verified by motion monitoring systems.

D. Joint Industry Project (JIP)

The *JIP* is a collaboration of nine parties to explore the possibilities of different inspection techniques in order to reduce the inspection cost and move away from a conservative preventive SIM towards a Risk-Based SIM. The motivation of the *JIP* arises from the New Directive, as stated in the introduction.

In this case study the research on motion monitoring systems goes a step further. As done in the other three case studies, standards which are appropriate to consider if they can be verified by motion monitoring systems are explored, but in addition standards which could be verified based on additional technologies and further research on motion monitoring systems are also explored. The aim is to indicate the standards which can have a high potential to be verified by motion monitoring systems and which can encourage further research.

For the *JIP* the offshore structure P15D is selected. P15D is a fix steel offshore structure located in the North Sea in the territorial waters of the Netherlands. The offshore structure belongs to TAQA Energy. The structure is in operation since 1993 and need to be re-certified in 2017. For the *JIP* a motion monitoring system is installed on the offshore structure P15D and the tilt (Figure 15) and periods (Figure 16) are measured.

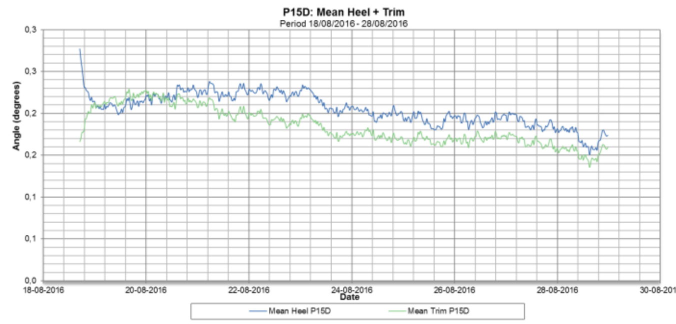

Figure 15. *Tilt (heel + trim) of the P15D during time.*

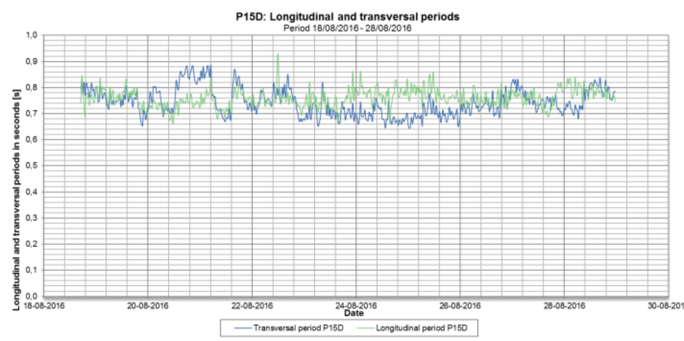

Figure 16. *Longitudinal and transversal periods of the P15D.*

Both figures underpin the figures in the *Maleo Producer*, *West Desaru* and *Brent Delta* case studies. In all cases standards which deal with tilt and periods are appropriate to consider if they can be verified by motion monitoring systems. In order to extent the possibilities in the re-certification process and find out under which circumstance the motion monitoring systems can be used in a broader way, the *JIP* case study explores what needs to be accomplished by the motion monitoring system.

The asset manager of the inspection program of the P15D offshore structure, which is based on ISO 19902, mentioned that it for 90% has to deal '*somehow*' with fatigue. Current inspection programs (and therefore used techniques) are in accordance with ISO 19902. In order to fully use the motion monitoring system, the system needs to be able to document any degradation caused by fatigue. However, it is unsure in the current stage if the motion monitoring system can detect all of the issues addressed in the current inspection program.

The integrity engineers of the certification body posited that the motion monitoring system needs to be able to document '*exact by the same things*' as the inspection methods which are currently used. In the current situation ISO 19902 mentions Remote Operated Vehicle's (ROV's) and Non-Destructive Testing (NDT) techniques as proper inspection techniques.

Based on the interviews held with the participants in the case studies, they all mentioned the sensitivity of motion monitoring systems as critical point for using the system as inspection technique. Furthermore, all experts from the involved certification body feel that, regarding motion monitoring, most benefit can be obtained if motion monitoring systems are used in combination with a model (e.g. SACS). For an effective use of motion monitoring systems in a model, the natural frequency needs to be obtained. However, the periods derived from the motion monitoring systems are natural periods, which differ from natural frequencies. It differs from the fact that the natural periods consist of the environmental impact on the structure (as illustrated in Figure 16) and the natural frequency is a theoretical value and is the frequency at which a system tends to oscillate in the absence of any driving or damping force. In the industry an offshore structure can be considered as a spring, which is anchored on the sea bed. In a single anchored spring is the natural frequency generally described as in (1) (Ugural & Fenser, 2003) whereby k = the stiffness of the spring and m = the mass of the spring:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \quad (1)$$

While this formula is the most basic description of natural frequency, certification bodies stated that models (for example SACS) are able to indicate the natural frequency and that these models can estimate the degradation of natural frequency based upon certain input values (e.g. collisions, storms, life-time). It does not mean that a structure is in a critical condition if the natural frequency changes, but the change is always due to some reason (or better, failure).

In conclusion of the *JIP* case study, standards for fixed steel offshore structures related towards tilt and natural periods are appropriate to consider that they can be verified by motion monitoring systems. In addition, further research should be carried out and focused on: 1) the sensitivity of the motion monitoring systems and in line with this 2) accurately calculate the natural frequency by the system. If both conditions can be obtained by motion monitoring systems, it enables us to assess the structural integrity of the structure in a broader way as it is done now. Therefore, all standards for fixed steel offshore structures related towards natural frequency and the use of models are appropriate to consider if they can potentially be verified by motion monitoring systems.

E. Standards for re-certification

The series of International Standards applicable to the different types of offshore structure, ISO 19900 to ISO 19906, constitutes a common basis covering those aspects that address design requirements and assessments of all offshore structures used by the petroleum and natural gas industries worldwide. For this study ISO 19902 (Fix steel offshore structures) is used as guiding norm for the fix steel offshore structure in the *JIP*. ISO 19902 is used as reference standard because it is the guiding standard for the *JIP* offshore structure.

ISO 19902 contains a total of 25 chapters within 271 pages (excl. Appendix). Two chapters can be directly related towards the re-certification process. Chapter 23 covers the requirements for 'in-service inspection and structural integrity management'. Chapter 24 covers 'assessment of existing structures'.

The requirements for concrete offshore structures used in this study are: *OFFSHORE STANDARD DET NORSKE VERITAS DNV-OS-C502.* This standard, developed by DNV GL, supplements existing international standards such as ISO 19903. The guidance in these standards is more specific as the ISO standards. Where ISO standards are generic, DNV supplement on ISO 19903 by DNV-OS-C502.

DNV-OS-C502 contains a total of eight sections within 87 pages. One chapter can be directly related towards the re-certification process. Section eight contains 'The In-service Inspection, Maintenance and Conditional Monitoring', the purpose of that section is '*to specify requirements and recommendations for in-service inspection, maintenance and condition monitoring of offshore concrete structures, and to indicate how these requirements and recommendations can be achieved. Alternative methods may also fulfil the intent of these provisions and can be applied provided they can be demonstrated and documented to provide the same level of safety and confidence'.* Therefore, it is appropriate to consider that motion monitoring contribution can be explored in this section.

F. Framework

The confrontation framework in Appendix Table 1 represents the DNV-OS-C502 requirements for concrete offshore structures, which can be verified by motion monitoring systems or whereby motion monitoring can contribute in the verification, based upon the *Maleo Producer, West Desaru* and *Brent Delta* case studies.

The confrontation framework in Appendix Table 2 represents the ISO 19902 requirements for fixed steel offshore structures, which can be verified by motion monitoring systems or whereby motion monitoring can contribute in the verification, in a direct way and under the assumption that the system is sensitive enough to detect the change in natural frequency, as a result from the *JIP* case study.

In the first column the number of the DNV section or ISO clause is stated, the second column contains the title of the section/clause, the third column cites the requirement, the fourth column provides which case study could verify the requirement and the fifth column gives a brief clarification.

V. DISCUSSION OF THE FINDINGS

This section of the paper contains the validation part of the research as shown in the research design in Figure 5.

Both frameworks (Table 1 and Table 2 in the Appendix) indicate that there are components of the standards which can be verified by motion monitoring systems. In this section the results are discussed and the opinion of an integrity engineer of a certification body on the results is given.

According to the experts in the *JIP* case study the ISO standards are quite broad and sensitive for different interpretations. One of the participants in the case study stated that the guidance part of inspections in the ISO standards are '*very vague'*. Therefore, certification bodies make standards (e.g. DNV-OS-C502) which are very often developed to supplement existing international standards. The results of the framework (Table 2 in Appendix) of fixed steel offshore structures are validated by an integrity engineer of the certification body in the *JIP* case study, who has over a decade experience in re-certification programs of fixed steel offshore structures worldwide. Table 2 in Appendix could be validated by the integrity engineer, because the fixed steel offshore structure is one of his expertise. For the concrete offshore structures, the framework could not be validated because no integrity engineer with expertise on concrete offshore structures was involved in the case studies.

First, the integrity engineer stated that motion monitoring in general needs to ensure that the underlying probability of failure given by the ISO standards and DNV GL standards should be documented at all times. A change in natural period can indicate that 'something' went wrong, but for an operator in offshore structures that might not be enough. There need to be documented that the structure is in compliance with all clauses in the ISO standards at all time, the results presented in both frameworks (Table 1 and 2 in Appendix) do not cover all clauses and therefore motion monitoring cannot replace the current re-certification process in its entirety.

The integrity engineer, however stated that the confrontation framework in Table 2 in the appendix is clear and relevant for the industry. Some of the results are valid and support the use of motion monitoring systems in the re-certification process. The points which have the highest certainty of being verified by motion monitoring systems are indicated in Table 2 in the last column. The certainty indication is based upon the feedback of the integrity engineer. For Table 1 the certainty is made based upon the certainty results of Table 2, sections which are supplement clauses are classified similar.

Points where the integrity engineer agreed about the use of motion monitoring systems are indicated with a high certainty. The points where the integrity engineer has some doubts are indicated with a medium certainty. Most of this points are related towards the accuracy of the motion monitoring system and calculating the natural frequency. If further research is needed the indication (R) is additionally given.

Further research mainly contains the parts which treats the accuracy and naturally frequency, this are also related towards eachother. The accuracy of the motion monitoring system has to be incredible in order to calculate the natural frequency. Offshore operators nowadays carry out visual inspections. Visual inspections are able to detect cracks. From this crack, the potential crack growth can be calculated in a fracture mechanics analysis, whereas motion monitoring systems will fail to detect any crack of potential failure, unless the change in natural frequency is above 0.5%, which is a lot for static indeterminate (redundant) offshore structures. The integrity engineer advises more sensitivity studies and validation, which are required in order for motion monitoring systems to provide the same level of confidence that is obtained from NDT techniques or complex analyses (in combination with visual inspection) calibrated towards numerous physical tests.

Last point of the integrity engineer is that there are also clauses which still (additionally) need to be verified by the current inspection methods (e.g. ROV, NDT, diving) or whereby the integrity engineer feels little potential in the use of motion monitoring, if together the results cannot fully support the clauses, these clauses are indicated with a low certainty classification.

In this research there were also some limitations. First, ISO 19902 is used and DNV-OC-C502. While ISO 19902 contains fixed steel offshore structures, ISO 19903 contains the concrete offshore structures. A confrontation with the ISO 19903 is not made, which could be interesting because the results can be used on a larger scale. Second, this research has relatively little empirical data. Only four case studies were used, three for concrete offshore structures and one for fixed steel offshore structures. This was due to a lack of offshore structures equipped with motion monitoring systems. Third, there is also little empirical data on the validation of the frameworks. The validation is mainly done by one involved integrity engineer of DNV GL, who only has expertise in fixed steel offshore structures. A comprehensive validation of the concrete offshore structure confrontation framework could therefore not be made. For further research the framework could be validated more extensively. Beside that the confrontation framework is validated by the integrity engineer its own opinion and not that of the certification body, the feedback on the confrontation framework has not been through any type of quality assurance or control, and must therefore be treated as the personal opinion. The integrity engineer posited that 'other people within his company or within other certification bodies might have different opinions'. Nevertheless, the results provide a good base for implementing motion monitoring systems in the re-certification process, especially for the sections and clauses which are certain and validated. Last point for improvement and further research is comparing the results of motion monitoring systems with reports of the results of the inspection methods which are used for the re-certification process.

VI. Conclusion

In this study, two confrontation frameworks (Table 1 and 2 in Appendix) were established, based on standards applicable to offshore structures, in order to assess the use of motion monitoring systems for the re-certification process of existing offshore structures. This assessment was conducted by applying the case study methodology. In total four case studies were investigated. This study focuses in detail on the standards which are used in the re-certification process of existing offshore structures and explores if sections or clauses of these standards could be verified by motion monitoring systems. This because previous research on motion monitoring systems in relation to re-certification or SIM has never focused on verifying sections and clauses of the standards. The motivation for this research comes from the New Directive initiated by the EU, which makes it possible to explore new inspection techniques for offshore operations.

The results of this study show that there are clauses and sections in the ISO 19902 and DNV-OS-C502 standards which could be verified by motion monitoring systems. These results are illustrated in Table 1 (DNV-OS-C502) and Table 2 (ISO 19902). In both tables is illustrated which sections or clauses have the highest certainty to be verified by motion monitoring systems. This certainty classification is based upon the assessment of the framework by an integrity engineer of a certification body, who has over a decade of experience in this field. The clauses of ISO 19902 which are certain are based directly upon the review of the integrity engineer. The certainty of the sections of DNV-OS-C502 are based upon the certainty classification of the clauses in ISO 19902 and indirectly on the feedback of the integrity engineer.

The main benefits of the motion monitoring systems can be found in the sections and clauses which treats the tilt/settlement, natural periods and historical data analysis. Therefore, the installation of motion monitoring systems on existing offshore structures can contribute in the re-certification process, especially if it comes to verifying these clauses. However, the amount of sections and clauses which can be verified by motion monitoring systems is relatively small compared to the entire standards. Additional traditional inspection techniques are still needed for the re-certification process of existing offshore structures.

Sections and clauses whereby the natural frequency needs to be conducted cannot be fully verified by motion monitoring systems based on the results of this study and the benefits of motion monitoring for these sections and clauses is therefore less certain. Further research, on the sensitivity of motion monitoring systems and the possibility of accurately calculating the natural frequency by motion monitoring systems need to be carried out.

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VIII. Appendix

***Table 1**. Confrontation framework DNV standards (related to concrete offshore structures).*

DNV-OS-C502	Section	Requirement	Referred case study	Clarification	Certainty
Section 5 501	Loads and analyses requirements Additional requirements for dynamic analysis under wave load	*In cases where the structure can respond dynamically, such as in the permanent configuration (fixed or floating), during wave load or earthquakes or in temporary floating conditions, additional parameters associated with the motions of the structure shall be determined.*	Maleo Producer West Desaru Brent Delta	The determination of the additional parameters associated with motions can be derived from the motion monitoring systems. As shown in Figure 6, 10 and 14.	High
Section 5 503	Loads and analyses requirements Additional requirements for dynamic analysis under wave load	*The effects of motions in the permanent configuration such as those occurring in an earthquake, floating structures or in temporary phases of fixed installations during construction, tow or installation, on internal fluids such as ballast water in tanks, shall be evaluated.*	Maleo Producer West Desaru Brent Delta	Based on the results of motion monitoring systems (e.g. figure 6, 10 and 14) the effects of motions in the permanent configuration can be evaluated. However, these section does not contain fixed existing offshore structures.	Medium
Section 5 701	Loads and analyses requirements Structural analysis Mass simulation	*A suitable representation of the mass of the structure shall be required for the purposes of dynamic analysis, motion prediction and mass-acceleration loads.*	Maleo Producer West Desaru Brent Delta	Motions do not need to be predicted if motion monitoring systems are installed. The motion monitoring systems can indicate the motions as is done in Figure 6, 10 and 16. On the other hand, the representation of the mass of the structure can also be compared with the motion monitoring results, in order to evaluate the representation.	Medium
Section 8 501	In-service inspection, maintenance and conditional monitoring Programme for inspection and condition monitoring	*The first programme for inspection and condition monitoring should provide an initial assessment, as described in A602 of the condition of the structure, i.e. the assessment should have an extent and duration which, as far as possible, provides a total description of the condition of the structure (design verification).*	West Desaru	Motion monitoring can contribute in the total description of the condition of the structure. Figure 10 shows periods in combination with a design value period, which enables us to conduct a design verification.	High
Section 8 606	In-service inspection, maintenance and conditional monitoring	*Inspection and condition monitoring should be conducted after direct exposure to a design environmental event (e.g., wave, earthquake, etc.). Special inspection following a*	Maleo Producer	While motion monitoring does not directly encompass critical areas of the structure, it can trigger to do so. Motion monitoring is able to indicate a direct exposure to the design	Medium

		design environmental event shall encompass the critical areas of the structure. Special inspections following accidental events may, in certain circumstances, be limited to the local area of damage. Inspection should also be conducted after severe accidental loading (e.g., boat collision, failing object, etc.)		environmental event, as shown in Figure 6.	
Section 8 703	In-service inspection, maintenance and conditional monitoring Documentation	*Up-to-date summary inspections shall be retained by the owner/operator. Such records shall describe the following:* - *inspection findings, including thorough descriptions and documentation of any anomalies discovered.*	Maleo Producer West Desaru Brent Delta	Any anomalies need to be recorded. The data received from motion monitoring enables us to detect anomalies in 'tilt' and 'periods'. These anomalies can be documented and trigger any further inspections if any doubt of structural integrity come across by the owner/operator.	High
Section 8 806	In-service inspection, maintenance and conditional monitoring Important items related to inspection and condition monitoring	*In addition to the aspects listed for the Atmospheric and Splash zones, the inspection and condition monitoring of the Submerged Zone should focus on:* - *Settlement*	Maleo Producer West Desaru Brent Delta	Based on the tilt, the settlement of offshore structures can be calculated. For the *Maleo Producer* the system was installed with the aim to record the historical settlement of the structure.	High
Section 8 1004	In-service inspection, maintenance and conditional monitoring Inspection and condition monitoring types.	*The structure may be instrumental in order to record data relevant to pore pressure, earth pressure, settlements, subsidence, dynamic motions, strain, inclination, reinforcement corrosion, temperature in oil storage, etc.*	Maleo Producer West Desaru Brent Delta	Data relevant to dynamic motions can be obtained by motion monitoring systems. Inclination and settlements can be calculated by the tilt	High

Table 2. *Confrontation Framework ISO 19902 (related to fix steel offshore structures).*

ISO 19902	Clause	Requirement	Referred case study	Clarification	Certainty
9.8.1	Action for in-place situations Equivalent quasi-static action representing dynamic response caused by extreme wave conditions General	*Actions caused by waves vary with time. Any structure subjected to these actions will therefore experience dynamic response to a greater or lesser degree…… For the applicability of the approximate procedure described in 9.8, it is required that: b) the magnitude of D_e (Equivalent quasi-static action in design environmental conditions) be considerably smaller than the magnitude of E_{wce} (Extreme quasi-static action caused by waves and currents) These requirement is considered to be satisfied if the following two conditions are met: - the dynamic response is stiffness controlled, which may be assumed if the fundamental natural period of the structure is less than one-fifth of the peak period of the wave spectrum of the design sea state. - the magnitude of D_e is less than one-half of the magnitude of E_{wce}.*	JIP	For the calculation of D_e the natural frequency of the structure is needed. If motion monitoring can identify the natural frequency of the structure it can contribute in calculating D_e for clause 9.8.1 (formula A.9.8-1 & A.9.8-2). By having the natural period there can be verified if these is less than one-fifth of the peak period of the wave spectrum and if it is less than one half of the magnitude of E_{wce}.	Low (R)
10.1.3	Accidental situations General Accidental situations	*after the hazardous event has occurred, check the after damage design situation in relation to specified environmental actions*	JIP	Hazardous events are measurable by third party instrumentations (e.g. weather logger). The impact of the hazardous event can be related towards a shift in natural periods and a change in tilt. In case a shift and a change is detected by the motion monitoring system, the results can trigger further inspection actions.	Medium
10.1.6.2	Accidental situations General Damaged structures Assessment of structures following damage	*The modelling of the structure for the corresponding after damage design situation shall reflect the assessment of the actual damage as accurately as possible.*	JIP	A model of the structure corresponding after damage design situation can be reflected accurately if input of the motion monitoring systems is used.	High (R)
11.6.1	Seismic design considerations Abnormal level earthquake requirements General	*the structure does not globally collapse during the earthquake*	JIP	A collapse would be directly measurable by the motion monitoring systems. Tilt and periods would radically change. The extent of motions during the earthquake would be recorded.	Medium

12.5.1	Structural modelling and analysis Types of analysis Natural frequency analysis	*A natural frequency analysis shall be carried out to determine whether dynamic behavior is significant. A reasonably accurate structural model, including both stiffness and mass, shall be developed and analyzed so that the natural frequencies of the structural system can be compared to the frequencies of any excitations.*	JIP	If motion monitoring is sensible enough to detect the natural frequency, the natural frequency of the structural system (model) can be compared to the frequencies of any excitations (derived from the system).	High (R)
12.5.2	Structural modelling and analysis Types of analysis Dynamic responding structures	*Structures for which dynamic behavior is significant are generally referred to as dynamically responding structures. Redundant, multi-legged fixed structures (e.g. jackets, towers, etc.), with fundamental natural periods or having one or more components with natural periods greater than 2,5 s to 3 s usually respond dynamically to wave action during sea tow or in-place situations. For other types of structures, such as monotowers and caissons, dynamic behavior can be significant even with natural periods of 1 s or less. Other actions to which the structural system can be subjected, such as wind turbulence, seismic events, impact and explosion, can also cause dynamic effects of significant magnitude at other natural periods.*	JIP	Dynamic behavior of offshore structure can be measured by motion monitoring systems. Based on the type of offshore structure and the location where the motion monitoring sensor is placed, measuring natural periods can indicate if an offshore structure is a dynamically responding structure. Other actions to which the structural system can be subjected can also cause dynamic effects of significant magnitude at other natural periods, these actions can be recorded by motion monitoring systems and analyzed.	High (R)
16.1.5	Fatigue General Fatigue assessment by other methods	*Normally, a fatigue assessment requires detailed analyses using rational methods. However, when it can be demonstrated that either the fatigue limit state will not be reached in the design service life or, alternatively, when relevant prior experience exists to reliably indicate that this will be the case, a detailed fatigue analysis as per 16.1.3 or 16.1.4 may be replaced by a simpler assessment(s).*	JIP	Based on the natural frequency in combination with a model, the stiffness of the structure can be calculated and a fatigue limit state can be set. This can be a simpler assessment than a detailed fatigue analysis.	Low
16.1.6	Fatigue General Fatigue assessment of existing components	*Fatigue assessments of components in existing structures may be based on fracture mechanics methods or on a careful evaluation of inspection results, in lieu of a detailed fatigue analysis using the long-term stress range history and S–N curves.*	JIP	Results of motion monitoring (as inspection) can be evaluated, in lieu of a detailed fatigue analysis. The natural frequency of the structure should therefore be analyzed and comprehensive enough for fatigue assessment, in line with a model of the structure.	Low
16.4.4.1	Fatigue Performing the global stress analysis Dynamic analysis General	*The position of the platform natural frequencies relative to the peaks and troughs of the transfer function of the applied wave action can have a profound effect on the level of dynamic response. Since the natural frequencies can vary significantly, depending upon design assumptions and operational*	JIP	Motion monitoring systems which can indicate the natural frequency of the offshore structure are constantly adjusting. The results can be used to determine the effect on the level of	High (R)

		deck mass, the theoretical natural frequencies shall be reviewed and their position adjusted if necessary.		dynamic response applied by wave action.	
16.4.4.3	Fatigue Performing the global stress analysis Dynamic analysis Stiffness	*The foundation stiffness shall be modelled by an equivalent linear representation, such that the foundation deflections and rotations in a sea state representing wave conditions that contribute significantly to fatigue damage are correctly reflected. The centre of fatigue damage sea state, calculated as described in A.16.7.2.3, is appropriate for this purpose. The foundation stiffness can have a large effect on the natural period(s) of the structure. When assessing the range of natural period values which can occur, upper and lower bound foundation stiffness values shall be considered.*	JIP	The centre of fatigue damage sea state can be calculated based upon the natural frequency derived from a model (as stated in A.16.7.2.3). However, if natural frequency can be derived from the motion monitoring systems the calculations become more reliable. Besides that, natural period values do not need to be assessed, because these value can be directly derived from the motion monitoring systems.	Low
23.2	In-service inspection and SIM Data collection and update	*Essential aspects of structural integrity management are the validity, extent and accuracy of the structure's data and inspection history.*	JIP	Motion monitoring records data and can be used for validity of accelerations and periods. Figure 16 shows a certain timeframe. Motion monitoring provides a continually, extent and accuracy data of tilt and natural periods. Together with the time frame a history of this data is provided.	High
23.4.3 a)	In-service inspection and SIM Inspection types Scheduled inspections	*Periodic inspections are conducted to assure structural integrity by detecting any deterioration and degradation over time and discovering any defects.*	JIP	Deterioration and degradation can be conducted by motion monitoring systems. Change in tilt and natural periods indicate deterioration and degradation, because these change is always due to a reason. Beside that the system even extends the periodic inspections towards continuing inspection. The system can trigger any further inspection if there is confusion about the reason.	Medium
23.4.3 b)	In-service inspection and SIM Inspection types Unscheduled inspections	*Unscheduled inspections are conducted to evaluate a structure's condition following:* *- an environmental event (e.g. storm, earthquake, mudslide), or* *- an incident (e.g. vessel impact, dropped object, explosion).*	JIP	Structure its condition is continuously monitored, any environmental event or (significant) accident (as stated in the requirement) can be evaluated. Further (unscheduled) inspections can be done	Medium

				trigged by the results of motion monitoring systems.	
23.6.1	In-service inspection and SIM Inspection requirements Baseline inspection requirements	*The minimum scope shall consist of:* *- tilt and structure orientation*	JIP	From all the offshore structures in the case studies the tilt could be measured and hence the orientation. Motion monitoring can accommodate the minimum scope.	High
23.6.2.2	In-service inspection and SIM Inspection requirements Periodic inspection Level 1 periodic inspection	*A level I inspection shall consist of a below water verification of the performance of the cathodic protection system (e.g. a drop cell), and of an above-water visual survey, to determine:* *- indications of obvious overloading, design deficiencies and any use which is inconsistent with the structure's original purpose.*	JIP	From analyzing periods, indications of overloading can be determined under the condition that weather impact is known and operations on the structure. West Desaru case study showed that design deficiencies can be indicated by setting a design value period (as shown in Figure 10). Abnormalities can trigger further inspections	Medium (R)
		- bent, missing, or damaged members,	*JIP*	Natural frequencies of a model can be compared with the natural frequencies detected by the motion monitoring systems. In case members are damaged or missing, there will be a relation with the measured frequency and the frequency derived from the model. The results can trigger further inspections in certain areas of the offshore structure.	
23.6.3	In-service inspection and SIM Inspection requirements Special inspections	*Special inspections shall be undertaken:* *a) to assess the performance of repairs undertaken to ensure the fitness-for-purpose of the structure, the minimum requirement for such repairs being a visual inspection (with marine growth cleaning as necessary) conducted approximately 1 year after completion of the repair.*	JIP	While motion monitoring cannot be classified as visual inspection, it can assess the performance of repairs undertaken to ensure the fitness-for-purpose by analyzing the periods over time.	High
24.3.1	Assessment of existing structures Data collection Structure data and history	*The following data shall, where possible, be reviewed as part of the assessment:* *- information on structure history* *- information on present condition*	JIP	Motion monitoring provides information (periods, tilts, accelerations) on structure history (depending on the measurement period) and present condition. The data can be assessed.	High