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1. INTRODUCTION

1.1. PETROBRAS will manage the structural integrity of the hull structure with a Hull Structure Health Monitoring System (HSHMS), which is part of the DIGITAL TWIN implementation.

1.2. The Hull Structure Health Monitoring System (HSHMS) shall be designed to monitor key structural response parameters of the hull as well as important environmental and loading parameters in a synchronized way. The system must be able to provide information on the hull integrity during the lifetime of the FPSO and help PETROBRAS to understand the real age of the vessel. In order to provide this information, the system shall monitor structural responses and loading and assess the fatigue by coupling the measured information back to the design tools. The system shall consider the measurements of the environmental parameters and loading conditions, as well as the structural response, to update the design model inputs and obtain the actual fatigue response. This system shall help the owner with approval of possible hull lifetime extension and assessment of fatigue loading.

1.3. Finally, it is very important to highlight that the system shall be field-proven and must already have been used regularly in FPSOs around the world, for at least 5 years. The system shall also be approved for its intended use by Classification Society.

1.4. This document is intended to describe the HULL SUPPLIER's scope of work for the design and installation of the Hull Structure Health Monitoring System.

2. ABBREVIATIONS

- ATEX - Explosive Atmospheres
- CIFS - Common Internet File System
- CS - Classification Society
- CSS - Control and Safety System
- DMZ - Demilitarized Zone
- DOF - Degree-of-freedom
- ESD - Emergency Shutdown
- EX-e, Exe - Increased Safety
- EX-I, Exi - Intrinsic Safety
- FAT - Factory Acceptance Test
- FPSO - Floating Production Storage and Offloading
- GPS - Global Positioning System
- HSHMS - Hull Structure Health Monitoring System
- IECEx - International Electrotechnical Commission Scheme for Certification to Standards Relating to Equipment for use in Explosive Atmospheres (IECEx Scheme)
- IS - Intrinsic Safe
- ITP - Inspection and Test Plan
- LBSG - Long Base Strain Gauge
- MRU - Motion Reference Unit
- PC - Personal Computer
- RAO - Response Amplitude Operator
- SAT - Site Acceptance Test
- UPS - Uninterruptible Power Supply

3. REFERENCES

3.1. HULL SUPPLIER shall carry out the detailed engineering design of the Hull Structure Health Monitoring System based on the documents listed in the project “DOCUMENT LIST” and the other engineering requirements contained in this document.

4. SCOPE OF WORK

4.1. To implement an HSHMS system onboard the FPSO HULL the following scope of work is to be considered: design, detail engineering, material procurement, manufacturing, inspection, testing, certification, installation, commissioning and documentation of all components of the HSHMS. It is also within the scope of work the update of the FPSO documentation in order to reflect the alterations due to the installation of the system. All the scope is to be provided by the HULL SUPPLIER.

4.2. Furthermore, it is responsibility of the HULL SUPPLIER to provide the following items:

a. Layout definition (sensor, main panel position, etc.);

b. Main panel with UPS (Uninterruptible Power Supply) and hardware equipment;

c. Instrument junction boxes;

d. Sensors;

e. Cabling, cable trays and penetrations;

f. Sensor supports;

g. Data acquisition software;

h. Cabling and connections with other FPSO systems (Navigation, Metocean and Loadmaster);

i. Cabling and connections of the main panel to the special monitoring network DMZ according to Telecommunication Basic Design documents and to the project's specific document entitled SPECIAL MONITORING SYSTEMS.

j. Perpetual licenses for the required software, with maintenance and updates for at least two years after the start of FPSO oil production;

k. Structural analyses required to define:

1) The optimal location of sensors including detailed information of all steps performed to define the sensor locations;

2) The conversion matrices used to obtain local stresses from global strains measured by the sensors, including detailed information of all steps performed to obtain the conversion matrices for all drafts. For the information regarding the structural model in terms of loading conditions, drafts, heading directions etc. please see HULL STRUCTURAL REQUIREMENTS;

l. Reports from the analyses performed to design the HSHMS, including location of sensors and conversion matrix, shall be delivered, observing the requirements from HULL STRUCTURAL REQUIREMENTS.

m. Report for validation of the methodology to calculate fatigue damage in the selected hot spots from the data that will be measured along life, using:

1) Stress RAOs at selected cold spots obtained from stochastic analyses, according to HULL STRUCTURAL REQUIREMENTS;

2) Conversion matrices for the selected hot spots;

n. Operation and maintenance training course to selected PETROBRAS employees. This course shall enable the participant: a) to understand the operation of the equipment in their general aspects of hardware and of software, including theoretical background on treating the data collected for the purpose of the system; b) to be able to knowhow all of the procedures of maintenance; c) to be able to accomplish corrective and preventive maintenance in the equipment and identification of failures and substitution of parts. Didactical material and manuals shall be provided for the training course, in English and Brazilian Portuguese.

4.3. HULL SUPPLIER shall also implement three (3) dashboards with information from Hull Structure Health Monitoring System (HSHMS). These dashboards are defined in the following items:

a. Hull Structural Fatigue – Current Data 1: Monitoring the current state of the structure showing the fatigue damage trends on 3D model of the hull structure (with the use of conversion matrix);

b. Hull Structural Fatigue – Current Data 2: Monitoring the current state of the structure showing the fatigue damage trends on hot/cold-spot charts and tables for easy insight on the structure current condition;

c. Hull Structural Fatigue – Historical Data: Accessing all past measured and calculated data including fatigue damage and data from connected systems (strains at sensors, tank fillings, environmental conditions, etc.) in form of charts and tables.

4.4. The functionality of selecting data by time frames and of exporting data and figures shall be available in the dashboard.

5. FUNCTIONAL REQUIREMENTS

5.1. The HSHMS System shall:

a. Provide near real-time fatigue damage trends for the three cases:

i. Measured life time consumption: obtained with the actual measurements of the structural response;

ii. Predicted life time consumption: obtained with the design tools, using predicted environmental and loading conditions;

iii. Calculated life time consumption: obtained with the design tools, using measured environmental and loading conditions.

b. Provide subsidies to assess why fatigue damage rates are above or below the rates predicted during the design of the vessel by comparing measured data with both predicted and calculated data using the actual encountered environments.

c. Provide input to the planning and scheduling of inspection, maintenance & repair programs.

d. Provide an understanding of the potential for life extension of the hull and interface structures.

e. Monitor the current state of the structure showing the fatigue damage trends both on 3D model of the hull structure (with the use of conversion matrix) and on cold/hot-spot for easy insight on the structure current condition.

f. Export data and reports for Digital Twin dashboards.

g. HSHMS main panel shall be cabled to special monitoring network DMZ according to Telecommunication Basic Project documents.

6. DESIGN, ENGINEERING AND DOCUMENTATION

6.1. The following dedicated documents must be issued, by the HULL SUPPLIER, as part of the HSHMS project.

No.	Document title
1	Vendor document Register
2	Weight data sheet
3	Instrument data sheet, with complete specification of each component acquired
4	Name plate drawings
5	Instrument / Electrical Panel Layout and Detail Drawing
6	Instrument / Electrical Interconnection Diagram
7	Terminal / Wiring Diagrams
8	Serial Communication Mapping List (Modbus list)
9	IS calculations
10	Packing / Unpacking and Preservation Procedure
11	Pre-commissioning / Commissioning Procedure
12	Packing list
13	Inspection and Test Plan (ITP)
14	Factory Acceptance Test (FAT) Procedure
15	Site Acceptance Test (SAT) Procedure
16	Factory Acceptance Test (FAT) Report
17	Class certifications
18	Installation, Operating and Maintenance Manual
19	Cable schedule / layout
20	External data exchange
21	Software manual and User Interface documentation
22	Sensor arrangement plan and 3D modeling
23	Penetrations drawings and 3D modeling

24	Data format description for stored data
25	Database format description
26	Reports requested by this TS including annexes (e.g. conversion matrices, model etc.)

6.2. The HSHMS engineering drawings (panel layout, wire diagrams, penetrations, sensor positioning, etc.) must be prepared (issued for construction) and sent to PETROBRAS for approval. Only upon approval of the documents, the construction of supports, penetrations, etc., as well as the installation of the panel, junction boxes and other components of the system may be started. As built versions of all documents must be provided upon installation of the HSHMS equipment.

6.3. The manuals from item 18 shall be provided in English and Brazilian Portuguese.

6.4. Class Society shall approve all structural modifications related to the installation of HSHMS.

7. DESCRIPTION OF HSHMS SYSTEM

7.1. HSHMS equipment shall comprise at least a main panel with required equipment and UPS (with dimensions 800x800x2000, in mm), (instrument) junction boxes, sensors, cabling, penetrations and software. The sensors shall comprise Long Base Strain Gauges (LBSG), strain gauges and a Motion Reference Unit (MRU).

7.2. Strain gauges sensors may be based on traditional Wheatstone Bridge or Fiber Bragg Grating technologies. Other technology depends on Petrobras approval. The cabling and equipment shall be adjusted considering the adopted sensor technology.

7.3. The sensors shall be designed to avoid or minimize influence of other quantities than the quantity it is intended to measure. LBSG sensors measure the global strain and shall have a length of 1.5 to 2.0 meters. Other LBSG sensor length depends on Petrobras approval. The LBSG sensors shall be mounted such that to minimize influence of local stress concentration.

7.4. A strain gauge measures the local strain and the positioning of the sensors shall consider the stresses it will measure as well as the presence of cold/hot spots.

7.5. The locations of the HSHMS sensors shall be defined based on a set of criteria which comprises:

a. Stress dominated by one load component (hull girder bending, local wave loading) only

b. Cold spot location close to analyzed hot spot location

c. Similar and symmetrical locations at portside and starboard side

d. Mid ship location for maximum hull girder bending stresses

e. No locations in cargo oil tanks for safety reasons

7.6. In Figure 1 the FPSO capacity plan with the preliminary proposed positions of the sensors, (instrument) junction boxes and main panel is presented. This is an example considering the main panel located in the accommodation area. The layout shall be adapted considering the respective project main panel position. The layout and the position of the sensors shall be proposed by the HULL SUPPLIER and approved by PETROBRAS.

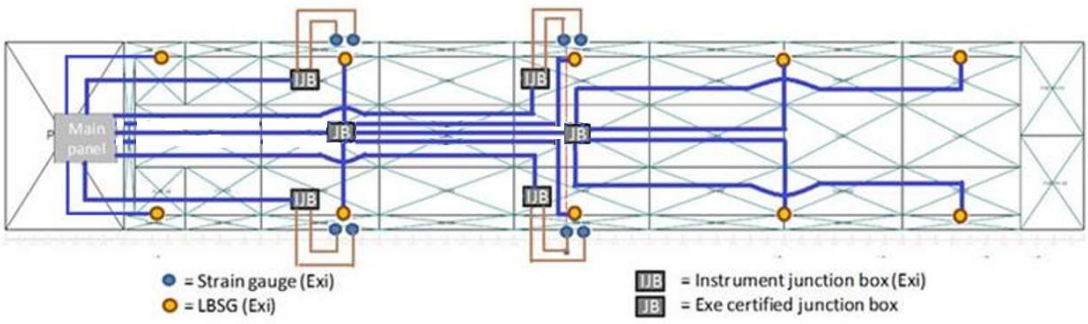

Figure 1 - Instrumentation layout of HSHMS onboard the FPSO HULL

7.7. The HSHMS system shall comprise at least the following sensors: 10 LBSG sensors and 8 strain gauges.

7.8. The LBSG sensors shall be mounted on deck in positions defined to properly capture the global behavior of the hull structure (stresses due to global bending, torsion, etc., both at wave and low cycle frequency ranges as well as high frequency such as whipping ranges).

7.9. The strain gauges shall be mounted on stiffeners and stringers in the water ballast tanks in positions defined to properly capture the structural response to the load phenomena which is of interest (stresses caused by local external and internal pressures, both at wave and low cycle frequency ranges) close to the vertical hull girder neutral line. As the deck plate is a primary structure of the FPSO, Class Society approval shall be provided for the cabling deck penetrations according to the CS applicable rules. In addition, these deck penetrations must assure the watertight integrity of the main deck.

7.10. As shown in the schematic from Figure 1 it is proposed to mount the sensors in five cross sections at both portside and starboard side. The sensors located on the main deck shall be mechanically protected. The sensors located inside the ballast tanks shall be protected by long term resistance coating.

7.11. In Figure 1, two sensors are positioned in four water ballast tanks and are connected to stainless steel S316L instrument junction boxes which are mounted on deck. These instrument junction boxes comprise intrinsically safe strain gauge amplifiers or other equipment needed for an adequate signal. From the instrument junction boxes cabling runs to the main panel in the accommodation area, forecastle or other proper position defined in the layout of the system to minimize the number of cabling and to facilitate the installation. Each LBSG sensor shall be connected to an Exe certified junction box from which cabling runs to the main panel. The cabling of the LBSG closest to main panel might run directly to the main panel. Changes in cabling layout shall be submitted to Petrobras for approval.

7.12. The main panel shall include also a 6 DOF MRU to monitor the wave frequency motions of the FPSO.

7.13. For the cabling between strain gauges and instrument junction boxes underwater shielded cabling with a polyurethane jacket and a high notch resistance to avoid damage along sharp edges shall be used (marked as brown in Figure 1).

7.14. The system shall include a computer with sufficient capacity to perform the tasks required, e.g. process the sensor signals, network transfers, etc. The computer shall have enough storage capacity to store at least one year of raw and processed data measurements. The system shall have the capability to back-up the recorded data on a medium suitable to be read on a personal computer (PC). The data back-up file(s) shall include all the recorded data presented on a suitable format. The file(s) shall include sufficient information to clearly describe the content of the file(s). The system shall upload the raw and processed data as well as reports to PETROBRAS network storage at least once a day.

7.15. The system must have the technical capability to access a remote drive using the CIFS protocol, with the objective of writing the results of the analyses and raw data as required by Petrobras.

7.16. If the HSHMS uses more than one computer, each computer shall have their own network connections to a switch and no other network connection between those computers is allowed. This requirement will facilitate management, maintenance and future updates of the software and operating system.

7.17. The sensors measurements shall be digitized with at least 20 Hz. The system shall have the technical capability to adjust the sampling rate. The measurements frequency as well as environmental and loading parameters update frequency shall be approved by PETROBRAS.

7.18. The signal conditioning units shall be matched to the connected sensor. The signals from analog sensors shall be properly treated prior to digitizing to avoid signal noise. The filters shall be matched to the frequency range for the different sensors.

7.19. All electrical components that are exclusively used in the hull monitoring system shall be powered through an UPS. In case of main power failure, the system UPS shall have sufficient capacity to maintain normal operation of the hull monitoring system for at least 10 minutes. The hull monitoring system shall automatically shut down in a controlled manner within the UPS power reserve time. When ESD signal is received from CSS, the system shall start a safe shutdown procedure, including deenergizing field sensors. The hull monitoring system shall automatically re-start at return of main power.

7.20. The complete HSHMS system including all its parts shall have at least two year warranty after the start of FPSO oil production.

7.21. The instrument junction boxes shall be made of 316L stainless steel and shall have at least IP-56 protection degree, according to IEC 60529 and shall be classified as Ex-e, according to IEC-60079. The strain gauge sensors shall be intrinsically safe (Ex-i). The equipment installed on hazardous areas shall have ATEX and IECEx certification.

7.22. The installation of strain gauge sensors shall be supervised by vendor who shall issue a certificate of approval.

7.23. Additionally, for the case of fiber optic sensor technology, vendor shall provide all fiber optic cabling from main panel to each strain sensor, the required junction boxes for fiber optics connection or fusion. Tests for fiber optic certification shall also be carried out considering all interfaces, in order to avoid error of incompatibility between them. Fiber optic and Equipment certification shall be provided. Spare cabling shall be provided for the fiber optic between main panel and main deck main junction box.

8. DESCRIPTION OF HSHMS SOFTWARE

8.1. The HSHMS system shall have an interface with the Loadmaster system and the Metocean system onboard the FPSO to obtain actual information on ship's loading condition (draft, trim, filling level of water ballast tanks and cargo oil tanks) and the environmental conditions (waves and wind). Also, an interface with the navigation system shall be provided to obtain the FPSO heading and GPS position. All data (draft, trim, filling level of water ballast tanks, cargo oil tanks and other tanks, waves, wind and structural response) shall be measured, processed and stored in a synchronized way such that to save the time history of load parameters and respective structural response. All data (measured and processed) shall be provided, made available and uploaded to the PETROBRAS Network Storage in a non-proprietary, license-free, not encoded and non-binary or platform specific format. Data format shall be documented and should specify field types, any requirements such as valid values and any inter-table relationships. Metadata shall be made available and specify at least time of origin, source and data owner. Data flow and sensor system shall have traceability and be identifiable.

8.2. The quality of data shall be assured and the data requirements (database format, data format, schema, metadata, algorithms, etc.) shall be approved by Classification Society and PETROBRAS.

8.3. All the necessary cables must be purchased, pulled and connected from the other systems to HSHMS panel as well as for the network switch for a connection to the PETROBRAS data network in the FPSO. The interface with Loadmaster, Metocean and Navigation systems must be tested.

8.4. In Figure 2 an overview of the HSHMS interfaces is given.

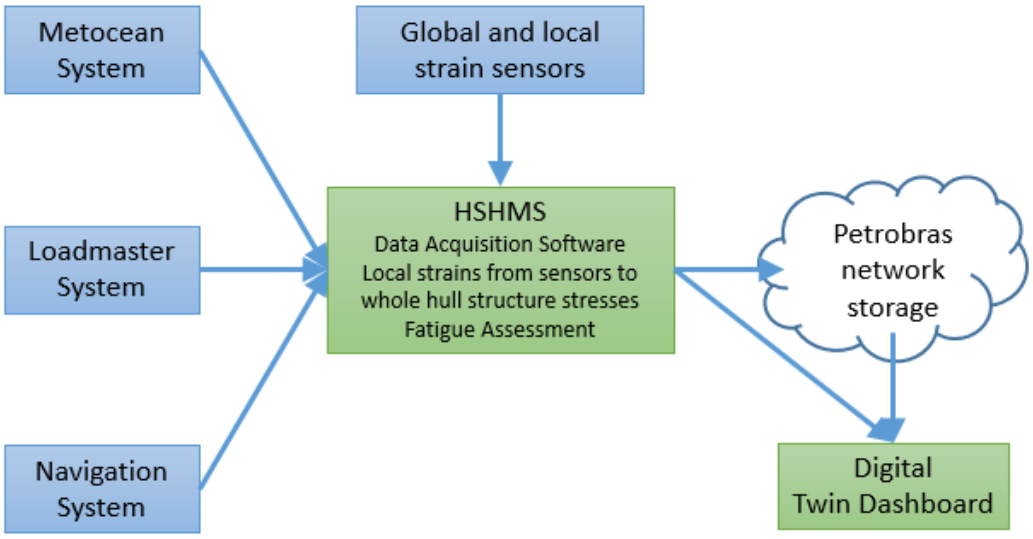

Figure 2 - HSHMS software and interfaces

9. COMMISSIONING, CLASSIFICATION CERTIFICATION AND QUALITY CONTROL

9.1. COMMISSIONING

9.1.1. Commissioning prior to delivery of the HSHMS all equipment must be tested according to the ITP. During FAT all equipment must be calibrated. In addition, the following tests must be performed as part of FAT; visual inspection tests, dimensional checks, earth continuity tests, functional tests, insulation resistance, startup tests, black-out recovery tests and software tests. The results of the tests must be reported.

9.1.2. In addition, during the commissioning phase, the HSHMS system and all its components, including sensors, equipment, connections, software as well as interaction with other systems, shall be tested. The results of the tests must be reported.

9.2. CERTIFICATION

9.2.1. The HSHMS data will be used as a standalone hull monitoring system and no classification notation will be requested. Anyway, the plan approval, certification of equipment and cabling and approval of the HSHMS shall be issued by the Classification Society aiming at acceptance of the measurement data as an assessment of the real in-service performance of the FPSO hull structure and in order to avoid false warnings. Stochastic fatigue analyses performed to obtain the stress RAOs shall be part of the documents reviewed and approved by Classification Society.

9.2.2. Certification of HSHMS shall at least cover the following scope:

9.2.2.1. Measured data are to be collected and recorded for the later use;

9.2.2.2. Hull girder stress measurements with the use of strain gauges;

9.2.2.3. Local stress measurements with the used of strain gauges;

9.2.2.4. Fatigue monitors applicable to areas of possible deterioration and designated fatigue prone areas;

9.2.2.5. Loading Computer direct data link that is capable of continuously updating the loading conditions to the HSHMS;

9.2.2.6. Navigation system link to the HSHMS to retrieve navigation data;

9.2.2.7. Wind monitors to measure relevant data;

9.2.2.8. Ship Motion monitor to measure relevant data;

9.2.2.9. Sea State monitors to measure relevant data.

9.2.3. Certification scope shall be sent to PETROBRAS for approval.

9.3. QUALITY CONTROL

9.3.1. The requirements of data and data quality shall be in accordance with DNVGL-RU-OU-0300 or equivalent from other Classification Society.