OTC-35240-MS

Digital Twin: Hybrid Virtual Simulation and Physical Monitoring Strategy for Long-Term Safe Operation of Floating Production Platform-Hybrid Polyester Mooring Lines-Steel Catenary Risers Multibody System in the South China Sea

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This paper was prepared for presentation at the Offshore Technology Conference held in Houston, TX, USA, 6 – 9 May, 2024.

Abstract

As the first self-development ultra-deepwater gas field, the project adopts the floating production platform-subsea production system. The platform is kept in position by sixteen hybrid polyester mooring lines. The gas and other fluids associated to the production process are conveyed to the platform by six steel catenary risers. The field has an operational design cycle of 30 years.

With the purpose of ensuring long-term safe operation for offshore structures, this case fuses physical monitoring and virtual simulation to build an integrated platform management system. Monitoring data from the environment, platform, mooring lines and risers are periodically collected from the in-situ sensors. The system applies the Long short-term memory neural network to reconstruct the virtual simulation model of the dynamic response of offshore structures under environmental loads.

The system has two main functions: mechanical behavior prediction and mooring strategy adjustment. Combined with the monitoring data of environmental elements in the current operation area, the system can realize real-time prediction and calculation of platform movement, mooring lines tension and riser dynamic configuration, and visualize the health status of offshore structures. In case of severe operational conditions such as typhoon, the platform operators can obtain the platform displacement window and the corresponding mooring tension adjustment strategy through the operating system to maintain the riser stress safety.

This case gives a real-time solution for the safe operation of offshore structures with physical monitoring and virtual simulation, which can guide the operators to adjust the platform displacement to maintain the mooring lines and risers in the safety zone for a long time.

Introduction

Since 2000, over 70% of global major oil and gas discoveries have been made in deepwater. The deepwater area have become the future growth hotspot for hydrocarbon exploration and development in the world. Under the backdrop of the world oil and gas industry development focus to the deepwater, Floating production systems (FPS) are gradually established as the primary choice in deepwater oil and gas production activities. Different types of floating production structures represent the key equipment in FPS, such as semi-submersible production platforms and floating production storage and offloading unites (FPSO). They are kept in place by mooring lines and are connected to subsea production system by risers.

Currently, there is a large number of FPS installed in typical deepwater areas around the world, such as the Brazilian Atlantic Deepwater Basins, Gulf of Mexico, West African Deepwater areas, and the South China Sea. Considering the high investment feature of deepwater projects, the managers tend to require the FPS to maintain safe operation for a long time to reap the rewards.

The FPS is a complex coupled system. The platform is positioned via mooring lines. The risers connects the platform to the wellhead for oil and gas transportation. Under the wind, wave, and current loads, the platform drives the mooring lines and risers to move, and in turn the mooring lines and risers provide restoring force and damping to the platform. During long-term operation, the mooring lines and risers tend to suffer from continuous fatigue damage. When encountering extreme sea states, there is a potential risk of sudden failures, such as buckling and breakage. The need to monitor and assess the long-term operation safety of FPS has already been widely acknowledged.

Appropriate sensing technologies coupled with virtual simulation could provide the tracking and feedback of ocean environments, motion attitudes, operational conditions, cumulative damages and the overall safety status for the basis of scientific decisions of inspection, repair and scrap. In this context, this work presents a hybrid virtual simulation and physical monitoring strategy applied in the long-term safe operation in the South China Sea. The strategy begins by collecting historical ocean environment and structural response information from in-situ monitoring sensors. With such information, a "digital twin" model that hybridizes virtual simulation with physical monitoring is generated to represent the field FPS dynamic response. It is employed to perform a series of analyses that provide the platform motion, mooring lines tension, SCRs dynamic response, stiffness changes in mooring lines, and cumulative fatigue damage in SCRs. These information allow to check whether the mooring lines and risers are still meeting with the safe design criteria; if not, control method should be taken to maintain the system to a safe operational condition.

Gas field development project profile

The gas field is located in the western continental shelf of the northern South China Sea, with water depth of 1220m to 1560m. As shown in Fig 1. The development consists of one semi-submersible production platform, subsea production system, and subsea pipelines.

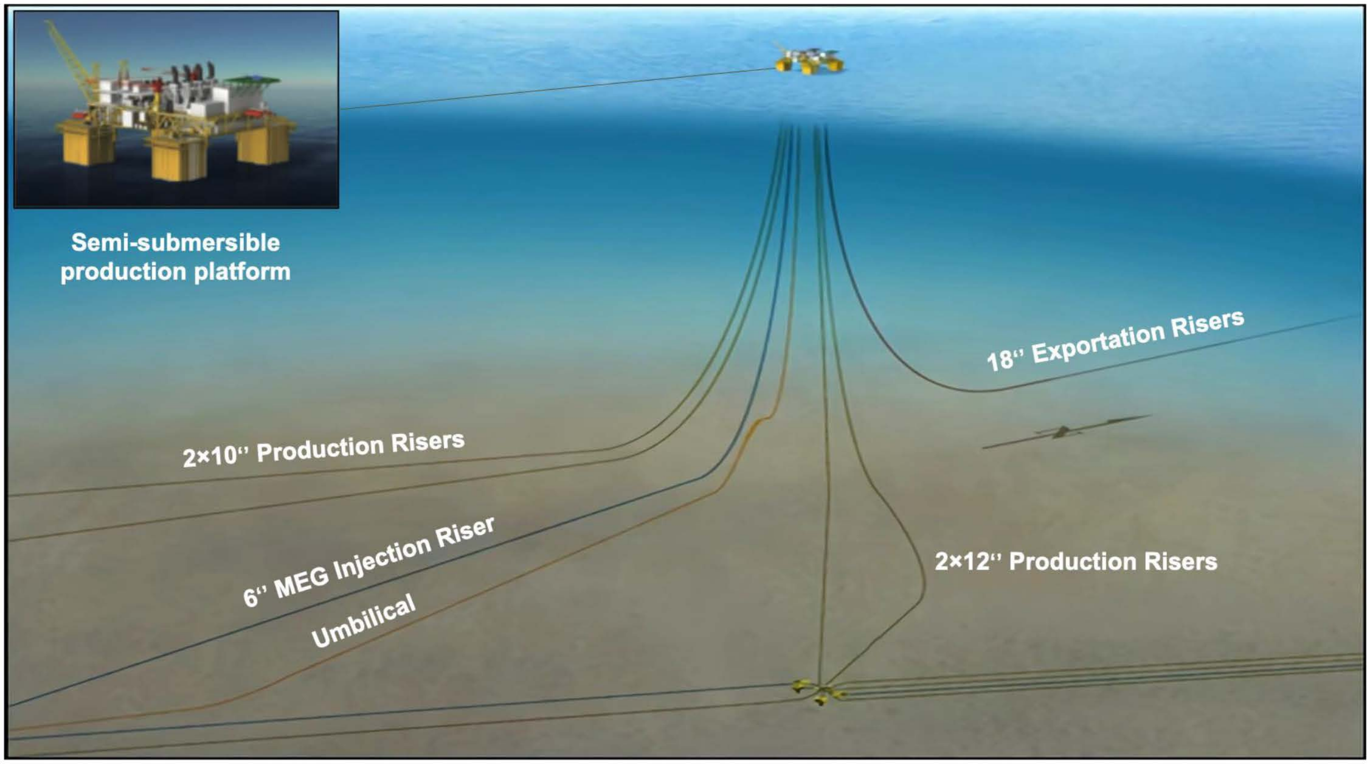

Figure 1—The platform and risers layout

The FPS adopts 4 sets multiply 4 hybrid polyester mooring lines to form a tensioned system for platform positioning. A single mooring line employs steel anchor chain at the subsea mudline area and the platform link, while the rest is made of polyester rope. Steel catenary risers (SCR) are selected as the connecting structure between platform and subsea production system. Well fluid from all east manifolds will be transported to platform for process through two 12" SCRs. Well fluid from all west manifolds will be transported to platform for process through two 10" SCRs. The platform to subsea distribution unit is arranged with a 6" Mono Ethylene Glycol (MEG) injection riser and a dynamic umbilical cable. After processing, qualified natural gas shall be pressurized and transported to land terminals through a 18" SCR. A detailed description of the SCRs is shown in Table 1.

Table 1—Steel catenary risers introduction

SCRs	Porch Name	Size	Suspension Angle	Catenary Segment Length
Production (From East Manifolds)	P1, P2	12"	12deg	1807m
Production (From West Manifolds)	P3, P4	10"	12deg	1746m
MEG Injection	MEG1	6"	12deg	1746m
Gas Exportation	GE	18"	10deg	1686m

Physical monitoring strategy

With an operational design cycle of 30 years, the focus on monitoring field loads and responses is increasing to enhance the understanding of complex dynamic behavior, warn anomalies and detect structural damages. From the monitoring perspective of ocean environment and structural response, as shown in Fig 2, the FPS is equipped with various sensors to assist operators in detecting structural damage and performing early maintenance.

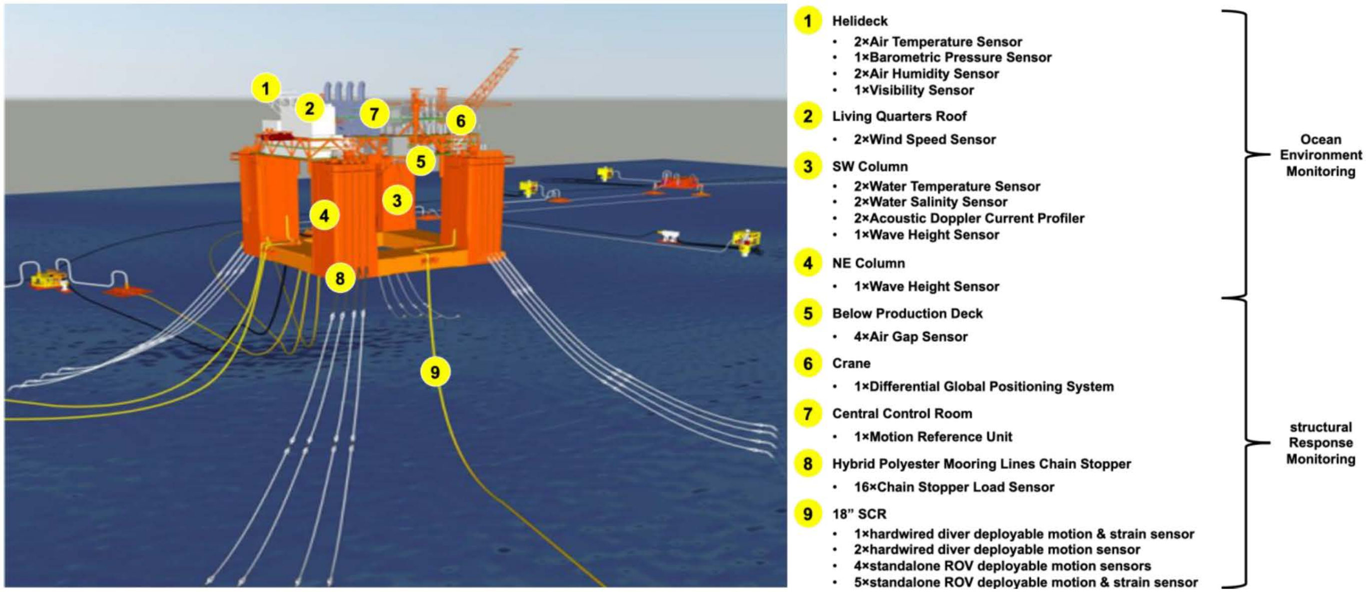

Figure 2—Physical Monitoring Sensors on FPS

Ocean environment monitoring

As shown in Table 2, there are nine types of sensors for air condition, water condition, wind load, wave load and current load monitoring.

- **Air condition monitoring**: Two air temperature sensors, one barometric pressure sensor, two air humidity sensors and one visibility sensor serve in air temperature, barometric pressure, humidity and visibility data collection.
- **Water condition monitoring**: Two water temperature sensors and two water salinity sensors serve in water temperature and salinity data collection.
- **Wind load**: Two wind speed sensors serve in wind speed and wind direction data collection.
- **Wave Load**: Two wave height sensors serve in wave direction, wave direction and wave period data collection.
- **Current Load**: Two acoustic doppler current profilers serve in current velocity and current direction data collection.

All the ocean environment monitoring data is collected at 2-second intervals and transmitted to the control center for storage.

Structural response monitoring

As shown in Table 2, there are nine types of sensors for semi-submersible, hybrid polyester mooring lines and SCRs monitoring.

- **Semi-submersible production platform motion response**: Four air gap sensors, one differential global positioning system (DGPS) and one motion reference unit. Air gap sensors are used observe the change in draft under environmental loads. DGPS is used to monitor platform center coordinate. Motion reference unit is used to monitor six degree of freedom motions. The motion response data is collected at 2-second intervals and transmitted to the control center for storage.
- **Hybrid polyester mooring lines motion response**: Sixteen chain stopper load sensors. Chain stopper load sensors are used to capture the dynamics characters of each hybrid polyester mooring line. The motion response data is collected at 2-second intervals and transmitted to the control center for storage.

- **SCRs motion response**: One hardwired diver deployable motion & strain sensor, two hardwired diver deployable motion sensors, four standalone ROV deployable motion sensors and five standalone ROV deployable motion & strain sensors for 18" SCR. As shown in Fig 3, the 18" SCR motion response monitoring is divided into three areas. At the hang-off area, sensors transmit acceleration, angular rates and strain are collected at 2-second intervals and transmitted to the control center via umbilical cable. At the midpoint and touch done zone, sensors are battery-powered. Acceleration, angular rates and strain are stored briefly on an additional SD card and retrieved to the control center by the ROV cyclic subsea operation.

Table 2—Physical Monitoring sensors equipped on the FPS

Categorization	Sensor	Location	Type	Measurement	Range	Accuracy
Ocean Environment	Air Temperature Sensor	Helideck	Resistance Temperature Detector	Air Temperature	–50-50°C	±0.5°C
	Barometric Pressure Sensor	Helideck	Barometric Sensor with Remote Port	Barometric Pressure	850-1050hPa	±0.5hPa
	Air Humidity Sensor	Helideck	Capacitance	Air Humidity	0-100% RH	±2%RH(22°C)
	Visibility Sensor	Helideck	Visibility Sensor	Visibility	10m-75km	±4%
	Wind Speed Sensor	Living Quarters Roof	Microwave Radar	Wind Speed	0-70m/s	±0.5 m/s (< 5m/s) ±5% (5m/s)
				Wind Direction	0-360deg	±1deg
	Water Temperature Sensor	SW Column	Conductivity	Water Temperature	0-50°C	±0.02°C
	Water Salinity Sensor	SW Column	Conductivity	Water Salinity	0~70ms/cm	±0.25ms/cm
	Acoustic Doppler Current Profiler	SW Column	ADCP (Vertical)	Water Velocity	0-10m/s	1% of measured value ± 0.5cm/s
				Water Direction	0-360deg	±1deg
	Wave Height Sensor	NE and SW Columns	Microwave Radar	Wave Height	0-60m	±12mm
				Wave Direction	0-360deg	±2deg
				Wave Period	1-100s	±50ms
	Air Gap Sensor	Below Production Deck	Microwave Radar	Air Gap	3-65m	±12mm
	Differential Global Positioning System	Crane	Differential Global Positioning System	Platform Center Coordinate	Region of Interest	±1m
Structural Response	Motion Reference Unit	Central Control Room	6 Degrees of Freedom	Surge	0-50m	±5cm(or 5%) which is greatest
				Heave	0-50m	±5cm(or 5%) which is greatest
				Sway	0-50m	±5cm(or 5%) which is greatest
				Yaw	0-45deg	±0.01deg
				Pitch	0-45deg	±0.01deg
				Roll	0-45deg	±0.01deg
	Chain Stopper Load Sensor	Hybrid Polyester Mooring Lines Chain Stopper	Tension Sensor	Hybrid Polyester Mooring Lines Tension	0-6000kN	±100N
	Hardwired Diver Deployable Motion & Strain Sensor	18" SCR Hang-off Zone	Motion Sensor	Acceleration	-19.6-$19.6 m/s^2$	$\pm 0.02 m/s^2$
				Angular Rates	–4-4deg/s	±0.05deg/s
			Strain Sensor	Strain	–2300-2300 με	±0.3 με

Categorization	Sensor	Location	Type	Measurement	Range	Accuracy
	Hardwired Diver Deployable Motion Sensor	18" SCR Hang-off Zone	Motion Sensor	Acceleration	–19.6-19.6m/s^2	±0.02m/s^2
				Angular Rates	–4-4deg/s	±0.05deg/s
	Standalone ROV Deployable Motion Sensor	18" SCR Midpoint and Touch Down Zone	Motion Sensor	Acceleration	–19.6-19.6m/s^2	±0.02m/s^2
				Angular Rates	–4-4deg/s	±0.05deg/s
	Standalone ROV Deployable Motion & Strain Sensor	18" SCR Midpoint and Touch Down Zone	Motion Sensor	Acceleration	–19.6-19.6m/s^2	±0.02m/s^2
				Angular Rates	–4-4deg/s	±0.05deg/s
			Strain Sensor	Strain	–2300-2300 με	±0.3 με

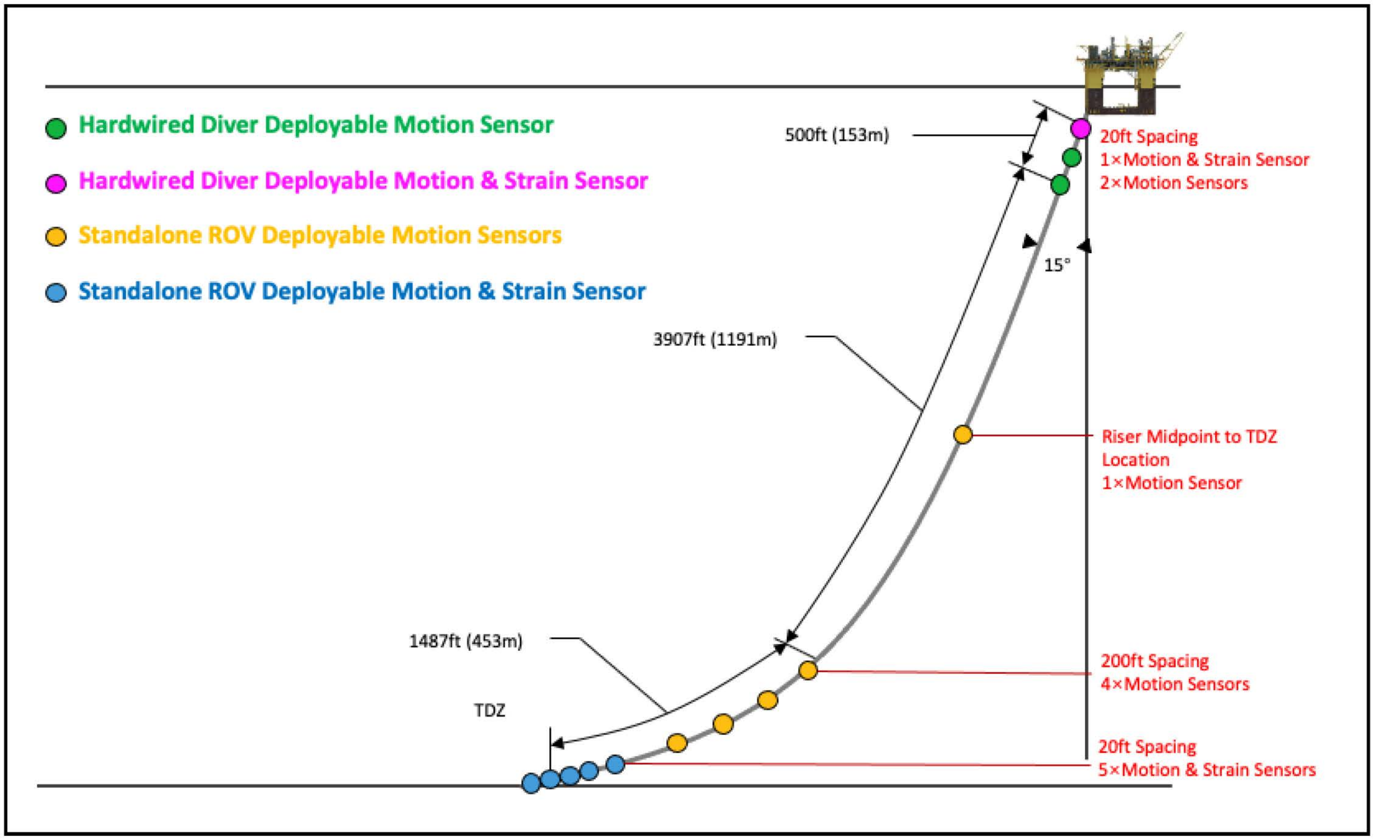

Figure 3—Structural response monitoring sensors for 18" SCR

Physical monitoring strategy advantages and disadvantages

FPS served in ocean environments has complex failure modes that can be divided into two types: transient failures and progressive failures. The former is caused by extreme loads such as storms and freak waves, which are random and may result in rupture and buckling of structural materials. The latter is caused by long-term cyclic reactions such as fatigue and corrosion, which are continuous and may also result in damage and deterioration to trigger more serious failures. With the structural response monitoring sensors, the operators can obtain the key discriminative parameters in real time for risk identification, such as platform offset, mooring tension and riser strain. Coupled with the design threshold, it is possible to make a judgment on the possibility of transient failures to the FPS. Neither of them can be effectively identified by periodical inspections and routine safety operations. In-situ structural response monitoring can provide effective multibody motion information to warn of design limits and to evaluate damages.

However, for vulnerable structures such as mooring lines and SCRs, the operators are more concerned with the possible failures prediction in extreme ocean environment and the continuous cumulative fatigue assessment in long-term operation. Thus, there are two main disadvantages exposed in the physical monitoring strategy.

- **Real time monitoring without intelligent prediction:** On the one hand, the sensors provide real time monitoring information about the ocean environment and the structural response, but do not have the ability to predict the motion response of mooring lines and SCRs according to weather changes. Consequently, the operators have to rely on the design criteria and personal experience to anticipate failure risks. On the other hand, for subsea sensors with no real time feedback capability due to water depth limitations, as shown in Fig 3, any structural faults could only be detected by engineers post-processing historical monitoring information. In this case, any serious real time malfunctions problems couldn't be found in time.
- **Transient failure recognition without continuous damage assessment**: In the case of mooring lines, exposure to the long-term ocean environment loads can lead to changes in the stiffness of the mooring system due to a range of factors, such as creep of synthetic ropes, damage to rope structures, interlink wear of mooring chains, seabed trenching of mooring lines, excessive ocean growth and loss of mass weights on mooring lines. Such changes in stiffness can alter the dynamic response of the platform. It may increase the offset in extreme sea states beyond the allowable design offset limits. In the case of SCRs, Under the influence of platform motion and the ocean environmental loads will lead to the dynamic changes in the SCR morphology and the touchdown zone. The vortex vibration and pipe-soil interaction could directly generate a continuous accumulation of fatigue damage on the SCRs. In the practical operational context described above, the sensors could summarize the current state, but do not have the ability to autonomously calculate the cumulative damage and remaining strength.

The operator's management objectives for FPS long-term safe operation

Although physical monitoring sensors could fulfill the demand for real-time states feedback of the ocean environment, platform motion, mooring lines tension and 18" SCR hang-off area motion response. However, during long-term service cycle, FPS operators are more concerned about the potential damage risks, current health state and remaining service life in all mooring lines and SCRs. Through a detailed survey towards the relevant operators, they proposed the following objectives for the long-term safe operation of mooring lines and SCRs.

For long-term safe operation of mooring lines:

- Vulnerable zone
- Changes in stiffness
- Tension prediction of all mooring lines under customized environmental conditions
- Breakage risk in extreme environmental conditions
- Time to perform maintenance activities

For long-term safe operation of SCRs:

- Vulnerable zone
- Cumulative fatigue damage of all SCRs
- Dynamic response prediction of all SCRs under customized environmental conditions

- Breakage risk in extreme environmental conditions
- Control method to extend service life
- Time to perform maintenance activities

Hybrid virtual simulation and physical monitoring solution for long-term safe operation

According to the aforementioned discussion, a reliable workflow based on the physical monitoring strategy for long-term safe operation should integrate four more capabilities: "Dynamic response Calculation", "Continuous cumulative damage assessment and potential transient failures advanced identification", and "Control method for service life extension". This work proposes a hybrid virtual simulation and physical monitoring solution for long-term safe operation. The flowchart of Fig 4 illustrates the solution that comprise the long-term safe operation.

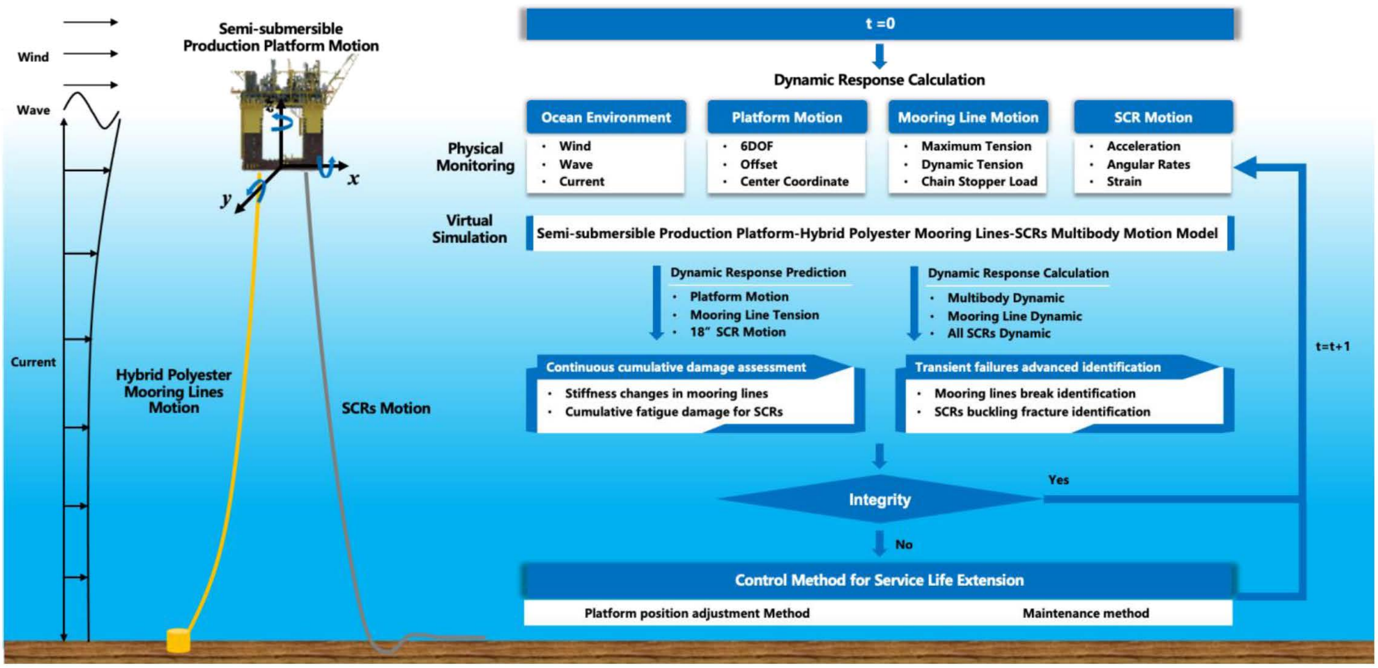

Figure 4—FPS long-term safe operation flowchart

Dynamic Response Calculation

The large amount of physical monitoring data contains regular information about the response of the platform, mooring lines and SCRs under a certain ocean environment. With machine learning method, it is an option to predict the motion response of the platform motion, mooring lines tension and 18" SCR motion. Coupled with the field investigation and historical monitoring data, the mechanism model could be modified to calculate the dynamic response of all SCRs. Therefore, the hybrid virtual simulation and physical monitoring solution makes it possible to realize the global response calculation of the platform-mooring lines-SCRs multibody system, as shown in Fig 5. It is also the basis for subsequent damage assessment and control strategy development.

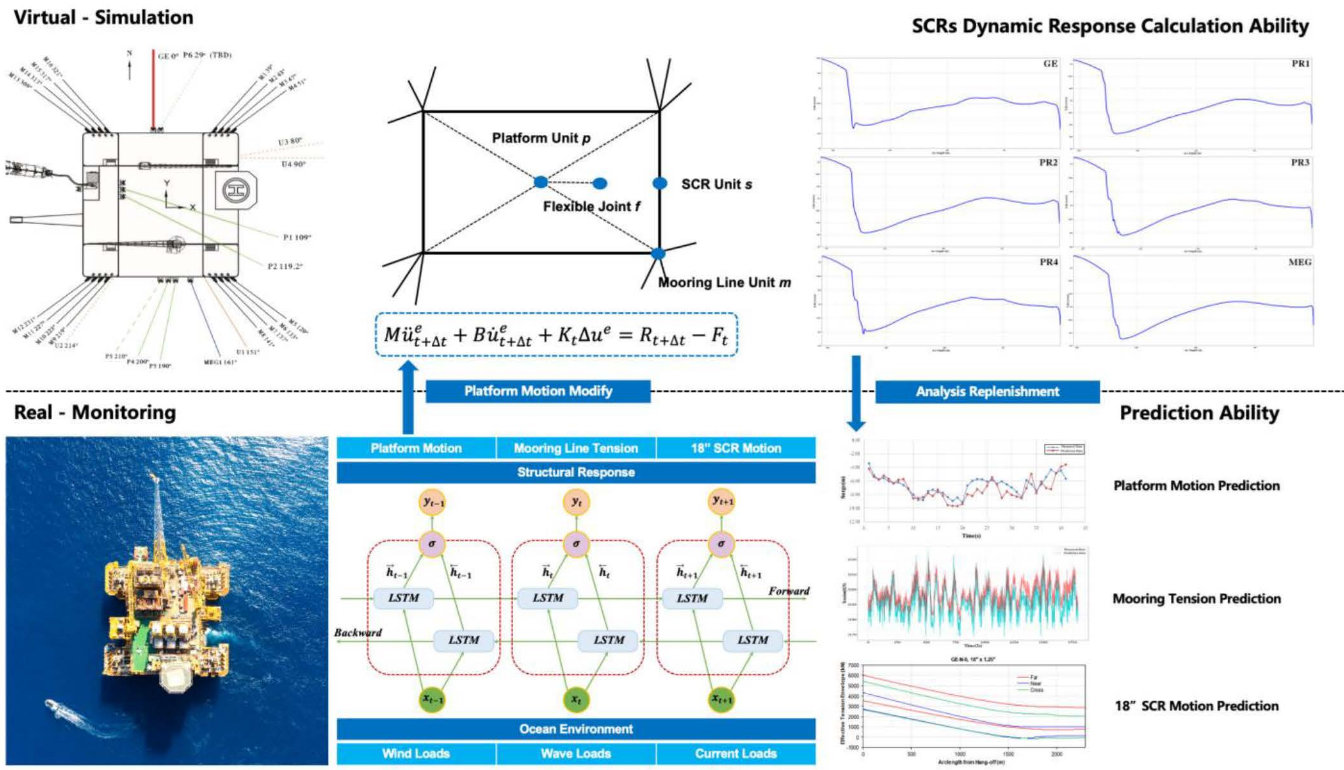

Figure 5—Hybrid virtual simulation and physical monitoring model establishment and dynamic response calculation

FPS dynamic response inversion based on the physical monitoring sensors. Environmental loads such as wind, wave, and current acting on FPS are the main factors resulting in FPS complex coupled motions. By combining the historical monitoring data of ocean environment and structural response, it is possible to summarize the dynamic motion behavior under specific environmental states through data inversion analysis. A FPS dynamic responses prediction model can be formed based on the long short-term memory (LSTM) neural network.

The flowchart of Fig 5 illustrates the process that forms a FPS dynamic motion response prediction model. All the ocean environment and structural response data are arranged in chronological order. x_t consists of environmental input data, including wind speed, wind direction, wave height, wave direction, wave period, current speed and current direction. y_t represents the structural response output data, including platform motion, mooring line tension and 18" SCR motion.

FPS virtual simulation model reconstruction based on the field investigation. Conventional FPS multi-body coupled simulation are commonly used in the project design stage due to the uncertain input parameters. In the production, the field layout of semi-submersible production platform, hybrid polyester mooring lines and SCRs is determined. Based on the field investigation, this work applies the multi-point constraints based on the rigid body theory to transfer the interaction among the platform unit, the mooring lines unit and the SCRs unit. As shown in Fig 5, it is assumed that the node number of the platform unit is p. The mooring line unit is m. A dummy node f is created as the connection point between the flexible joint and the platform, and then node d is connected to the SCRs unit s by means of linear and torsion springs, so that the role of the flexible joint can be fully taken into account. According to the real time ocean environment and platform motion obtained by physical monitoring sensors, the dynamic response calculation of the mooring lines and SCRs could be implemented through the motion equations and coordinates change.

Continuous cumulative damage assessment and potential transient failures advanced identification
Long-term damage concerns for mooring lines focus on changes in stiffness. It can be extracted from comparing the change in tension at the same platform offset in similar sea state. Fatigue is the major contribution factor to long-term SCRs damage. The cumulative fatigue damage and the remaining service life could be derived by retracing the dynamic response since SCRs were put into service since commissioning. Maintenance measures should be taken when the loss of mooring cable stiffness and riser fatigue damage exceed safe design limits. When the loss of mooring lines stiffness and SCRs fatigue damage exceeds safe design limits, maintenance measures should be taken.

In the event of extreme sea states such as typhoons, the concept of the safe operation zone is used as a measurement for transient failures advanced identification. Once the platform offset exceeds the safe operation zone, a potential breakage risk exists and control method need to be taken.

Continuous cumulative damage assessment.
Stiffness change in hybrid polyester mooring lines
Given the historical monitoring data available for the ocean environment and mooring tension, the change in restoring force curve of the mooring lines can be evaluated using data inversion methods motioned above to determine the effect on the mean platform offset for a mean environmental load, as shown in Fig 6. Thus, quantifying the difference between the expected and measured offset for a known environmental load can be used to quantify changes in mooring stiffness.

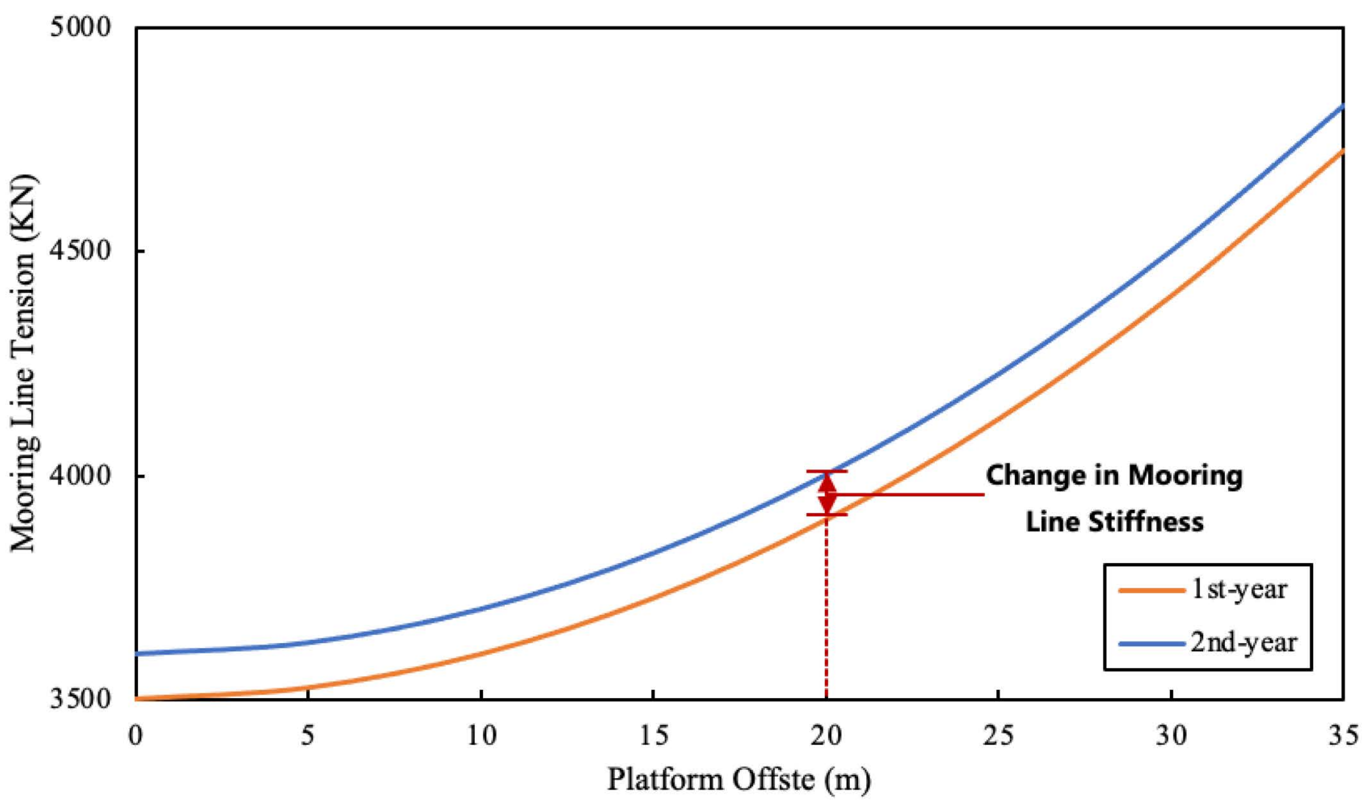

Figure 6—Stiffness change example of the mooring lines

Cumulative fatigue damage for SCRs
Considering the design life of the SCRs, appropriate safety factors, and other design variables and factors, the fatigue damage and remaining fatigue life of the SCRs can be obtained. For example, from the virtual simulation model mentioned in the previous section, the overall time-domain dynamic response of the SCRs is available for cumulative fatigue damage assessment. The different SCR stress spectra are expressed as

histograms of stress reversals using the Rain flow counting method. The Miner's rule and the S-N curve can then be applied to accumulate the fatigue damage of the SCRs at each location.

Transient failures advanced identification.

Safe operation zone for mooring lines

With the 1-year return period, 10-year return period and 100-year return period extreme condition statistics, it is feasible to derive superimposed combinations of wind, wave and current in different directions. Taking the maximum breaking load as the threshold, the limit platform offset of a single mooring line without breaking is calibrated by forcing the platform offset in each environmental loads combination direction. All the limit offset points form the safe operation zone for mooring lines, as shown in Fig 7 (a).

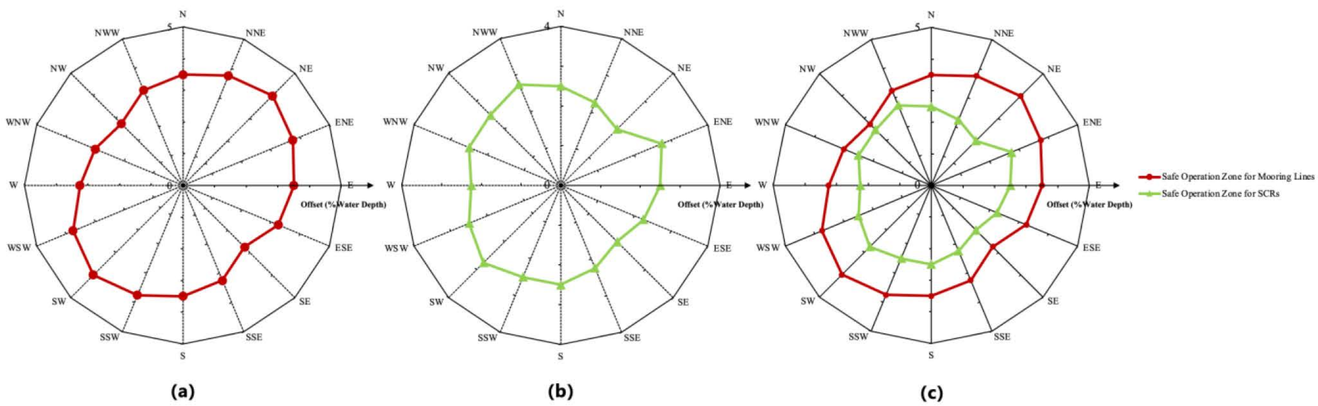

Figure 7—Safe operation zones for mooring lines and SCRs

Safe operation zone for SCRs

Similar to the generation of safe operating zones for mooring lines, when it comes to safe operation zone for SCRs, the threshold is modified into yield stress. The limit platform offset of a single SCR without breaking is calibrated by forcing the platform offset in each environmental loads combination direction. All the limit offset points form the safe operation zone for SCRs, as shown in Fig 7 (b).

The common safe operation zone of the mooring lines and SCRs in Fig 7 (c) is the safe platform offset range under extreme sea states. The operators could control platform offset within the safe operation zone by proactively adjusting the mooring lines tension to prevent potential breakage risk incidents.

Control method for service life extension

Due to the short-term extreme sea states, the SCRs is more prone to generate fatigue damage accumulation, which will greatly shorten their service life. The fatigue damage in the SCRs is proportional to its exposure time to the applied fatigue load, which in turn depends on the variation in the SCRs position and configuration. Therefore, the purpose of controlling fatigue damage can be realized by controlling the morphology of the SCRs during the field production activities. This process will be accomplished through platform position adjustment.

In this project, the concern center focuses on the safety of 18" SCR. Therefore, with the objective function of minimizing the top tension, touch down zone stress and bending stress along the 18" SCR, the ideal platform position could be found out within the safe operation zone in aforementioned discussion. The selection strategy is performed according to the following steps:

- Establishing a polar coordinate system at the center of the platform
- Forcing the platform offset Δx within the safe operation zone in each direction
- Recording each traversal position of Top *tension, TDZ compresion*, and Bending stress

- Selecting the ideal platform position that satisfies the target function requirements
- Adjusting the mooring lines tension to relocate the platform position

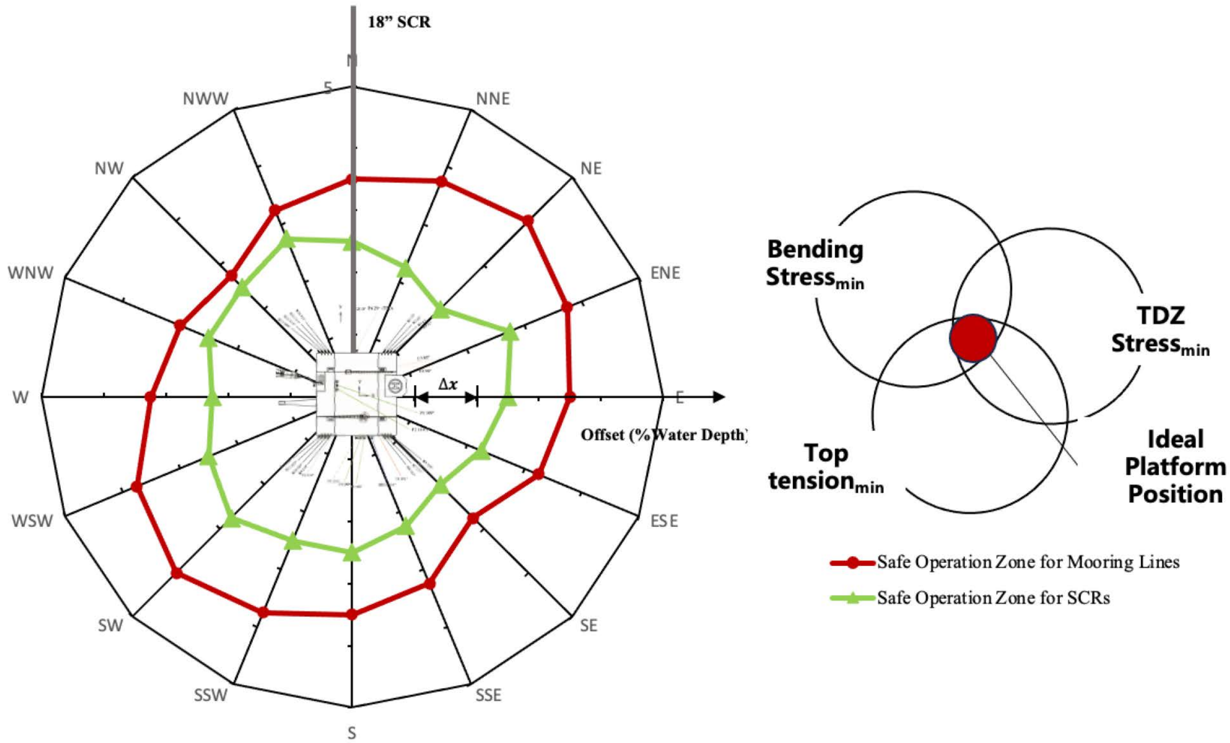

Figure 8—Platform position removal strategy for extending 18" SCR service life

Conclusions

This work describes a solution for real-time running status monitoring, dynamic response calculation, damage assessment and control methods to achieve FPS long-term safe operation. The solution relies on environmental and structural response information obtained from physical monitoring sensors. Taking advantage of such information, a digital twin model incorporating virtual simulation is generated for FPS dynamic response calculation and prediction. It provides the basis for continuous damage assessment and transient failures advanced identification. By tracing back the dynamic information of the mooring lines and the SCRs, changes in the mooring lines stiffness and cumulative fatigue damage of the riser can be assessed. Once the mooring lines stiffness and SCRs fatigue damage exceed the design limits, it indicates that the operators should take maintenance method, such as shutdown and docking for replacement. Before encountering extreme environmental conditions, the potential risk of mooring lines and SCRs transient failures under could be determined through the safe operation zone. To mitigate, the riser morphology can be changed by adjusting the platform position to extend the service life of the riser. To mitigate the damage to the SCRs caused by short-term extreme loads, the SCRs morphology could be changed by adjusting the platform position to extend the service life.

Under the trend of digital transformation in the oil and gas industry, this solution could better guide field operators to take practical interventions to achieve long-term safe operation and reduce maintenance costs. it could be part of an intelligent integrity management for offshore floating structures.

Acknowledgements

This work is supported by the National Key Research and Development Program (No. 2022YFC2806100) and CNOOC China Limited Hainan Branch (No. CCL2023HNFN0275).

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