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Research on the characteristics and fundamental mechanism of a newly discovered phenomenon of a single moored FPSO in the South China Sea

Yu Ma [a], Zhiqiang Hu [a,*], Yan Qu [b], Gang Lu [c]

[a] State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[b] Deepwater Engineering Key Laboratory, Technology Research Department. CNOOC Research Institute, Beijing 100027, China
[c] Wenchang 13-1/2 Oilfield Operation Company, CNOOC, Zhanjiang 524057, China

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ABSTRACT

During a full-scale measurement project for Fenjin Floating production, storage and offloading (FPSO), an unusual phenomenon, herein named "swing", was discovered. Until now, little research on this phenomenon has been done; in this study, it was defined and its characteristics and fundamental mechanisms were analyzed, including the threat that it poses to the safety of the FPSO. Data collected during the period of the measurement project (October 2007 to October 2009) were statistically analyzed and several criteria for distinguishing swing were assessed. The number of occurrences of swing during the measurement period was obtained as well as the timing of the FPSOs yaw motion for each occurrence. Also, the tensile forces in the mooring lines during one swing motion were calculated. The effect of swing on the mooring system and the offloading operation process were also assessed. A preliminary speculation as to the cause of the swing is proposed, based on wave, wind and current data. A fundamental hydrodynamics mechanical model for the low-frequency motions of FPSO was constructed, and a MATLAB program was written in-house to calculate the yaw motion of the FPSO in the time domain to enable the swing mechanism to be studied.

1. Introduction

Floating production, storage and offloading (FPSO) units play a dominant role in the production of oil and gas in the South China Sea. Due to the complex environmental conditions at sea, submerged turret production (STP) mooring systems are always used to moor FPSOs permanently in a given area to minimize the loading on the vessel due to the weathervane effect. Therefore, the hydrodynamic behavior of FPSOs remains a critical issue for designers and engineers. There are three ways of studying the hydrodynamic characteristics of offshore structures: numerical simulation, model testing, and full-scale measurement. Of these, full-scale measurement has higher credibility, provided the measurement methods and equipment are sufficiently reliable, since neither numerical simulation nor model testing resembles all aspects and details of the actual situation. Furthermore, some distinctive phenomena might be found during full-scale measurement not observed or simulated by the other two methods.

In the past several decades, however, few full-scale measurement projects for offshore structures have been carried out, mainly because of their high cost and the limitations of the measuring techniques and instrumentation. To date, only a small number of the results of these projects have been published. Two reports of typical full-scale measurement projects have been selected to demonstrate their importance (van den Boom et al., 2005; Van Dijk and van den Boom, 2007).

One project was the real-time monitoring study on the Marco Polo tension-leg platform (TLP) in the Gulf of Mexico from March 2004 to May 2008, a joint industry project (JIP) headed by MARIN and supported by Anadarko, ABS, BHP Billiton, BP, Enterprise, Hess, Modec, MMS, and Worley Parsons Sea, conducted with the purpose of evaluating the design in operation when exposed to hurricanes and loop-current conditions (Aalberts et al., 2008). During the measurement period the Marco Polo TLP was subjected to three major hurricanes, which provided a large amount of valuable data including the motion response of the platform in hurricane conditions, and environmental wave, wind and current data. Based on these data a series of studies were carried out, including the effect of hurricanes on the cumulative fatigue life consumption of the TLP (Aalberts et al., 2008), and wave characteristics in hurricane conditions. Aside from data for conventional analysis of motion response, structural deformation and fatigue loads on the platform, during the project, and following further data analysis, researchers found some unexpected but valuable phenomena; one of which was that the measured extreme wave heights of 26.9 m (including the correction for platform motions) with an associated crest

* Corresponding author. Tel.: +86 21 34207053 2131; fax: +86 21 34207058.
E-mail address: zhqhu@sjtu.edu.cn (Z. Hu).

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height of 17.4 m, exceeded the expected values in hurricane conditions. Also, high frequency vibrations were observed at the deck level of the platform due to the impact loads of these extreme waves on the columns.

The other project considered here was the JIP for monitoring the GlaDowr FPSO in the North Sea, conducted over the period October 1997 to August 1999. The objective was to collect factual data for computer model development, for understanding fatigue loading on FPSOs, and for validating new and existing fatigue load prediction models used by five classification societies (van den Boom et al., 2000). Data were collected for movement and structural strains in the FPSO, and from pressure gauges recording the effects of bow-slamming impact and green water on the deck, as well as observational data of environmental conditions. Based on this information, short- and long-term analyses were conducted and useful conclusions were reached (van den Boom et al., 2000; Bultema et al., 2000).

As discussed, full-scale measurement is of crucial importance to studies of the hydrodynamics of offshore structures. To fill the knowledge gaps in this area and apply an improved approach to research on FPSO's hydrodynamic characteristics, a joint industry project on full-scale measurement for the Fenjin FPSO, headed by Shanghai Jiao Tong University and sponsored by CNOOC, was carried out between October 2007 and October 2009. Much of the analytical results of this work have subsequently been published (Hu et al., 2011; Zhao et al., 2011; Wei et al., 2011).

During the processing and analysis of the FPSO's motion data it was found that, under certain circumstances, the heading angle of the FPSO changed appreciably within relatively short periods beyond the normal range of either the weathervane effect or fishtailing effect, potentially increasing the loading on the mooring system and endangering the FPSO and the shuttle tanker during offloading. To date, few studies have been reported on this phenomenon, which is provisionally termed "swing" in this paper to distinguish it from other kinds of movement. The definition, characteristics and mechanism of the swing phenomenon, and the extent of its threat to the safety of FPSOs, are valuable for future research.

The present study focused on the characteristics of the swing phenomenon for a single moored FPSO, using statistical analysis techniques. Some preliminary deductions as to its cause were derived from the environmental data analysis, and a fundamental analysis of the swing mechanism was carried out using time domain simulation methods for the numerical calculations combined with hydrodynamic analysis to validate the results.

2. Description of the full-scale measurement project of the Fenjin FPSO

2.1. Fenjin FPSO

The Fenjin FPSO, one of the largest in the South China Sea, is located in the Wenchang offshore oil field. The South China Sea is well known for experiencing some of the most severe sea conditions in the world, including the effect of typhoons in summer and fall. The Wenchang area is also subject to monsoons and different ocean currents throughout the year, all of which greatly complicate the environmental conditions. For FPSOs located in the area, safety and operational efficiency under such environmental conditions are crucial issues. Therefore, Fenjin FPSO was chosen as the subject of the joint industry project on full-scale measurement, with the environmental data measuring apparatus to be installed on jacket platforms 13-1 and 13-2 located near the FPSO.

The FPSO is moored by an STP mooring system comprising nine moorings in three groups of three; the mooring lines are numbered from 1 to 9. Groups of moorings are separated by 120°, and moorings within each group are separated by 5° (Fig. 1). Mooring lines are each 900 m long, assembled in four parts in a 'chain-wire-chain-wire' catenary configuration with pre-tension set at 330 kN, giving an 877 m horizontal mooring distance. The major scantlings of Fenjin FPSO are listed in Table 1. Mooring line characteristics are shown in Table 2.

Model testing was carried out at the design stage to evaluate the hydrodynamic performance of the Fenjin FPSO. This included decay tests, current and wind force tests, irregular wave tests, and offloading tests with a tanker moored in tandem with the FPSO. Relevant test results were supplied by CNOOC for use in the present study.

2.2. Description of the full-scale measurement project

The project ran from October 2007 to October 2009. Figs. 2–4 give an overview of the relative locations of measuring systems on FPSO, the composition of one of the measuring systems, and photographs of the main apparatus components.

During the 25 months' data collection, the research team obtained a very large volume of first-hand data, including the FPSO's six degrees-of-freedom (6-DOF) motion data, three sets of acceleration data at different locations on the hull, wave parameters including wave height, period and direction, and wind and current conditions including velocity and direction.

The 6-DOF motion data and acceleration data were measured at a frequency of 5 Hz. Wind velocity and direction measured

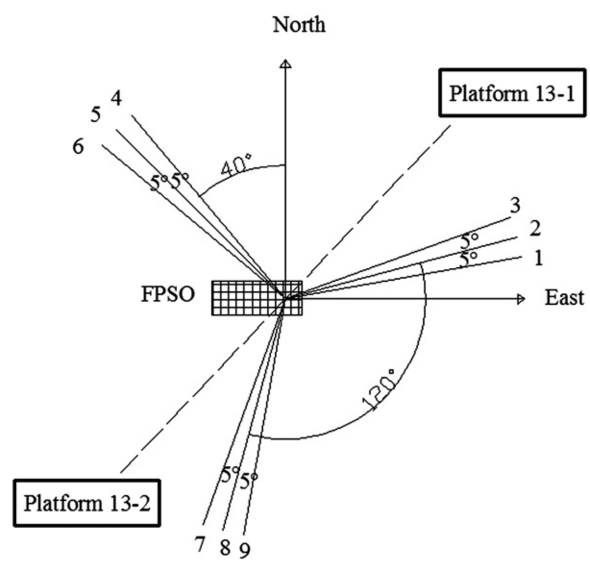

Fig. 1. Mooring system arrangement.

Table 1
Major scantlings of the Fenjin FPSO.

Scantlings	Full loading	Ballast loading
Length overall (m)	262.2	
Length between perpendiculars (m)	250	
Width (m)	46	
Depth (m)	24.6	
Operational draft (m)	16.5	7
Displacement (t)	176000	73000
Center of gravity vertically above baseline (m)	16	11