Monitoring Systems in Shipping and Offshore Industry

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Maritime transport is the main mode of international trade (up to 80% of goods); thus, marine structures are critical because of its specific influence to trade. Ships and offshore structures are used worldwide for a variety of functions and in a variety of water depths and environments. Monitoring the health of marine structures plays a key role in reducing the risk of structural failure. The incorporation of a health-monitoring system makes it possible to optimize the design, operation and/or maintenance, moving from criteria based on experience or conservative estimates, to others that take advantage of source of information about real-time in-service behavior. Structural monitoring also makes it possible to reveal the start of damage in structures that would otherwise remain invisible until a catastrophic/unexpected manifestation of damage occurs, allowing for decisions such as decommissioning for unscheduled maintenance actions or continuing until the next scheduled maintenance.

marine structural health monitoring sensors

1. Ship Structures

Table 1 depicts the typical sensors located on board for the common commercial vessel types.

Table 1. Structural sensor for common commercial vessel types [1].

Direct Measurand	Container Ship	Bulk Carrier	Oil Tanker	Ro-Ro Ship	LNG	Passenger Ship
Vertical accelerations at bow	Accelerometer (ACC) (*)					
Transverse acceleration amidships	ACC (*)		-	ACC (*)	-	ACC (*)
Ship motion (at center of gravity)	Motion reference unit (MRU) (**)	MRU (*)	MRU (*)	MRU (**)	MRU (*)	MRU (*)
Global longitudinal stress amidships (port and starboard side)	LSBG (**)					
Global longitudinal stress at quarter length fore and aft of	LSBG (**)			LSBG (*)		

Direct Measurand	Container Ship	Bulk Carrier	Oil Tanker	Ro-Ro Ship	LNG	Passenger Ship
midship (port or starboard side)						
Local transverse stress at transverse deck strip amidships	Short baseline (SG) (**)	-				
Global longitudinal stress below neutral axis amidships (port and starboard)	LSBG (*)		-			
Double bottom bending stress	SG (*)		-			
Lateral loads at bowflare or bottom near forward perpendicular (Slamming pressure)	Pressure Transducer (PT)/SG (*)					
Lateral loads at side shell (wave pressure)	PT/SG (*)					
Sloshing response of liquid in tanks	-		PT/SG (*)	-	PT/SG (*)	-

(*) optional/recommended, (**) typically required.

Yu et al. [2] presented a full-scale measurement solution designed to monitor the ship motions, wave conditions and structural response on an 8063 TEU container ship. Nielsen et al. [3] obtained a calculation method for the prediction of fatigue damage ratio in hull structures considering whipping stresses, by means of full-scale wave-induced stress ranges in a container ship in which the related fatigue damage ratios are calculated. Chen et al. [4] investigated a new approach to calculate the directional wave spectra from the measured ship responses in different scenarios of a large 10,000 TEU container ship under the combination of different stress and movement sensors.

Chen et al. [5] extracted data from the full-scale measurements of a 14,000 TEU double bottom container ship, whose sea states are similar to those of numerical simulation among the existing time series, in order to analyze the correlation between the double bottom and hull girder bending, on wave and vibrational response. Miyashita et al. [6] presented full-scale calculations (longitudinal stresses) of an 8600 TEU container ship carried out during four years and two months. The longitudinal stresses measured through sensors located on the midship are divided into horizontal bending stresses, hull girder vertical bending stresses, axial stresses and warping stresses. Chen et al. [7] discussed an approach, based on wave spectra that are estimated from restricted measurement data, to reproduce unmeasured hull stress responses.

1.2. Bulk Carrier

Kim et al. [8] showed the typical general arrangement of a bulk carrier with the common location of sensors on this type of vessel.

1.3. Oil Tankers

Several monitoring installations were carried out on ships in 1990 [9] and on other ships between 1990 and 1991 [10]. This system consists of about six long deformation sensors, two pressure sensors, an accelerometer and motion sensors. Hu and Prusty [11] found that in order to obtain more data on the deformation of ship hulls, it is necessary to deploy more strain gauges on the side hulls and transverse bulkhead. In terms of the dynamic loads of the ship, it is necessary to install pressure sensors at different locations on the side hulls. Accelerometers need to be mounted in three directions to measure the pressure of cargo oil.

1.4. Others

Stull et al. [12] reported the results of an active research project aimed at employing pattern-based structural health monitoring approaches on emerging and current hull structures. Takaoka et al. [13] focused on the implementation of fatigue damage sensor (FDS) on FPSOs for fatigue life consumption. Zhang et al. [14] provided a statistical and artificial intelligence approach to conduct resilient condition monitoring applied to a hawsers system in a FPSO oil offloading system. Kaminski [15] described the data processing and interpretation tools to prevent the fatigue damage of FPSOs. Thomas et al. [16] studied the application of extended stress, motion and hull wave measurements, together with a sophisticated finite element model, under asymmetric loading case.

Sato [17] conducted a fatigue monitoring program on a 135,000 m3 LNG carrier consisting of a comprehensive range of measurement elements. Yamamoto et al. [18] distributed a compact fatigue damage sensor into LNG carrier that can identify accumulated fatigue damage in welded structures by mounting it to the component and inspecting it after a certain time. Drummen et al. [19] presented the setup of two types of hull-structure-monitoring (HSM) systems. One is an overall system focused on global load effects and strains. The other is a local system aimed at detecting cracks through acoustic emission (AE) monitoring. Long base strain gauges are an important part of the global HSM system that was installed on USCGC STRATTON. The location of these sensors was optimized using hydro-structural calculation tools [20].

Cusano et al. [21] described and compared both full-scale and model-test monitoring campaigns and the most significant collected data, referring to the occurrence of slamming events on the MDV−3000 mono-hull ro-ro passenger fast ferry, focusing on the longitudinal bending moment amidships. Jensen et al. [22] studied a fast patrol boat (KNM Skjold), a twin-hull surface effect ship (SES) made of fiber-reinforcement polymer (FRP) sandwich composites with 47 m long and 13.5 m wide through the Composite Hull Embedded Sensor System (CHESS) project, of which the main objective was to design, develop, fabricate and install strain-monitoring systems using distributed fiber optic sensors for hull structure monitoring. These contents presented a method for measuring the global loads based on extensive finite-element analyses and strain measurements from networks of FO strain Bragg sensors attached to the hull of KNM Skjold.

Torkildsen et al. [23] presented a thorough introduction to the ship hull structural health-monitoring system, with the analysis of the data recorded onboard the Royal Norwegian Navy (RNoN) Mine Counter Measure Vessel (MCMV) “HNoMS Otra”. The HSV-2 Swift (HSV 2) is a high-speed vessel (wave piercing catamaran) of the United States Navy. Sielski [24] studied this vessel for detecting damage in the structure and to extend this detection capability to a prognosis capability [25]. Another investigation that also deals with the HSV-2 vessel is the one proposed by Mondoro et al. [26], where they provided a method for predicting the responses of vessels in non-observed cells by integrating data from the observed limited number of cells.

Majewska et al. [27] presented and discussed experimental research on tall sailing ships using fiber Bragg grating (FBG) sensors for the foremast. They determined the stress/strain level of the foremast during her normal operation to establish the effectiveness, quantity and configuration of the sails for the strain/stress level of the foremast. Hageman et al. (2015) [28] conducted a hull fatigue monitoring system for FPSO by coupling a minimum sensor array with automated data planning processing to collect the hull response, fatigue loading and wave conditions encountered. Ferreira et al. (2017) [29] described a fiber optic strain gauge sensor-based monitoring system used to recreate in real time the form of a sail using an algorithm developed and integrated to convert strain readings into deformations.

Söder et al. [30] presented a method for monitoring the stresses in ro-ro vessels by real-time measurement of ship motions. Johnson et al. [31] proposed a wireless, rapidly deployable hull monitoring system with an associated analytical framework that employs hull measurements to evaluate the lifecycle performance of a ship.

Yan et al. [32] suggested a new technology for the monitoring of the structural health of the stinger of a large deep-water pipe-laying vessel. Roberts et al. [33] presented field tests on the 138 m passenger and vehicle ferry Smyril, operating in the North Atlantic Ocean, using GPS and FBG kinematic sensors. Hageman and Thompson [34] assessed, through a virtual monitoring technique, the structural behavior of a frigate ship. There is a multi-purpose cargo vessel (INF 2 classified) named Atlantic Osprey with four fatigue damage sensors on board [35].

2. Offshore Structures

The monitoring of offshore structures can be classified as metocean factors related with the environmental conditions (wind, waves, currents, ice, etc.) and structural operational status [36][37].

2.1. Tension Leg Platform (TLP)

Van Dijk and van de Boom [38] evaluated, by means of full-scale monitoring, the Marco Polo Tension Leg Platform under exposure to hurricane and loop-current conditions, under high- and low-frequency modes of motion, under the fatigue loading of the platform, and under the dynamic behavior of the tendons and risers with focus on the vortex-induced vibrations.

2.2. Wind Turbine

Mieloszyc and Ostachowicz [39] presented an application of the structural health monitoring (SHM) system based on FBG sensors dedicated to an offshore wind turbine support structure (tripod) model. Nejad and Moan [40] studied the health monitoring of a 5 MW spar wind turbine drivetrain by means of a decoupled analysis method. Kim et al. [41] suggested and tested a structural health-monitoring method for floating offshore wind turbines

(FOWTs) by using modal analysis with signals from numerical sensors. Kou et al. [42] studied, for a semi-submersible platform under repair, eight old main supports that connect the columns to the pontoon in order to substitute them with new ones, by means of a structural stress monitoring of eight key points calibrated with finite element models.

Moreira and Guedes Soares [43] found a technique using artificial neural networks to estimate wave-induced vertical bending moment and shear force from ship movements to incorporate it into a hull monitoring system. Vidal et al. [44] proposed a methodology for the detection and localization of damage in a wind turbine with jacket foundations, using eight triaxial accelerometers to identify any anomaly in the structure's dynamic behavior. Yang et al. [45] proposed an offshore wind turbine deck-structure-monitoring system consisting of vibration, deformation and corrosion.

2.3. Jacket Platform

Lotfollahi-Yaghin et al. [46] conducted a numerical investigation in a jacket offshore platform that operates in 70.2 m water depth in the Persian Gulf. Sun et al. [47] studied the dynamic response of a jacket offshore platform under a seismic excitation model based on the collection of data provided by the FBG sensors and strain gauges. Ge et al. [48] examined the stress response of the jacket legs by FBG sensors to determine the impact strength on the same. Ali et al. [49] provided an experimental approach using piezoelectric sensor detection and finite element analysis method for the analysis of fatigue cracks in three types of joints. Tang et al. [50] proposed the methods of structural monitoring and early warning status on the basis of the aged coating characteristics of offshore platforms. Liu et al. [51] detected damage to the structure of the jacket platform by analyzing the acoustic emissions.

2.4. Jack up Platform

Archer [52] studied the monitoring of cyclic loads on a leg of the jack-up platform Nengue Sika during a transport from Singapore to West Africa. Shabakhty et al. [53] showed, based on a crack propagation approach and achieved information from inspection, that the remaining fatigue reliability of jack-up structures could be determined and updated by using a Bayesian procedure in the duration of the service time.

2.5. Spar

The dynamic response of the Neptune Spar platform was monitored under hurricane sea conditions [54]. Thethi et al. [55] presented a riser-monitoring strategy and implementation on a deepwater Gulf of Mexico Spar top tensioned riser. Karayaka et al. [56] installed riser and flowline monitoring (RFM) on Chevron Tahity Spar to study the dynamic response of the catenary [57].

References

1. American Bureau of Shipping. Advisory on Structural Health Monitoring: The Application of Sensor-Based Approaches. ABS. Available online: https://t.ly/JSKG (accessed on 8 November 2022).
2. Yu, H.; Choi, J.; Park, G.; Han, S.; Tai, S. Full-scale measurement of a large container carrier on the Far-East Europe route. In SNAME Maritime Convention; OnePetro: Houston, TX, USA, 2008.
3. Nielsen, U.; Jensen, J.; Pedersen, P.; Ito, Y. Onboard monitoring of fatigue damage rates in the hull girder. Mar. Struct. 2011, 24, 182–206.
4. Chen, X.; Okada, T.; Kawamura, Y.; Mitsuyuki, T. Estimation of on-site directional wave spectra using measured hull stresses on 14,000 TEU large container ships. J. Mar. Sci. Technol. 2020, 25, 690–706.
5. Chen, J.; Okada, T.; Kawamura, Y.; Mitsuyuki, T. A study on whipping related double bottom response as well as its statistical characteristics based on full-scale measurements. J. Mar. Sci. Technol. 2021, 26, 846–860.
6. Miyashita, T.; Okada, T.; Kawamura, Y.; Seki, N.; Hanada, R. Statistical characteristics of whipping response of a large container ship under various sea states and navigational conditions based on full-scale measurements. In Practical Design of Ships and Other Floating Structures; Lecture Notes in Civil. Engineering; Springer: Singapore, 2021; Volume 64.
7. Chen, X.; Okada, T.; Kawamura, Y.; Mitsuyuki, T. Estimation of directional wave spectra and hull structural responses based on measured hull data on 14,000 TEU large container ships. Mar. Struct. 2021, 80, 103087.
8. Kim, M.; Kim, D. Ship and Offshore Structures. In Encyclopedia of Structural Health Monitoring; Wiley Online Library: Hoboken, NJ, USA, 2009.
9. Witmer, D.; Lewis, J. The BP Oil Tanker Structural Monitoring System. Mar. Technol. SNAME News 1995, 32, 277–296.
10. Melitz, D.; Robertson, E.; Davison, N. Structural Performance Management of VLCCs—An Owner’s Approach. Mar. Technol. SNAME News 1992, 29, 250–262.
11. Hu, Y.; Prusty, B. A new method for oil tanker structure condition monitoring. Ships Offshore Struct. 2007, 2, 371–377.
12. Stull, C.; Earls, C.; Koutsourelakis, P. Model-based structural health monitoring of naval ship hulls. Comput. Methods Appl. Mech. Eng. 2011, 200, 1137–1149.
13. Takaoka, Y.; Nihei, K.; Vargas, P.; Aalberts, P.; Kaminski, M. SS: FPSOs and floating production systems: Application of fatigue damage sensors in the Monitas system. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 3–6 May 2010.

14. Zhang, X.; Ni, W.; Liao, H.; Pohl, E.; Xu, P.; Zhang, W. Improved condition monitoring for an FPSO system with multiple correlated components. Measurement 2020, 166, 108223.
15. Kaminski, M. Sensing and understanding fatigue lifetime of new and converted FPSOs. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 30 April–3 May 2007.
16. Thomas, G.; Davis, M.; Holloway, D.; Roberts, T. Extreme asymmetric slam loads on large high speed catamarans. In Proceedings of the 6th Symposium on High Speed Marine Vehicles, Castello di Baia, Italy, 18–20 September 2002.
17. Sato, K.; Ohira, H.; Tatani, M.; Yoshida, T. Long-Term Fatigue Monitoring for LNG Carrier; Gastech: Ayase, Japan, 2005.
18. Yamamoto, N.; Koiwa, T.; Dobashi, H.; Muragishi, O.; Takaoka, Y. A study of a fatigue management system for long LNG carriers using a new fatigue damage sensor. Ships Offshore Struct. 2007, 2, 361–370.
19. Drummen, I.; Rogers, L.; Benhamou, A.; Hageman, R.; Stambaugh, K. Hull structure monitoring of a new class of US coast guard cutters. In Proceedings of the ASNE Technology, Systems & Ships, Washington, DC, USA 18–20 June 2019.
20. USCGC Stratton. Available online: https://t.ly/_QHi (accessed on 7 November 2022).
21. Cusano, G.; Monti, S.; Velasco, A. Full scale and model test investigation of slamming effects on fast monohull vessels. In Proceedings of the Hydroelasticity in Marine Technology, Oxford, UK, 15–17 September 2003.
22. Jensen, A.; Taby, J.; Pran, K.; Sagvolden, G.; Wang, G. Measurement of Global Loads on a Full-Scale SES Vessel Using Networks of Fiber Optic Sensors. J. Ship Res. 2001, 45, 205–215.
23. Torkildsen, H.; Grovlen, A.; Skaugen, A.; Wang, G.; Jensen, A.; Pran, K.; Sagvolden, G. Development and Applications of Full-Scale Ship Hull Health Monitoring Systems for the Royal Norwegian Navy; Norwegian Defence Research Establishment: Kjeller Norway, 2005.
24. Sielski, R. Ship Structural Health Monitoring Research at the Office of Naval Research. JOM 2012, 64, 823–827.
25. Soliman, M.; Barone, G.; Frangopol, D. Fatigue reliability and service life prediction of aluminum naval ship details based on monitoring data. Struct. Health Monit. 2015, 14, 3–19.
26. Mondoro, A.; Soliman, M.; Frangopol, D. Prediction of structural response of naval vessels based on available structural health monitoring data. Ocean. Eng. 2016, 125, 295–307.
27. Majewska, K.; Mieloszyk, M.; Ostachowicz, W.; Król, A. Experimental method of strain/stress measurements on tall sailing ships using Fibre Bragg Grating sensors. Appl. Ocean. Res. 2014, 47, 270–283.

28. Hageman, R.; Aalberts, P.; Shaik, M.; Henk, V. Development of an Advisory Hull Fatigue Monitoring System. In SNAME Maritime Convention; OnePetro: Bellevue, WA, USA, 2013.
29. Ferreira, P.; Caetano, E.; Pinto, P. Real-time flying shape detection of yacht sails based on strain measurements. Ocean. Eng. 2017, 131, 48–56.
30. Söder, C.; Rosén, A.; Palmquist, M. Motion-based monitoring of racking stresses in ro-ro ships. Ships Offshore Struct. 2012, 7, 389–398.
31. Johnson, N.; Lynch, J.; Collette, M. Response and fatigue assessment of high speed aluminium hulls using short-term wireless hull monitoring. Struct. Infrastruct. Eng. 2018, 14, 634–651.
32. Yan, H.; Wei, D.; Wang, X.; Chen, Y.; Meng, X. Research of structural health monitoring system for stinger of large deep water pipe-laying ship. Ocean. Eng. 2019, 171, 361–376.
33. Roberts, G.; Hancock, C.; Lienhart, W.; Klug, F.; Zuzek, N.; Ligt, H. Displacement and frequency response measurements of a ship using GPS and fibre optic-based sensors. Appl. Geomat. 2021, 13, 51–61.
34. Hageman, R.; Thompson, I. Virtual hull monitoring using hindcast and motion data to assess frigate-size vessel stress response. Ocean. Eng. 2022, 245, 110338.
35. CrackFirstTM Fatigue Monitoring. Available online: https://www.jf-strainstall.com/media/case-studies/crackfirst-fatigue-monitoring/ (accessed on 19 November 2022).
36. Wang, P.; Tian, X.; Peng, T.; Luo, Y. A review of the state-of-the-art developments in the field monitoring of offshore structures. Ocean. Eng. 2018, 147, 148–164.
37. Van den Boom, H.; Koning, J.; Aalberts, P. Offshore monitoring: Real world data for design, engineering, and operation. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 2–5 May 2005.
38. Van Dijk, R.; van den Boom, H. Full scale monitoring marco polo tension leg platform. In Proceedings of the 26th International Conference on Offshore Mechanics and Arctic Engineering, San Diego, CA, USA, 10–15 June 2007.
39. Mieloszyk, M.; Ostachowicz, W. An application of Structural Health Monitoring system based on FBG sensors to offshore wind turbine support structure model. Mar. Struct. 2017, 51, 65–86.
40. Nejad, A.; Moan, T. On model-based system approach for health monitoring of drivetrains in floating wind turbines. Procedia Eng. 2017, 199, 2202–2207.
41. Kim, H.; Kim, M.; Choe, D. Structural health monitoring of towers and blades for floating offshore wind turbines using operational modal analysis and modal properties with numerical-sensor signals. Ocean. Eng. 2019, 188, 106226.

42. Kou, Y.; Yang, J.; Xu, S.; Peng, T.; Liu, J.; Wu, Z. Structural Stress Monitoring and FEM Analysis of the Cutting Operation of the Main Bracket of a Semi-Submersible Platform. China Ocean. Eng. 2019, 33, 649–659.
43. Moreira, L.; Guedes Soares, C. Neural network model for estimation of hull bending moment and shear force of ships in waves. Ocean. Eng. 2020, 206, 107347.
44. Vidal, Y.; Aquino, G.; Pozo, F.; Gutiérrez-Arias, J. Structural Health Monitoring for Jacket-Type Offshore Wind Turbines: Experimental Proof of Concept. Sensors 2020, 20, 1835.
45. Yang, S.; Chung, C.; Wu, H.; Chang, Y.; Wu, Y.; Lyu, J.; Chen, S.; Lee, Y. Structural health monitoring of offshore jacket structure. In Proceedings of the 2018 International Conference on Renewable Energy and Power Engineering, Toronto, ON, Canada, 24–26 November 2018; pp. 39–42.
46. Lotfollahi-Yaghin, M.; Shahverdi, S.; Tarinejad, R.; Asgarian, B. Structural health monitoring (SHM) of offshore jacket platforms. In Proceedings of the 30th International Conference on Ocean, Offshore and Arctic Engineering, Rotterdam, The Netherlands, 19–24 June 2011; Volume 1, pp. 579–588.
47. Sun, L.; Li, H.; Ren, L.; Jin, Q. Dynamic response measurement of offshore platform model by FBG sensors. Sens. Actuators A Phys. 2007, 136, 572–579.
48. Ge, H.; Li, X.; Yang, J.; Tian, X. Field monitoring of fender collision force during the float-over installation. Ocean. Eng. 2016, 34, 19–27.
49. Ali, L.; Khan, S.; Bashmal, S.; Iqbal, N.; Dai, W.; Bai, Y. Fatigue Crack Monitoring of T-Type Joints in Steel Offshore Oil and Gas Jacket Platform. Sensors 2021, 21, 3294.
50. Tang, Y.; Qing, Z.; Zhu, L.; Zhang, R. Study on the structural monitoring and early warning conditions of aging jacket platforms. Ocean. Eng. 2015, 101, 152–160.
51. Liu, G.; Wang, S.; Xie, Y.; Tian, X.; Leng, D.; Malekain, R.; Li, Z. Damage detection of offshore platforms using acoustic emission analysis. Rev. Sci. Instrum. 2018, 89, 115005.
52. Archer, M. Monitoring of the cyclic loads on a leg of the jack-up platform nengue sika during a transport from Singapore to West Africa. Bull. Tech. Bur. Veritas 1984, 13, 225.
53. Shabakhty, N.; van Gelder, P.; Boonstra, H. Reliability analysis of jack-up platforms based on fatigue degradation. In Proceedings of the 21st International Conference on Offshore Mechanics and Arctic Engineering, Oslo, Norway, 23–28 June 2002; Volume 2, pp. 265–273.
54. Hua, D.; Paradkar, M.; Garcia, S.; Young, S.; Hogelin, P.; Webb, T.; Farmakakis, K. Neptune spar life extension assessments. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 1–4 May 2017.

55. Thethi, R.; Howells, H.; Natarajan, S.; Bridge, C. A fatigue monitoring strategy and implementation on a deepwater top tensioned riser. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 2–5 May 2005.
56. Karayaka, M.; Chen, J.; Blankenshipp, C.; Ruf, W.; Podskarbi, M. SS: Tahiti on-line monitoring system for steel catenary risers and flowlines. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 4–7 May 2009.
57. Ren, P.; Zhou, Z. A state-of-the-art review on structural health monitoring of deepwater floating platform. Pac. Sci. Rev. 2012, 14, 253–263.