Review on Structural Health Monitoring of Offshore Platform

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Abstract. The structural health monitoring (SHM) and damage detection of offshore platforms, one of the most common marine structures operating in a hostile environment, have gained global attention in recent years. This paper presents a review of vibration-based damage identification methods used for SHM of offshore platforms. The application and progress of these methods are discussed and some case studies are analyzed. The challenges and future work for vibration-based damage identification are summarized.

1. Introduction
Structural Health Monitoring (SHM) of civil structures is a matter of increasing concern. It integrates sensor networks, new engineering materials, and computer-based knowledge systems to help engineers examine how built-up structures are performing over time. SHM procedure includes four levels: 1) Determine if the structure is subjected to damage. 2) The identification of damage location. 3) Measurements of damage severity. 4) Residual life prediction [1]. It is particularly of use for high profile mechanical systems such as pipelines, offshore structures, aircraft, spacecraft, ships, where performance is crucial but on-site damage detection is demanding or even impossible [2]. Among these structures, offshore platforms have a major impact on the oil and gas industry. Offshore platforms in a hostile environment are subject to wave load, wind load, boat impacts, sea quakes, corrosion and so on [3]. Moreover, the construction and maintenance of offshore structures are costly and time consuming. Thus, the long-term usage of offshore platforms badly requires robust SHM systems.
Most developments in SHM of offshore platforms stem from 1970s by the offshore oil industry. Scholars in various countries have conducted plenty of studies and have drawn many useful conclusions. This paper presents a brief overview of the methods and application in SHM applied to offshore platforms.

2. Modal-based methods
Modal-based methodology plays a significant role in assuring the safety and efficacy of operating systems and the integrity management of various structures. According to the modal analysis in engineering application, they display the variable relationship between modal parameters (notably natural frequencies, mode shapes, and damping ratios) and the physical properties. The basic principle of the vibration-based method is that changes in the physical properties will induce detectable changes in the modal properties. In that independence of external excitation gives modal parameters an edge over other measured structural responses, considerable effort has been spent in obtaining a relationship...
between the changes in modal parameters, the damage location and the damage size by using shifts in resonant frequencies, mode shape changes, strain mode shape, flexibility matrix or updating structural model parameters. Some of these methods have been successfully used in SHM of offshore platforms.

2.1. Mode shape changes

The underlying assumption of this method is that the modal vectors of degrees of freedom (DOFs) near the damaged members should vary more than those of the degrees of freedom away from the damaged members. Numerical data in previous studies demonstrated the usefulness of the modal assurance criteria (MAC) approach. Then many researchers have presented more sensitive indicators, such as Node line MAC and coordinate MAC (COMAC). Viero et al. [4] compared the performance of MAC and COMAC. Two indicators were applied on hydro-elastic offshore platform models which were all to scale based on the similitude theory. Zarrin et al. [5] exploited modes of vibration to improve the accuracy of static pushover analysis for the design of jacket type offshore platforms (JTOPs) under the abnormal level earthquake (ALE). Haeri et al. [6] conducted a case study where they used mode shapes as one of the damage indexes and employed the inverse vibration technique on the models located in the Persian Gulf.

| Noise levels (%) | Mean (μ) (%) | Standard deviation (σ) | Coefficient of variation (σ/μ) |
|------------------|--------------|------------------------|-------------------------------|
| 5                | 14.91        | 0.0459                 | 0.0536                        |
| 10               | 14.93        | 0.0394                 | 0.0374                        |
| 15               | 14.93        | 0.0621                 | 0.0718                        |

To illustrate the effectiveness and feasibility of the proposed procedure, three levels (5%, 10% and 15%) of random error were considered. As shown in Table 1, the coefficient of variation varied slightly. In terms of random errors, the proposed procedure was robust.

2.2. Mode shape curvature/strain mode shape(SMS) changes

When a structure experiences damage or change, the change of force distribution can be noted from the SMSs of the structure measured before and after the damage. Since force redistribution is, in general, greatest near the damaged area, the location of damage is implicitly identified by the severity of the SMS change. Researchers dramatically improved results by using measured strains instead to measure curvature directly or new indexes such as the Difference between the Real and Estimated Curvature Function, DREC [7]. Kondo et al. [8] made use of the identified modal properties. The damage region containing a damaged member was isolated from the whole structural system in terms of the curvature change ratio for detecting the local damage of flexible offshore platforms.

Nonetheless, there exist several obstacles which impede the application of modal-based methods. For instance, plenty of measurement locations are indispensable to provide better accuracy in mode information. In addition to that, mode shapes and their derivatives often present larger variability of statistical data than natural frequencies.

3. Frequency response functions (FRFs) and their variants

Modal-based methods are susceptible to measurement noise, while extensive studies indicate that FRF based methods are more reliable. FRF data are acquired directly from vibration response signals. Another advantage of using FRF data is that it provides enough information and equations in the frequency domain. Wang et al. [9] derived an algorithm which achieved damage localization and measured the magnitude of the damage based on nonlinear perturbation equations of FRF data that were weighted by a further developed technique. Teloli et al. [10] visualized the damping ratio in the experimental FRF and combined the Bouc-Wen model with higher-order FRF data as an alternative,
resolving conundrum involving experimental bolted joints with data fluctuation. Transmissibility, a variant of the FRF, is found more sensitive than FRFs [11]. Amin Fathi et al. [12] applied a new Bayesian model updating framework combined with incomplete noisy FRF data in the health monitoring of an offshore platform for the first time. The accuracy between the actual and predicted damaged values of the research results was compared with that conducted by Liu et al. [13], who used the mode shapes and natural frequencies for damage detection of the fixed platform by calculating the Mean Sizing Error (MSE) and Root Mean Square Error (RMSE).

| Error criteria | Damage scenarios | A1 | A2 | B1 | B2 |
|---------------|------------------|----|----|----|----|
| MSE (Amin Fathi et al., 2020) | 0.0309 | 0.0319 | 0.0319 | 0.0334 |
| MSE (Liu et al., 2018) | 0.0721 | 0.0459 | 0.0536 | 0.0411 |
| RMSE (Amin Fathi et al., 2020) | 0.0368 | 0.0394 | 0.0374 | 0.0367 |
| RMSE (Liu et al., 2018) | 0.0862 | 0.0621 | 0.0718 | 0.0529 |

As shown in Table 2, the value of error criteria for the method using FRF data developed by Amin Fathi et al. was lower than that in Liu et al. research in all numerical damage scenarios, indicating the efficiency and effectiveness of the proposed framework using FRF data. The adverse effects of finite element uncertainties and noise on the results of the parameter estimation were insignificant by using FRF data.

4. Recent development

With the advancement of mathematical heuristic methods, more complicated and developed methodologies have been studied for SHM of marine platforms, among which wavelet based methods, the use of neural networks and model updating have gained much attention worldwide. But some of these studies have employed complicated procedures which render them still far from real engineering cases.

4.1. Wavelet based methods

The wavelet transform (WT), one of signal processing-based methods, has been widely used in both civil and mechanical SHM applications. The strength of WT lies in its capability to provide multiple levels of details and approximations of the transient signal [14]. Wavelet packet transform (WPT) is another form of the WT, which can eliminate noise, process and extract sensitive features of the signal. Filho et al. [15] analyzed the signals through wavelet transform and the results were compared with those obtained by the FRF based method, verifying that wavelet transform was more sensitive than the classical frequency response methods. The WT, however, is unfit for the higher frequency region. Hence, more WT techniques such as Wavelet multi-resolution analysis (WMRA) and wavelet packet transform have been developed to overcome the limitation. Asgarian et al. [16] used WPT to analyze experimental results of a prototype scaled marine platform under several damage conditions. Lotfollahi-Yaghin et al. [17] used the wavelet packet energy rate index as damage indicator for a jacket type offshore platform in Persian Gulf.
Figure 1. 3D numerical model of jacket type platform and damage detection using WPERI

As shown in figure 1, WPERI-ULWPERI values that exceeded the threshold indicated possible damage occurrence. The WPT-based damage indicators can effectively detect the changes in the signal characters.

4.2. Machine learning (ML) methods

Machine learning has proved to be suitable for a broad range of industrial applications, divided into supervised, unsupervised and semi-supervised learning modes [18]. To avoid results highly depending on the users' judgment, Yuen et al. [19] developed a practical and rational Bayesian ANN design method and apply it to a damage diagnosis method as an illustrative example. Aqdam et al. [20] presented new architecture of RBF (Radial Basis Function) neural network, a new design of ANN, for the SHM of mooring lines, essential components in marine platforms. Bao et al. [21] explored the possibility to use the one-dimensional convolutional neural network (CNN) (figure 2) and optimize it through a data processing procedure. The results of this method were confirmed by using a numerical simulation and experimental study of a marine platform respectively.

Figure 2. Flowchart of the one-dimensional CNN for damage detection.
The performances of CNN method for damage localization for case 3 and 4 (figure 3) is shown in Table 2, Table 3. As shown in Table 2 and Table 3, the total predicted accuracy of damage location on multiple members is 100% and 60.4%, respectively. In terms of multiple full member damage scenarios, CNN method reaches a superior performance level. Nonetheless, the results are not satisfactory for very minor multiple-damage locations on local elements, especially under a random wave excitation [21].

![Figure 3. Case 3 (left) and case 4 (right)](image)

**Table 3. Prediction of damage location of case 3 under a random wave.[21]**

| Actual label | Predicted label | 1 | 2 | 3 | 4 | 5 | Total | Accuracy (%) |
|--------------|-----------------|---|---|---|---|---|-------|---------------|
| 1            | 50              | 0 | 0 | 0 | 0 | 0 | 50    | 100           |
| 2            | 0               | 50 | 0 | 0 | 0 | 0 | 50    | 100           |
| 3            | 0               | 0  | 50 | 0 | 0 | 0 | 50    | 100           |
| 4            | 0               | 0  | 0  | 50 | 0 | 0 | 50    | 100           |
| 5            | 0               | 0  | 0  | 0  | 50| 0 | 50    | 100           |
| **Total**    |                 |   |   |   |   |   |       | **250**       |

**Table 4. Prediction of damage location of case 4 under a random wave.[21]**

| Actual label | Predicted label | 1 | 2 | 3 | 4 | 5 | Total | Accuracy (%) |
|--------------|-----------------|---|---|---|---|---|-------|---------------|
| 1            | 50              | 0 | 0 | 0 | 0 | 0 | 50    | 100           |
| 2            | 0               | 29 | 6 | 13 | 2 | 50 | 58    |
| 3            | 0               | 5  | 19 | 16 | 10| 50 | 38    |
| 4            | 0               | 7  | 11 | 30 | 3 | 50 | 60    |
| 5            | 0               | 10 | 10 | 6  | 24| 50 | 48    |
| **Total**    |                 |   |   |   |   |   |       | **250**       |

Key factors limiting the widespread implementation of neural network solutions in industrial scenarios have been the difficulty of demonstrating that the deep networks are robust and reliable enough to ensure the authenticity and accuracy of outcomes.

4.3. **Model updating methods**

The model updating procedure is aimed to minimize the disparities between the numerically and experimentally signals through regulating uncertainty parameters. Thus model updating procedure comes down to optimization problems [22]. SHM systems have used model updating methods based
on incomplete modal data [23], FRF data [12], dynamic strain responses [24] and so on. Mojtahedi et al. incorporated the fuzzy logic system and FE-model updating (FEMU) for health monitoring of offshore jacket platforms [25].

5. Conclusion
Many researchers have combined the aforementioned methods when conducting studies. Many emerging procedures for SHM of offshore platforms are still at the theoretical level, far from the practical goals. At present, most methods are based on modal parameters used for damage identification and localization. Due to the limitation of modal parameter extraction in actual operation, especially when there exists the influence of noise, the result of extraction is far from good as the experiment. The damage identification and location methods are generally limited to the simulation study of the model, and many researchers have carried out the studies on the scaled offshore platform models. Future research needs to make the SHM based on vibration measurements combined with more developed procedures and mathematical theories a viable, practical, and commonly implemented technology.

References
[1] Doebling, S. W. , C. R. Farrar , and M. B. Prime . "A Summary Review of Vibration-Based Damage Identification Methods." Shock & Vibration Digest 30.2(1998):91-105.
[2] Giurgiutiu, Victor . "1 - INTRODUCTION." Structural Health Monitoring (2008):129-184.
[3] El-Reedy, Mohamed Abdallah . "Offshore structure loads and strength - ScienceDirect." Offshore Structures (Second Edition) (2020):19-77.
[4] Viero, Paula F. , and N. Roitman . "Application of some damage identification methods in offshore platforms." Marine Structures 12.2(1999):107-126.
[5] Zarrin, M. , A. Gharabaghi , and M. Poursa . "A multi-mode N2 (MN2) pushover procedure for ductility level seismic performance evaluation of jacket type offshore platforms." Ocean Engineering 220.1(2020).
[6] Haeri, M. Hassan , et al. "Inverse vibration technique for structural health monitoring of offshore jacket platforms - ScienceDirect." Applied Ocean Research 62(2017):181-198.
[7] Pooya, Seyed Majid Hosseini , and A. Massumi . "A novel and efficient method for damage detection in beam-like structures solely based on damaged structure data and using mode shape curvature estimation - ScienceDirect." Applied Mathematical Modelling 91(2021):670-694.
[8] Kondo, et al. "Local damage detection of flexible offshore platforms using ambient vibration measurements." International Journal of Machine Tools & Manufacture 76.76(1994):34-48.
[9] Wang, Z. , R. M. Lin , and M. K. Lim . "Structural damage detection using measured FRF data." Computer Methods in Applied Mechanics & Engineering 147.1-2(1997):187-197.
[10] Teloli, Rdo , et al. "Bayesian model identification of higher-order frequency response functions for structures assembled by bolted joints." Mechanical Systems and Signal Processing 151.2(2021):107333.
[11] Maia, Nmm, et al. "Damage detection and quantification using transmissibility." Mechanical Systems & Signal Processing 25.7(2011):2475-2483.
[12] A, Amin Fathi , et al. "Damage detection in an offshore platform using incomplete noisy FRF data by a novel Bayesian model updating method." Ocean Engineering (2020).
[13] Liu, Kang , R. J. Yan , and C. G. Soares . "Damage identification in offshore jacket structures based on modal flexibility." Ocean Engineering (2018).
[14] Hou, Z. K. , M. N. Noori , and R. S. Amand . "Wavelet-Based Approach for Structural Damage Detection." Journal of Engineering Mechanics 126.7(2000):677-683.
[15] A, Jozue Vieira Filho , F. G. B. A , and D. J. I. B . "Time-domain analysis of piezoelectric impedance-based structural health monitoring using multilevel wavelet decomposition." Mechanical Systems and Signal Processing 25.5(2011):1550-1558.
[16] Behrouz Asgarian, Vahid Aghaeidoost, Hamed Rahman Shokrgozar, "Damage detection of
jacket type offshore platforms using rate of signal energy using wavelet packet transform." Marine Structures 45.JAN.(2016):1-21.

[17] Lotfollahi-Yaghin, Mohammad Ali , et al. "Structural Health Monitoring (SHM) of Offshore Jacket Platforms." ASME 2011 30th International Conference on Ocean, Offshore and Arctic Engineering 2011.

[18] Hou, R. , and Y. Xia . "Review on the new development of vibration-based damage identification for civil engineering structures: 2010-2019." Journal of Sound and Vibration 491.9(2020).

[19] Yuen, Ka Veng , and H. F. Lam . "On the complexity of artificial neural networks for smart structures monitoring." Engineering Structures 28.7(2006):977-984.

[20] Aqdam, Hamed Rezaniae , M. M. Ettefagh , and R. Hassannejad . "Health monitoring of mooring lines in floating structures using artificial neural networks." Ocean Engineering 164.SEP.15(2018):284-297.

[21] B, Xingxian Bao A , et al. "One-dimensional convolutional neural network for damage detection of jacket-type offshore platforms." Ocean Engineering (2020).

[22] Modak, S. V. , T. K. Kundra , and B. C. Nakra . "Comparative study of model updating methods using simulated experimental data." Computers & Structures 80.5/6(2002):437-447.

[23] Sotoudehnia, E. , F. Shahabian , and A. A. Sani . "Damage detection of cylindrical shells based on Sander's theory and model updating using incomplete modal data considering random noises." European Journal of Mechanics - A/Solids 85(2020).

[24] Matarazzo, et al. "Postearthquake Strength Assessment of Steel Moment-Resisting Frame with Multiple Beam-Column Fractures Using Local Monitoring Data." Journal of Structural Engineering (2018).

[25] Mojtabedi, A. , et al. "Developing a robust SHM method for offshore jacket platform using model updating and fuzzy logic system." Applied Ocean Research 33.4(2011):398-411.

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