Adaptive meta-heuristic to predict dent depth damage in the fixed offshore structures

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ABSTRACT: The jacket structures are often employed in the range of shallow-moderate water depth. The bracing systems and jacket legs typically use the circular section in order to compromise the hydrodynamic resistance and high torsional rigidity. However, under lateral impact, these tubular bracing members are susceptible to local denting due to ship collisions or through impact of falling objects and that can weaken overall performance of the entire platform. It is a great significance for forecasting dent depth of these members accurately. This paper investigates the use of adaptive meta-heuristics algorithm to provide an automatic detection of denting damage in an offshore structure. A model is developed combining with the percentage of the dent depth of damaged member diameter and is used to assess the performance of the method. It is demonstrated that the small changes in stiffness of individual damaged bracing members are detectable from measurements of global structural motion.

1 INTRODUCTION

Offshore jackets play an important role in the oil and gas industry. The risk of platform failure is a higher risk issue when operating an ageing platform. As a result, the need for the development of techniques necessary to assess platform integrity is clearly established. Several standards and recommended practices list a detailed inspection methods and requirements for the underwater, splash zone and topsides structures (May et al. 2008). For the oldest of operational ageing platforms, the assessment is quite challenging due to the existence of deterioration or dent-damage of structural elements due to collision or impacts. The change of dent depth can dramatically reduce the axial and bending capacities of the individual jacket leg members and weaken overall performance of the entire structure (Bruin, 1995). Therefore, accurate prediction of dent depth and dent direction angle would provide valuable information for the operations and maintenance operations at offshore platforms.

Karamanos and Andreadakis (2006) studied on denting of tubular members subjected to lateral loads. The loading condition is quasi static and

the tubes are internally pressurized. The relation between denting force and displacements were evaluated through experiments and finite element simulations. Also relation between normalized forces and normalized denting displacements was deviated following both procedures. Wedge shaped denting tool was used in the experiment as well. Outcome of this research deliberates that the internal pressure in the tubular member increases the resistance against denting and reduce the denting length. Travanca and Hao (2014) discussed on the response of jackets on response to ship impact. Finite element formulations and calculations are derived to incorporate the dynamic aspects as well. The jacket was considered as a cantilever beam and the Degree of Freedom (DOF) was reduced for easiness of study. The outcome of the reduction of DOF was significant and showed similar outcome as from the FEM of original structure so far. Comparison of response time histories, deformation of modes, normalized deformation at different stages and the comparison of response histories from the original model and equivalent reduced SDOF model was contemplated for the parametric study. Moreover a four-legged jacket, a tripod jacket and a jack-up model were considered

for case study. Furthermore the effect of top mass are included and it is found that it is significant while the natural period has large value and the ratio of top mass and the jacket mass is high. Two stage dynamic analysis is also suggested to achieve more accuracy. Cosham and Hopkins (2004) illustrated on the dent effect on oil and pipelines which are especially used for oil and gas transmission. Different types of defects along with different types of dents are studied in this study. Burst strength and fatigue life are investigated for different types of dents. It was found that plain and smooth dent doesn't affect significantly on the burst strength but has effect on the fatigue life. Moreover, smooth dent reduces the fatigue life to a great extent. Kinked dents may be are dangerous for longitudinal cyclic stresses and are risky for external pressures with the internals. Moreover, it is noted that the smooth dent along with gouge is very unsafe considering both burst strength and fatigue which reduces considerably. Khedmati and Nazari (2012) explored the behavior of tubular members on response to impact loads. Strength and deformation characteristics are inspected in this work. Moreover the axial shortening behavior is also included. The effect of preloading and quasi static lateral load are also delineated. Storheim and Amdahl (2014) deliberates the design process of offshore platforms susceptible to ship collision. The ship-platform interaction is also represented. Four different collision contexts are incorporated. Force-displacements curves for different scenarios are interpreted. The outcome of the study suggested to revise the design specification for collision as the vessel size and bow configurations are changed a bit in recent years. Cerik et al. (2016) inspected denting damages in tubular members for low mass impact. Both experimental and numerical investigation was incorporated. It is observed that the numerical outcome has satisfactory similarity with the experimental test models. Local denting is considered along with the load-indenter displacements are also delineated. The deformation characteristics of single member with clamps are vastly studied. Cho et al. (2010) investigated the denting damage consequences of tubular members in offshore structures. Experimental denting test along with bending test was directed and a relation between dent depth and denting force was established. Moreover the residual strength of dented tubes can be predicted through the established equation which was derived from the relation of residual strength and bending moment. Cho et al. (2015) deliberated the response characteristics of impact loading in the context of tubular members in maritime structures. Drop test along with statistical analysis

was carried out to predict the behavior against dynamic impact loading. Consequences of local denting and global bending were discussed elaborately from the experimental and numerical outcome. Minor dented damages due to ship collision could be the cause of major reduction of ultimate capacity and it was illustrated by Pacheco and Durkin (1988). Moreover, a geometrically ideal dent can represent the actual damage in case of finite element analysis and it is also delineated in this research. Li et al. (2013) focused on the ship collision consequences on the tubular members of Jacket structures. Both elastic and plastic behaviors are elaborated. Different scenario of ship collisions were assessed for substantial conclusions. It is reported that in case of larger deformation, the standard guideline underestimate resistance-indentation relationship. The elastic response from the vessel-platform impacts should be noted more carefully to comprehend significant effect of it in terms of energy absorption during impact.

The damage detection can be considered as a problem of system identification or an optimization inverse problem (Farrar and Worden, 2012). The optimization techniques can be used to quantify the unknown parameters of the damage. Over the last few decades, the adaptive meta heuristic and predicting control methods have become more widely used in several scientific research especially in the damage detection under ambient vibration (Miguel et al, 2012) and in the optimization design of fixed jacket offshore platform under environmental loads (Nasseri et al, 2014). Although much have been reported, very little have been done for the dent examination of circular member in the jacket structure which is the most common problem type to investigate the structural damage after ship collision. Intelligent computational techniques such as metaheuristics can be served to highlight areas where the sensor technologies and structural integrity monitoring techniques might be useful.

In this work, an optimization problem for offshore dent detection is posed to find percentages of dent in element diameters and impact angles. Five well established self-adaptive metaheuristics include JADE (Zhang & Sanderson, 2009), CMAES (Hansen, Muller et al., 2003), SHADE (Tanabe and Fukunaga, 2013), L-SHADE (Tanabe and Fukunaga, 2014), and ASCDE (Bureerat and Pholdee, 2017) are used to perform detection within a simulated damage scenario of a finite element reduced model of an offshore jacket platform. The efficiency and accuracy of each optimizer is discussed. Finally, the main conclusions and recommendations of future work are summarized.

2 DESCRIPTION OF AN OFFSHORE JACKET PLATFORM FOR THE ADAPTIVE META-HEURISTIC ANALYSIS

2.1 Fixed offshore platform model

The offshore jacket platform is modeled with the 3D frame elements to conduct the adaptive meta-heuristic analysis. The physical configuration of the jacket platform in side view along with the front view is available in Figure 1.

The offshore jacket platform is simulated to operate at the water depth 65.53 m. The topside of the jacket platform emerges above the sea water level 17.68 m. The bracing system of the jacket platform consists of two types (single bracing and the K bracing). The bottom bracing systems of the jacket structure is the K-bracing so as to compromise the connecting angle between chord and brace members more than 30 degrees to avoid the welding problem. The remaining of bracing systems is the single bracing to optimize the structural weight.

The top side of the oil and gas platform is simplified as a lumped mass for finite element analysis. The total weight of the topside is 2500 tons, which is equally distributed over four legs where each leg, is conveying 625 tons at the top connection of the jacket structures platform.

The structural members of the offshore jacket platform are utilized according to the design specifications (DNV-RP-C203, 2001). This jacket structure consists of 11 groups of tubular cross section. The element properties are listed in Table 1. All the structural members have the same material density and elasticity modulus. The location of structural elements with different colors for each groups are illustrated in Figure 2. The annotations of the colors are clarified substantially in Table 1. The

Figure 1. 3D and side views of offshore platform.

Table 1. Element properties.

Group name	Color indicator	Outside diameter	Thickness
G1	Red	1.067	0.038
G2	Light Blue	0.457	0.010
G3	Dark Blue	0.406	0.013
G4	Purple	0.356	0.010
G5	Black	0.457	0.013
G6	Grey	0.356	0.013
G7	Light Grey	0.406	0.016
G8	Dark Blue	0.324	0.010
G9	Black	0.559	0.013
G10	Red	0.559	0.019
G11	Green	0.610	0.025

Modulus of Elasticity, $E = 2.1 \times 10^{11}$ N/m²;
Density of Steel = 7833 kg/m³.

Figure 2. Member group specifications.

formations of the groups are based on the outer diameter and wall thickness of the tubular section.

2.2 Denting data and assumptions

The assumption of denting members in the jacket platform comes from the consequences due to ship collision. There members from two different groups are assumed to be influenced due to ship collision. Member no 10 and 20 from G1 group and member no 88 from G9 group are the dented member. The vessel can impact to jacket platform in two directions either through bow or starboard direction. The location of dented members and impact direction are present in the Figure 3. Two members from leg and one bracing are impacted in according to the Figure 4. Denting is generally defined in terms of percentages of diameter reduc-

Figure 3. Ship collision and denting in members.

Figure 4. Denting sample in G1 and G9.

Table 2. Element groups of the jacket structure.

Group name	Element numbers	Outside diameter
G1	1–20	In element 10 & 20
G2	21–28	No denting
G3	29–32	No denting
G4	33–44	No denting
G5	45–52	No denting
G6	53–60, 117–120	No denting
G7	61–68	No denting
G8	69–72	No denting
G9	73–80, 85–92	In element 88
G10	81–84	No denting
G11	93–116	No denting

For members 41–44 and 57–60, are the members above the water level.

tion as per different code of practices (ISO 19901-3, 2014).

A sample of denting configuration for both type of members G1 and G9 are illustrated in Figure 4.

Figure 5. Denting of members for rotation of axis.

In this sample, 20% denting is contemplated. The diameters of the members as well as the dented length are identified in the following figure as well. Due to the denting effect, the stiffness of the member will be changed because of the changing of cross-sectional area and the moment of inertia but the mass will be unchanged.

It is assumed in this study that a single point of dented section will affect the whole member length. Moreover in reality, it is often not fixed whether the denting will occur along a certain axis or not.

As shown in Figure 5, the denting can occur in different angles if vessel impacts to the platform in the different direction of attack angle. The different local angle of denting member, as shown in Figure 5, can have different moments of inertia about two different axes. But the area will remain the same. For this reason, the angle for denting direction is also considered in this investigation and the range of the angle is between 0 and 360 degree. That is the ship can attack the offshore jacket platform from any direction and the denting can be occurred in any angles.

3 OPTIMIZATION PROBLEM OF OFFSHORE DENT DETECTION AND NUMERICAL EXPERIMENT SETUP

3.1 Frequency and mode shape changes

Dent detection of the offshore structure as detailed in the previous section is performed using vibration based damage detection. The main concept of vibration based damage detection is that updated mechanical properties of a mathematical model such as a finite element model and the modal data such as natural frequencies of the model agrees well the measured modal data. Damage of the

structure is identified by the detecting changes of the mechanical properties.

In this work, an optimization problem for offshore dent detection is posed to find percentages of dent in element diameters (P_d) and impact angles (θ) which consequently lead to the changes of mechanical properties (cross section area, second moment of area along y and z direction) and natural frequencies of the offshore structure. Since the natural frequencies can be accurately measured, an objective function in this case can be constructed in terms of changes in natural frequencies.

The percentage of dent damage in the tabular element can be found by solving an optimization problem to minimize the root mean square error (RMSE) between natural frequencies measured from the dented structure and natural frequencies computed by using the finite element model. The problem can be expressed as:

$$\text{Min: } f(\mathbf{x}) = \sqrt{\frac{\sum_{j=1}^{n_{\text{mode}}} (\omega_{j,\text{damage}} - \omega_{j,\text{computed}})^2}{n_{\text{mode}}}} \quad (1)$$

where $\omega_{j,\text{damage}}$ and $\omega_{j,\text{computed}}$ are the structural natural frequency of mode j obtained from a dented structure and that from the finite element model respectively. A vector $\mathbf{x}$ is a set of design variables including percentages of dent in element diameters and impact angles ($\mathbf{x} = \{P_{d1}, P_{d2}, \dots, P_{dn}, \theta_1, \theta_2, \dots, \theta_n\}^T$).

In this work, only element numbers 5, 10, 15, 20, 86, 88, 90 and 92 which are located at the sea level are set to have dent possibility. Therefore, the total number of design variables is set to be 16 (8 for percentages of dent in element diameters and other 8 for impact angles of the elements). The possibility of percentages of dent is set in rang of $[0, 0.7]$ while impact angle is set in the set of $\{0, 22.5, 45\}$.

3.2 Numerical experiment

To investigate the search performance of optimization methods on solving the proposed problem of dent detection of the offshore structure, the percentage of dent in element diameter and impact angle are pre-defined while natural frequencies are simulated by means of finite element analysis instead of using real measuring data. The percentages of dent in element diameters and impact angles are set as 0.3 percent dent at elements 10, 20 and 88 with impact angles of 0, 22.5 and 45 degrees respectively. Natural frequencies for the first six modes of the dented and undented elements (as shown in Table 3) are used for the objective function calculation.

Table 3. Natural Frequency (Hz) up to six mode.

Modes	Undented	Dented
1	0.680	0.674
2	0.690	0.714
3	0.919	0.989
4	2.506	2.507
5	2.527	2.527
6	3.179	3.145

To minimize the objective function, five well-established self-adaptive meta-heuristics (MHs) are used. Details and notations of these methods are available in the literature in the corresponding references of the methods and will not be detailed here. The MHs used include:

- Adaptive Differential Evolution (JADE) (Zhang & Sanderson, 2009).
- Evolution Strategy with Covariance Matrix Adaptation (CMAES) (Hansen, Muller et al., 2003).
- Success-History Based Adaptive Differential Evolution (SHADE) (Tanabe & Fukunaga, 2013).
- SHADE with Linear Population Size Reduction (L-SHADE) (Tanabe & Fukunaga, 2014)
- Adaptive Sine Cosine algorithm with integrating Differential Evolution mutation (ASCDE) (Bureerat and Pholdee, 2017)

Each optimizer is used to solve the offshore structure dent detection test problem for 10 optimization runs. The population size is set to be 30 whereas the number of iterations is set to be 300. All methods will be terminated with two criteria: the maximum numbers of functions evaluation as 30×300 , and the objective function value being less than or equal to 1×10^{-3} .

4 RESULTS AND DISCUSSIONS

After performing 10 optimization runs of all MHs on solving the offshore structure dent detection optimization test problem, the results obtained are given in Table 4. The mean of objective function are used to measure the algorithm rate of convergence in cases that the objective function threshold (1×10^{-3}) is not reached during searching. Otherwise, the mean number of FE runs is used as an indicator. The number of successful runs out of 10 runs is used to measure the search consistency. The algorithm that is terminated by the objective function threshold is obviously superior and any run being stopped with this criterion is considered a successful run (Bureerat and Pholdee, 2017).

Table 4. Comparison results among each optimizer.

Optimizers	Mean Obj.	Mean FEs	No. of successful run
CMAES	0.02428	8166	1
JADE	0.03626	8268	1
SHADE	0.03886	8367	1
LSHADE	0.02903	9000	0
ASCA	0.00095	2148	8

Table 5. The best results on finding the percentages of dent and impact angles obtained from all optimizers.

No	Simu- lated dent	CMAES	JADE	SHADE	LSHADE	ASCA
10	0.3	0.36	0.50	0.47	0.19	0.26
20	0.3	0.07	0.17	0.18	0.01	0.35
88	0.3	0.29	0.23	0.17	0.00	0.30
5	0	0.13	0.13	0.19	0.27	0.05
15	0	0.00	0.00	0.00	0.16	0.00
86	0	0.27	0.06	0.08	0.70	0.00
90	0	0.00	0.00	0.00	0.01	0.00
92	0	0.00	0.00	0.00	0.01	0.00
No	Simu- lated impact angle	CMAES	JADE	SHADE	LSHADE	ASCA
10	0	45	22.5	45	0	45
20	22.5	45	45	22.5	45	0
88	45	22.5	22.5	45	—	0
5	—	45	22.5	45	45	0
15	—	0	—	0	45	—
86	—	22.5	0	22.5	22.5	—
90	—	—	—	—	0	—
92	—	—	—	—	0	—
ω_1 (hz)	0.674	0.674	0.675	0.673	0.672	0.673
ω_2 (hz)	0.714	0.715	0.713	0.714	0.716	0.714
ω_3 (hz)	0.989	0.989	0.988	0.989	0.988	0.989
ω_4 (hz)	2.507	2.507	2.507	2.507	2.505	2.507
ω_5 (hz)	2.527	2.527	2.527	2.527	2.527	2.527
ω_6 (hz)	3.145	3.146	3.146	3.145	3.149	3.145

From Table 4, it can be seen that the best performer based on mean objective function values is ASCA while the second best and the third best algorithms are CMAES and LSHADE, respectively. When considering the number of successful runs, ASCA is said to be the most efficient optimizer which can detect the percentage of dent in element diameters and impact angles for 8 times out of totally 10 optimization runs with the average of 2,148 function evaluations.

Table 5 shows the best results on finding the percentage of dent and impact angles obtained from all

optimizers. It was found that MHs will only detect impact angle values in the elements having percentage of dent higher than zeros. From Table 5, it can be observed that ASCA can correctly detect the percentages of dent in the offshore structure while the others failed to achieve such results. For the impact angles, the results of all optimizer are not accurate and need further improvement. One idea of such improvement is to introduce some nodal displacements that can be picked out of numerical mode shapes in the objective function, which will be explored and presented in future work.

5 CONCLUSIONS AND RECOMMENDATIONS

Five meta-heuristics optimizers were tested for the the dent damage of circular member in the jacket structure. The damage detection problems are based on vibration measurement and can be treated as an inverse optimization problem. The comparative results reveal that the ASCA is outstanding for predicting denting diameter but not denting angles. The results from ASCA could be use as the baseline for further improvement and investigation of dent damage examination using meta-heuristics.

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