Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 11 (10): 1688-1697, 2011
ISSN 1812-5654 / DOI: 10.3923/jas.2011.1688.1697

Frequency Shift in Tracking the Damage of Fixed Offshore Structures

[1]S. Abdul Rahim and [2]A.J. Hillis
[1]Department of Mechanical Engineering, Malaysian Spanish Institute,
Universiti Kuala Lumpur, 09000 Kulim, Malaysia
[2]Department of Mechanical Engineering, University of Bath, Bath BA27AY, United Kingdom

Abstract: This study investigates a method of detecting and tracking damage in an offshore platform located in the North Sea under the excitation of a typical sea storm by performing a finite element simulation. A modal analysis and nodal displacement results from Finite Element (FE) simulation are adopted for analysing the dynamic characteristics of this platform. For this purpose, the JONSWAP spectrum and Morison equation are applied to simulate the typical wave force in the North Sea using Matlab and Simulink programmes. The associated mode shape vector obtained in modal analysis was correlated with the sea force vector which was the forcing function (force per unit length) to the structure. The determination of the dynamic response with realization to the real scenario was established by introducing some reduction of material stiffness in one of the diagonal member in stages. The results in time-displacement domain obtained from FE simulation were converted into time-acceleration domain before they were analysed in frequency spectrum using Power Spectrum Density in Matlab. The frequency analysis showed that there was a significant shift in peak frequency between the intact and damaged structure response with 30% stiffness reduction, provided that the sea force applied is in the direction of the damaged beam member orientation. This suggested that the shift in the natural frequencies of the dynamic response can provide a useful tool in monitoring the dynamic response and tracking the progression of fatigue failure of the structure.

Key words: Offshore platform, model analysis, FE dynamic simulation, frequency spectrum analysis

INTRODUCTION

As offshore oil and gas exploration enter into deeper waters, there is a significant increase in research and investigation into methods of examining vibration characteristics in monitoring structural integrity. This great need for the monitoring and evaluation of mechanical structures is attributed to the safety requirements for the structures themselves and also the people involved.

Technological advancements in computational processing, sensors and finite element methods presently contribute to the improvement in damage detection using a vibration-based method which has been developed since the early 70's (Smityh, 1988). The main purpose of this method is to establish an alternative inspection to traditional options like the Visual Inspection Method which is costly and difficult to implement especially when offshore structures are located in deep water and often susceptible to the unpredictable nature of sea conditions.

Offshore structures are more likely to experience structural damage than other civil engineering structures as they are continuously exposed to sea waves, currents, seismatic actions and marine growth. The damage will reduce the stiffness and alter the modal properties of the structure such as the natural frequency, damping ratios and mode shapes. The changes in these properties are the fundamental concepts when inspecting the vibration characteristics of the structure (Brincker *et al*., 1995). As offshore structures are regularly acted upon by hydrodynamic forces like sea waves which are variable with time, it is necessary to examine the effects of the sea wave on the dynamic response of the structure. The important aspect in examining the dynamic characteristics is to ensure the fundamental natural frequency of the designed platform is well separated from the frequency at which the peak energy of the wave occurs (Harnett *et al*., 1997).

Fundamental natural frequencies and mode shapes of the structure under free excitation is significantly important when examining the dynamic characteristics of the structure. In this study, the first mode shape of the platform is utilized in developing the sea force before applying on the nodes on the platform. In reality, the

---

Corresponding Author: S. Abdul Rahim, Department of Mechanical Engineering, Malaysian Spanish Institute, Universiti Kuala Lumpur, 09000 Kulim, Malaysia

measurement of the platform's natural frequency is achieved by analyzing the signal from the accelerometers; however mode shape determination is not feasible.

A modal simulation is carried out in the study to estimate the mode shapes of the platform which is utilized in developing the sea force. The modal analysis is also applied to build the top platform mass by tuning on the first natural frequency of the platform between 0.6 and 0.7 Hz.

The aim of this study is to investigate the dynamic response of an offshore structure subjected to sea wave forces and explore the frequency spectrum technique for detecting damage in the structure. The nodal displacement results obtained from FE dynamic analysis simulation is first converted into acceleration and finally into frequency response using Fast Fourier Transform (FFT) which is very useful in determine the peak frequencies of the structure's response.

The sea force which is the only forcing input for the platform is developed using Morison equation and JONSWAP frequency spectrum in Matlab. Some properties of the platform like area and volume of lumped mass and mode shape are described in the sea force model in Simulink. The frequency of the sea wave at which the peak energy occurs is also identified and compared with the fundamental natural frequency of the platform.

The key aspect in the Study is to perform the dynamic simulation which acquires input from the sea force data at various heights and angles. The dynamic response of the platform is analyzed based on the sea force applied in various directions named X, Z and 45° diagonal to X and Y directions. The dynamic response of the platform is then investigated by inspecting the shift in natural frequencies as the material stiffness in the diagonal member is reduced in stages. This study will determine whether the shift in natural frequency in the response is able to indicate a substantial damage in the structure as experienced in real life.

FORMULATION OF A WAVE LOADING

The sea force incident on the structure is normally random in nature and very complex to generate. However, they can be best formulated using the Morison sea force equation as described below.

When analyzing the offshore structures, it is essential to include the effects of surface waves on the structure. The JONSWAP spectrum is used to describe the spectrum frequencies of irregular ocean waves in the North Sea for a usual 100 year storm which is given as:

$$S(\omega) = \left(\frac{5H_s}{16\omega_p}\right)\left(\frac{\omega_p}{\omega}\right)^5 \exp\left[-1.25\left(\frac{\omega}{\omega_p}\right)^{-4}\right]\gamma^{\beta} \tag{1}$$

where, H_s = 7 m is the significant wave height, ω_p = 0.1 Hz is the peak frequency, γ = 3.3 and γ^{β} is a frequency-dependant factor which determines the peak sharpness and is given by:

$$\beta = \exp\left(\frac{-(\omega-\omega_p)^2}{2\tau^2\omega^2{}_p}\right) \tag{2}$$

where, $\tau = 0.07$ ($\omega \le \omega_p$), $\tau = 0.09$ ($\omega > \omega_p$)

By using Morison's equation, the wave force per unit length in single directions such as in x-direction at a height y from the seabed can be determined for an offshore structure as shown below. The velocity of the structure relative to the wave particle is neglected as the structure is considered to be initially at rest. The force per unit length for the structure is given as:

$$f(y,t) = \frac{1}{2}\rho C_D D(\dot{x}_W)^2 + \rho C_I \frac{\pi D^2}{4}\ddot{x}_W - \rho(C_I - 1)\frac{\pi D^2}{4} \tag{3}$$

where, x_w is the wave particle horizontal displacement at height, *y* and time, t. D is the structure's equivalent diameter, ρ is the density of the sea water, C_D = 1 is drag co-efficients and C_I = 2 is inertia co-efficients.

The total wave force acting on the submerged platform is calculated using the integral of the force per unit length over the submerged platform:

$$F(t) = \int_0^d f(z,t)\,\varphi(z)\,dz \tag{4}$$

where, ϕ (z) is the mode shape vector (Hillis, 2009).

FINITE ELEMENT METHOD

This model of the platform is created in ANSYS using key points which define the co-ordinates in the working plane. The model is also created based on element types where different element types have a different number of nodes and degrees of freedom.

BEAM189 element type which is used in this model of the structure is based on quadratic polynomials. This element type only supports nodal concentrated force besides surface loads and does not offset a distributed load. Therefore, in this study, the sea force is applied directly to the points where the nodes are defined (Fig. 1).

BEAM 189 is computationally efficient and has excellent convergence capability with respect to mesh refinement which is as accurate as a Hermitian element as described in the Formulating Beam Element. Specifically element BEAM189 is described as:

- Structural 3D Quadratic Finite Strain Beam
- 3 nodes in 3D space
- Degree of freedom: UX, UY, UZ, ROTX, ROTY, ROTZ

In this model, the simplest and by far most common application of linearly elastic and isotropic model has been used. It means when the load is removed from the structure, all the deformation is recovered because of the linear relationship between force and deflection. This assumption also implies that the displacement of the structure compared to its overall dimensions is small due to the non yielding load.

A beam element subjected to a uniform distributed load: The beam elements used in this study are subjected to nodal force and the theoretical concept shown below is relevant to this study. A uniform distributed load acting on a 2D beam of length L and its equivalent nodal loading can be presented here as shown in the Fig. 2 and 3 (ANSYS, 2000).

In this study, the sea force vector which is force per unit length and the associated height is applied to the selected nodes on the beam. The distribution force obtained from Simulink model is applied as nodal force on the specific nodes by multiplying the force per unit length with the distance between the selected nodes. This action will simulate a distribution load between the selected nodes.

The displacement in FE: In this study, displacement response is considered as one of the main parameter to detect the dynamic behaviour of the structure. The structure displaced states are wholly defined by translational displacements at the nodes. The displacement parameters are defined at three degrees of freedom at the nodes of the structural elements. For structural analysis, the degree of freedom consists of translation and rotational in X, Y and Z-direction. Thus, the displacement results are analyzed according to the number of degrees of freedom in the structure.

The interpolation of the node displacement under the action of external load can be written in the form:

$$u = Ne\ de \tag{5}$$

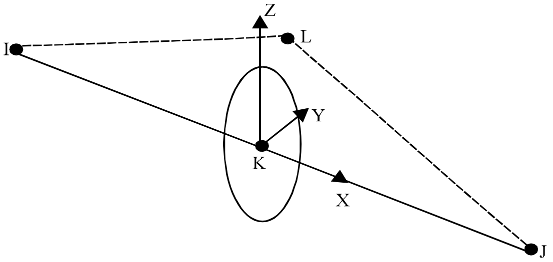

Fig. 1: Beam 189 is defined by nodes I, J and K in the global coordinate system (ANSYS, 2000)

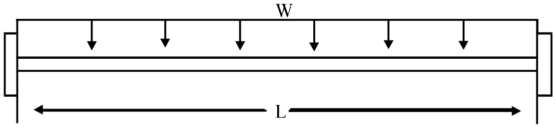

Fig. 2: Uniform distribution loading

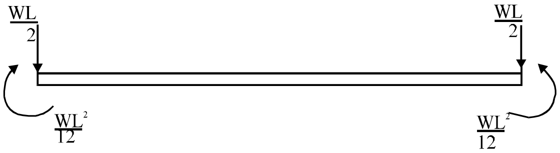

Fig. 3: Equivalent nodal loading

Where:

$$u = (u)$$

$$N_e = [n_1\ (x'), n_2\ (x')]$$

$$de = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$$

In this notation, u represents the displacement components at a point in the element. Ne is a shape matrix which determines the element shape and de is a vector which has the nodal displacements. The displacement in element BEAM 189 is calculated based on the Timoshenko theory and its element is shown in Fig. 4 (ANSYS, 2000).

MODEL ANALYSIS

Model analysis relates to free vibration analysis where the system is free from external forces. The analysis will determine the natural frequency of a dynamic system which is subjected to a dynamic load. This is an important analysis to ensure the structures will not vibrate to its natural frequency value. This is to avoid resonance which can lead to catastrophic failure in the structure.

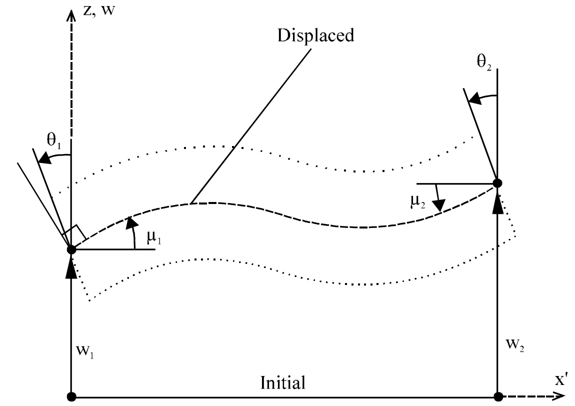

Fig. 4: Timoshenko beam element (Astley, 1992)

In finite element method, for a structure that undergoes free vibration, the system equation for an individual element can be represented as:

$$KD+M\ddot{D}=0 \tag{6}$$

The solution of the free vibration system can be written as:

$$D = \phi\exp(i\omega t) \tag{7}$$

where, ϕ is the amplitude of the nodal displacement, ω is the frequency of the free vibration, t is the time, M and K are the mass and stiffness of the element, respectively.

By substituting Eq. 7 into Eq. 6, an eigenvalue equation is obtained:

$$(K-\omega^2 M)\,\phi = 0 \tag{8}$$

By substituting $\omega^2 = \lambda$, the following equation can be derived:

$$(K-\lambda_i M)\,\phi_i = 0$$

where, λ_i is the eigenvalues corresponding to the system's natural frequency and ϕ_i corresponds to a vibration mode of the i th mode of the vibrating structure as illustrated in Fig. 5 (Smityh, 1988).

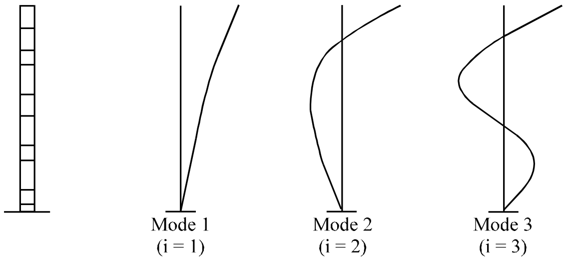

Fig. 5: The first three modes of a cantilever beam

DYNAMIC (TRANSIENT) ANALYSIS

In ANSYS, a dynamic analysis is also called as a transient analysis (sometimes called time-history analysis). It is a technique used to determine the dynamic response of a structure under the action of any general time-dependent loads.

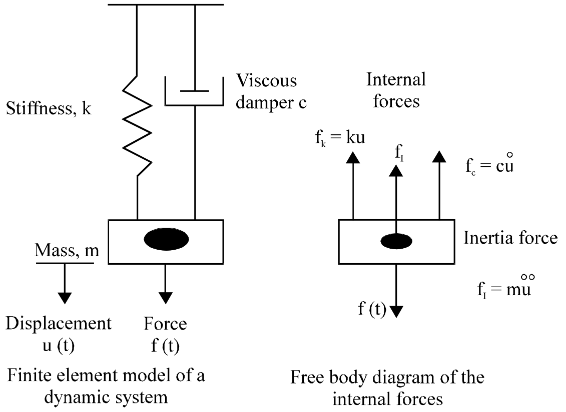

Fig. 6: The basic dynamic system (Maguire and Wyatt, 1999)

The linear dynamic behaviour of a structure depends on Eq. 9. The dynamic response is obtained by solving the following equation of motion:

$$(M)\{\ddot{u}\}+(C)\{\dot{u}\}+(K)\{u\} = \{F(t)\} \tag{9}$$

Where:

M = Mass matrix
C = Damping matrix
K = Stiffness matrix
$\ddot{u}$ = Nodal acceleration vector
$\dot{u}$ = Nodal velocity vector
u = Nodal displacement vector
F (t) = Load vector

Figure 6 shows a free body diagram of the internal forces accounted in the structure and its correspondence to a finite element model.

SIMULATION RESULTS

Finite element analysis is an efficient technique of analyzing the dynamic performance of most structures because it can reduce the time in design process, optimize the budget in the construction process and increase the safety of the structure.

A model analysis is carried out using FE simulation to determine the mode shapes of the intact structure before assigning the normalised mode shape vector into the sea force mode shape function parameter. The magnitude of the sea force is associated with the mode shape of the intact platform, thus the displacement of the structure is the determining factor for the magnitude of the sea force (the sea force magnitude increases as the displacement increases). The displacement increases significantly starting from the height of 35 m to the top of platform.

The mode shape's contour plots produced in ANSYS present the displacement in X-direction of the entire structure in good detail. The structure legs in mode 1 are found to be straighter than those in modes 2 and 3. These results are found to be consistent with the findings of Harnett *et al*. (1997).

The change in response signatures for the first mode of the intact platform is shown in Fig. 8.

Figure 7a-c describe the three main mode shapes of the intact platform under free excitation. The first three modes of the modal analysis have an associated natural frequency of 0.604, 0.671 and 0.741 Hz, respectively. The mode shapes show that the largest displacement occurs at the top (red contour plot) which are consistent for the three main modes. The structure of mode 1 has the least displacement throughout the structure jackets as compared to mode 2 and mode 3 as displayed by the dark blue plot (mode 1) in comparison to light green plot for modes 2 and 3. It is worth mentioning that mode shape 1 is utilised in the sea force mode shape function parameter in developing the sea wave force acting dynamically on the platform.

DYNAMIC ANALYSIS OF SEA WAVE

The sea force plot converted from time domain to frequency spectrum (Fig. 9) provides better approximation of the peak frequencies of the sea wave. The sea force magnitude increases significantly at the height of 40m, corresponding to the mode shape function of the platform (higher displacement approaching the top).

The peak frequency of the sea force is about 0.12 Hz, similar to the JONSWAP frequency spectrum for typical North Sea Storm conditions. This signifies that the sea force developed for this specific platform provides a good approximation of a typical storm in the North Sea which is one of the key objectives of this study.

Figure 10 shows the position of the selected nodes along the legs of the main structure and the directions of the respective sea wave forces applied on the nodes. The arrows represent the sea forces which act on the selected nodes.

DYNAMIC ANALYSIS OF THE PLATFORMS

FE dynamic simulation establishes the effects of material stiffness reduction on the structure acceleration response. A data conversion from time trace into frequency domain in Power Spectral Density (PSD) describes the effects of material stiffness reduction on the peak frequency response of the structure.

Primarily, this study investigated the influence of the reduction of material stiffness on the natural motion of the platform subjected to sea force in X, Z and at 45° angle diagonal to X and Y-directions. Detecting the dynamic response using frequency spectrum analysis is a deterministic method which adequately estimates the natural frequencies, comparable to a real situation on a platform. This is possible by converting the structural acceleration response obtained through mounted accelerometers into frequency domain (Harnett *et al*., 1997).

The material stiffness of one of the upper diagonal beam members of the platform (Fig. 10) was reduced by 10, 30, 50 and 90% for each of the sea wave directions. The structure with zero material stiffness reduction was recognised as an intact platform. The details are listed in Table 1.

As the stiffness was reduced, the peak frequencies for all intact and damaged platforms were identified, giving the approximate values of the natural frequencies. This result is in agreement with the study of Mangal *et al*. (2001) who reported that natural frequencies of a platform are identified by performing a Fast Fourier Transform (FFT) on the data.

The change of material stiffness from 30 to 90% had the greatest influence on the shift in peak or resonance frequencies when the sea force is excited in the X-direction and at 45° diagonal to XY as shown in Fig. 11 and 12 in relative to Z-direction (Fig. 13, 14). The shift in resonance frequencies is less apparent for damage induced by reduction in material stiffness by 30% or less.

The energy excitation for damaged platform IV (with 90% stiffness reduction) is almost eight times higher as compared to the intact platform. This significant excitation is primarily due to the large displacement of the platform when the diagonal member is almost totally damaged and

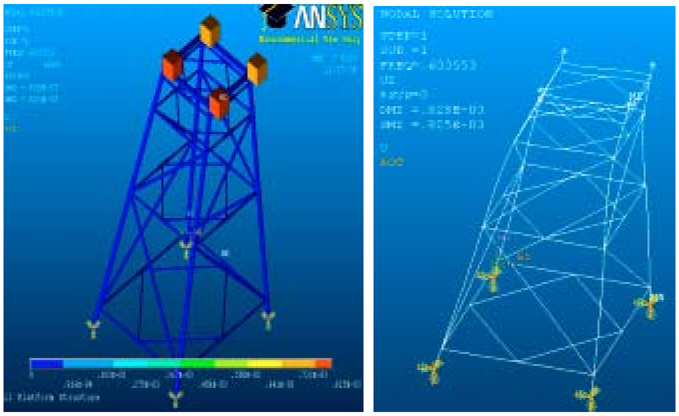

Fig. 7a: First mode

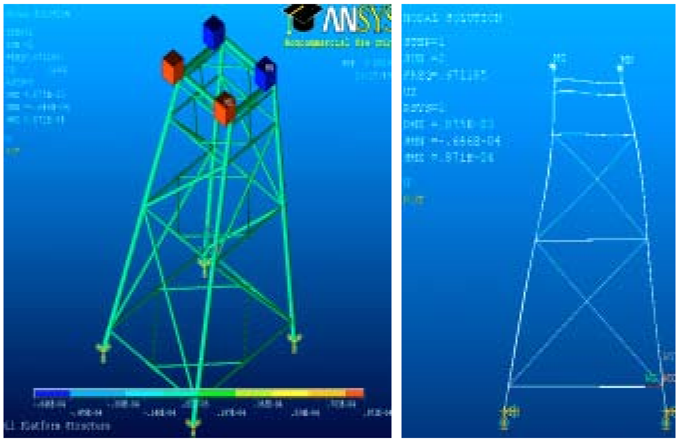

Fig. 7b: Second mode

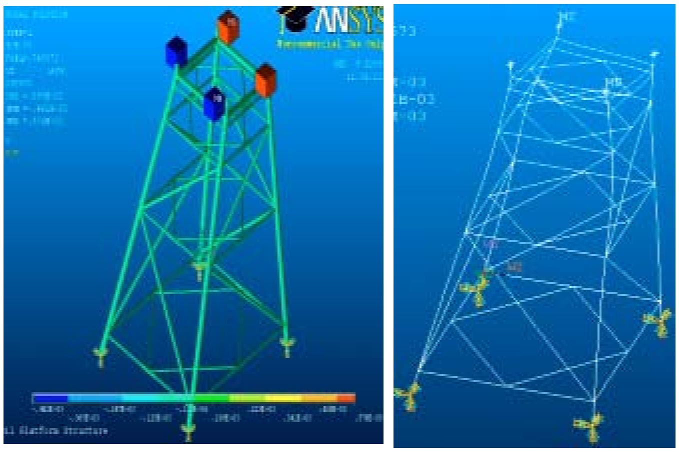

Fig. 7c: Third mode

the platform integrity is affected. This also indicates a lower damping ratio for the damaged platform as compared to the intact platform. The rotational acceleration of the platform (Fig. 15, 16) gives relatively

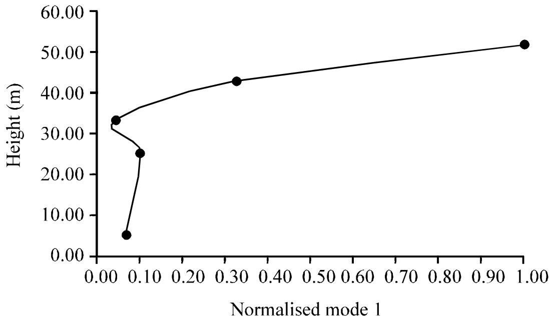

Fig. 8: Changes in vibration signatures in intact platform (no damage). The normalised modes are for leg No. 4 in X displacement which has been described into sea force mode shape function

Table 1: Damage intensity in the diagonal beam member

Damage intensity	Elastic modulus	Structure label
Undamaged	2.00E+11	Intact platform
10%	1.80E+11	Damaged platform I
30%	1.4E+11	Damaged platform II
50%	1.00E+11	Damaged platform III
90%	2.00E+10	Damaged platform IV

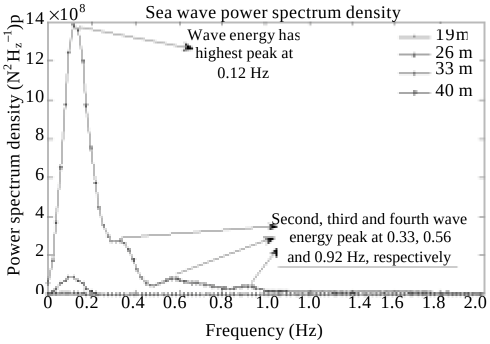

Fig. 9: Sea wave energy estimated by power spectrum density

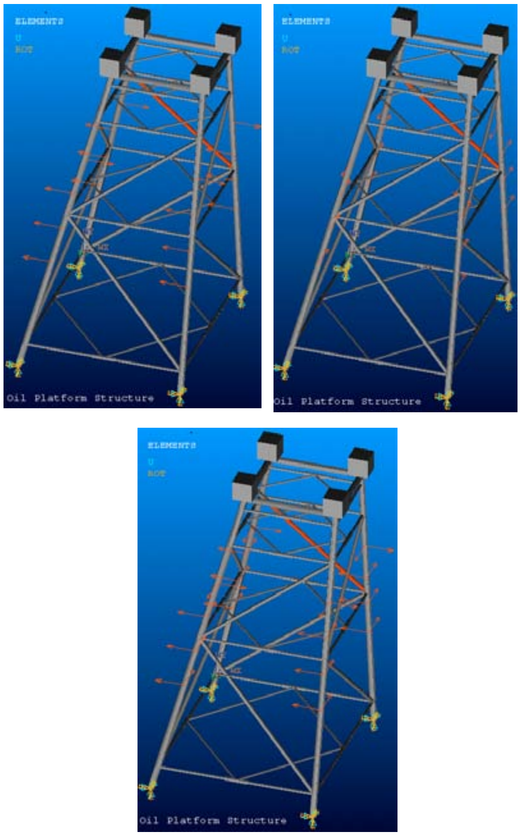

Fig. 10: Sea force applied in X and Z-directions and at 45° diagonal to XY

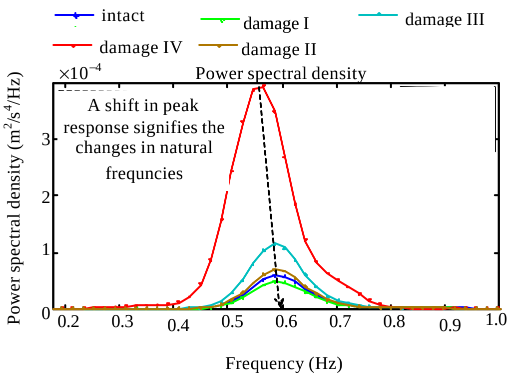

Fig. 11: Power spectral density of structure linear acceleration in X-direction due to sea force in X-direction

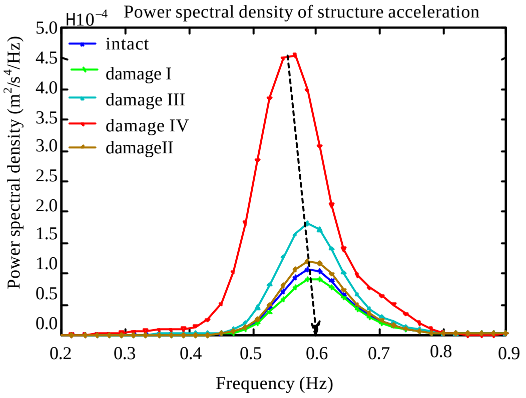

Fig. 12: Power spectral density of structure linear acceleration in X-direction due to sea force at angle of 45° diagonal to X and Y-directions

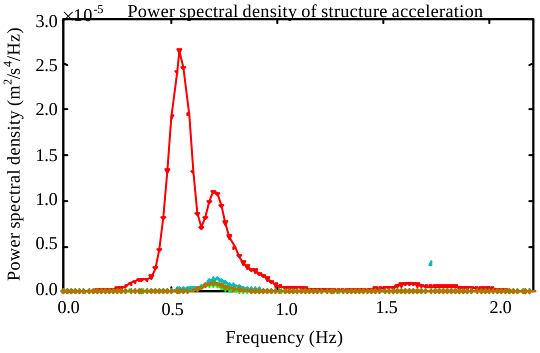

Fig. 13: Power spectral density of structure linear acceleration in Z-direction due to sea force at angle of 45° diagonal to X and Y-directions

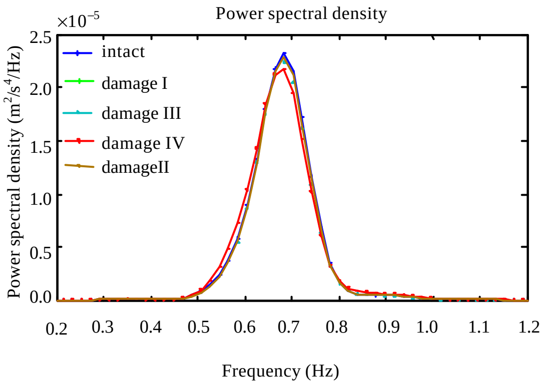

Fig. 14: Power spectral density of structure linear acceleration in Z-direction due to Sea force in Z-direction

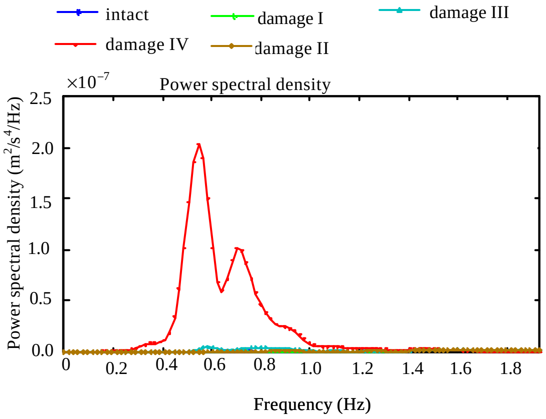

Fig. 15: Power Spectral Density of structure rotational acceleration about Y-axis due to sea force in X-direction

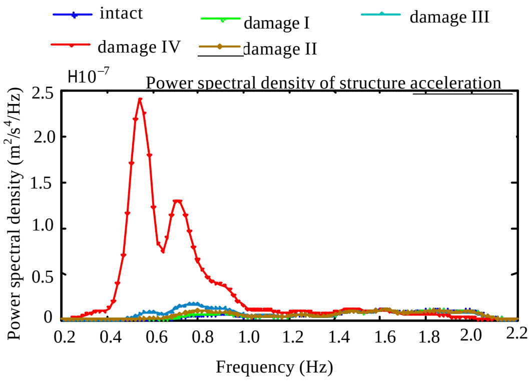

Fig. 16: Power spectral density of structure rotational acceleration about Y-axis due to sea force at angle of 45° diagonal to X and Y-directions

less effect on the natural frequency shift as compared to the linear acceleration. The magnitude of the rotation has a relatively insignificant effect on the platform's dynamic behaviour.

The sea force incident in the Z-direction has no influence on the shift of natural frequencies following the reduction in the member stiffness (Fig. 14, 17). This is due to the fact that the damaged beam member geometry is located in the X-plane and thus gives no effect on the structural integrity as the dynamic force is applied in the Z-direction. Applying this understanding, the location of the damaged beam member either in parallel or perpendicular to the X or Z-axis in the structure global co-ordinates can be identified if the direction of sea force is known.

The natural or resonance frequency shifts is apparent on the dynamic response of the platform when the sea force is excited at an angle of 45° diagonal to X and Z-directions (Fig. 12). As expected, by considering the vector sea force in X-direction, the peak frequency shift is more significant as the damage is induced by 50 to 90% reduction in material stiffness. There is little effect on the natural frequency shift for the intact and damaged platforms of 10 and 30% stiffness reduction in the diagonal member. However, the effects of frequency shift in the 10 and 30% are still detectable. Considering that the damage only occurs in one of the diagonal members of the platform, the detection of the damaged platform can be performed by examining the natural frequency shift in the dynamic response.

When the sea force is applied in the Z-direction, there is no effect on the resonance frequency shift. However, the energy excitation by a damaged platform with 90% stiffness reduction in the diagonal member is relatively much higher as compared to platforms with 50% or less stiffness reduction. It is not possible to consider the effects of frequency change in the Z-direction as the decrease in the natural frequencies are not consistent with the decrease in material stiffness. This is contributed by the fact that the location of the damaged beam is perpendicular to the sea force direction, thus the effect of the sea force is insignificant to the structure response.

The rotational acceleration about y-axis due to sea force at an angle of 45° diagonal to X and Z-directions is found to be in agreement with the rotational acceleration excited by sea force in the X-direction. There is apparent resonance frequency shift as the stiffness is reduced from 10 to 90%. However, the magnitude of the response is less significant as compared to the translational acceleration. It is also found that the sea force at 45° angle produces a slightly larger resonance frequency shift as compared to the sea force in X-direction. This is contributed by the fact that the sea force at 45° angle consists of sum vectors of sea force in X and Z-directions.

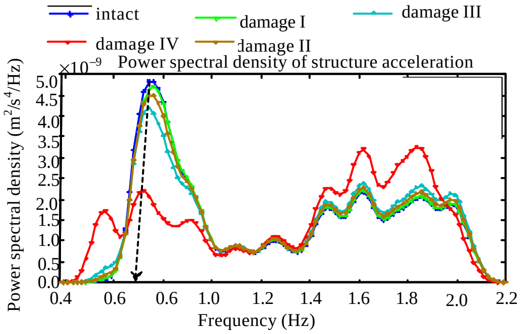

Fig. 17: Power spectral density of structure rotational acceleration about Y-axis due to Sea force in Z- direction

The structures with 30 and 50% stiffness reduction in the diagonal member show a detectable shift in resonance frequency and that with 90% stiffness reduction shows a very evident shift in resonance frequency. In reality, it is desirable to inspect and take appropriate measures on the weakened member before the stiffness is reduced up to 90%. Therefore, values at 30 and 50% stiffness reduction are more reliable when taking necessary action for the structure rehabilitation process. By measuring the structure acceleration via the mounted accelerometers on the platform, the time response should be converted into frequency spectra to determine the shift in natural frequency. By observing the shift in the peak frequencies, it indicates whether damage may have occurred in the structure beam.

CONCLUSION

This study presents the dynamic characteristics of an offshore structure due to sea wave excitation in the North Sea. It outlines some key procedures in performing the dynamic analysis of the platform under sea force action using finite element simulation. From the analysis carried out, it was shown that there was a detectable shift in resonance or natural frequencies of the platform according to the changes of the material stiffness in the structure. The shift in natural frequencies is only significant if the damaged member is in the same direction as the sea force and the member stiffness is reduced by more than 10%. The result of the dynamic analysis is considered reliable as only one diagonal beam is modelled as a damaged member with reduced material stiffness. Therefore, it can be concluded that the shift in the natural frequencies can be utilized as an indicator tool to monitor structural dynamic behaviour that are altered due to material stiffness reduction in the structural member while the platform is in service. By monitoring the structural response obtained using fixed accelerometers on the platform and converting them into frequency spectra, structural engineers should be able to identify any possibility of structure weakening due to corrosion or fatigue by detecting any shift in the peak frequencies response before further detailed inspection on the platform is carried out. This method of examining the shift in natural frequency offers an economical and convenient way in tracking the progression of damage in the structure.

REFERENCES

ANSYS, 2000. Basic guide: ANSYS release 11.0 documentation for ANSYS. http://www.kxcad.net/ansys/ANSYS/ansyshelp/ansys.set.html.

Astley, R.J., 1992. Finite Elements in Solids and Structures: An Introduction. 1st Edn., Chapman and Hall, London, ISBN: 9780412441608.

Brincker, R., P.H. Kirkegaard and P. Andersen, 1995. Damage detection in an offshore structure. Proceedings of the 13th International Modal Analysis Conference, February 1995, Nashville, Tennessee, pp: 661-667.

Harnett, M., T. Mullarkey and G. Keane, 1997. Modal analysis of an existing offshore platform. Eng. Struct., 19: 487-498.

Hillis, A.J., 2009. Active motion control of fixed offshore platforms. J. Syst. Control Eng., 224: 53-63.

Maguire, J.R. and T.A. Wyatt, 1999. Dynamics: An Introduction for Civil and Structural Engineers. 1st Edn., The Institute of Civil Engineers, London.

Mangal, L., V.G. Idichandy and C. Ganapathy, 2001. Structural monitoring of offshore platforms using impulse and relaxation response. Ocean Eng., 28: 8689-8705.

Smityh, J.W., 1988. Vibration of Structures: Application in Civil Engineering Design. 1st Edn., Chapman and Hall, New York.