System Identification of Steel Jacket Type Offshore Platforms using Vibration Test

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Abstract

Offshore platforms during their life-time due to severe environmental conditions need to monitoring continuity than the onshore structures. Structural health monitoring is a new method that used for most infrastructures in recent years. This method is a two-step process including the system identification and damage detection. The purpose of this paper is study the health monitoring of an experimental steel jacket type offshore platform in order to propose a dynamic system identification method for this type of infrastructures. Due to the time-varying loads and severe environmental condition of sea state affected on offshore platforms, system identification of this type of structure has principal role in conformance the quality of construction, validation or updating analytical finite element structure models, and specially conducting damage detection. In this paper, dynamic response measurement of a prototype jacket type offshore platform, SP, is performed using forced vibration imposed from an eccentric mass shaker. The prototype platform SP is installed on eight skirt piles embedded on continuum monolayer sand. Dynamic characteristics of the platform are identified using signal processing approach. Numerical simulation of responses for the studied structure is also performed using capability of ABAQUS software. The 3D model of ABAQUS is created using continuum elements for soil and piles, and beam elements for jacket, deck and pile elements. It can be seen that dynamic characteristics of such a platform can be extracted from experimental result of the system subjected to dynamic loading.

1. Introduction

Steel jacket-type offshore platforms are the most common kind of offshore structures that been widely used in offshore oil and gas industry. These large and complex structures during their service life are subjected to random sea environmental loads such as wave, current, wind and earthquake; therefore, proper maintenance to ensure the safety of their operation is an important issue. Using the common methods such as visual inspection for monitoring platform integrity are often hard and sometimes impossible due to sea condition or increasing the depth of water. These problems led to the development of simpler techniques for evaluation of structural performance. Structural health monitoring (SHM) is a new method for assessment of the integrity of structures in the last two decades. The goal of this process is to maximize the structure's performance and minimize risk. The major step of SHM is system identification. Most important infrastructure components such as bridges, tall buildings, dams and offshore
platforms can be conveniently instrumented to estimate their dynamic characteristics. The major advantage of using system identification is improvement fidelity of finite element models, minimizing inaccuracies and calibrating design codes. Inaccuracies in finite element models may be due to several factors such as the approximations made in the discretization, miss-modelling of structural elements, the difference in material properties and inaccuracy of dimension. System identification is also help to check the integrity of structures subjected to ever increasing loads and monitor the changes of structural characteristics and responses, and subsequently detects damages in the structure and predict the expected remaining life. The role of Structural Identification is also presented in the state of the art report by American Society of Civil Engineers (ASCE) and Structural Engineering Institute (SEI) committee (ASCE-SEI 2012). Many studies have focused to develop techniques for system identification and show reliable achievement (Arici and Mosalam 2005a and 2005b; Mohanty and Rixen 2006; Carden and Brownjohn 2008; Gul and Catbas 2008; Elshafey et al. 2009; Mojtahedi et al. 2011). In system identification process, a mathematical model is generally determined by observing its input–output relationships. This model may be classified to graphic or mathematical models. Sometimes a mathematical model can be constructed based on the physical laws that govern the system behaviour, but often such direct modelling may not be possible due to incomplete knowledge about system’s mechanism or change of properties of the system in an unpredictable manner.

The traditional fast Fourier transform (FFT) was proposed by Bendat and Piersol, (1993) for recognition dynamic properties of civil structures. The peaks of the averaged normalized power-spectral densities are determined the natural frequency of structures. In this method, the system properties are obtained by converting the measured data to the frequency domain by a Discrete Fourier Transform (DFT). Andersen et al. (1997) proposed Auto-Regressive Moving Average Vector (ARMAV) models. In his proposed model, it is assumed that the structure is linearly, time-invariant, and the unknown input force can be modelled by a white noise filtered through a linear and time-invariant shaping filter. The ARMAV is calibrated to the measured time signals by minimizing the prediction error. Van Overschee and De Moor (1996) suggested a method in which dynamic behaviour of a structure excited by white noise can be described by a stochastic state space model. The state space matrices identify based on the measurements and by using robust numerical techniques such as least squares. James et al (1995) demonstrated that the correlation functions can be used in the identification algorithms of traditional modal analysis. Classical techniques such as Least Squares Complex Exponential (LSCE) and Eigen system Realization Algorithm (ERA) are appropriate to extract the modal parameters from the measured response data of structures undergoing unknown forces.

Identification the dynamic characteristic of offshore platforms is so important problem both in the analytical analysis and implementation of structural health monitoring methods. The response of these structures is a function of several parameters such as loading properties and dynamic pile-soil structure interaction behaviour. Experimental investigations of scale models provide means to validate numerical calculations and evaluate the existing approaches and measuring instruments for measurement its response. They also provide a controlled environment in which the effect of specific parameters can be studied. The present paper reports the results of an experimental program that was carried out at K.N.Toosi University of Technology to investigate the dynamic response of a scaled model of a fixed offshore structure. For this purpose, a
A three dimensional 1:15 scaled model is fabricated as welded-steel space frame. The scale model is installed on eight skirt piles embedded in monolayer continuum soil. Experimental force vibration tests were performed by an eccentric mass shaker. Accelerometers and LVDTs were used to estimate the response of structures. Signal based identification, based on analysis of response signals of structures, has also been developed. The classical method of frequency domain analysis is applied by means of Fourier transform, and simultaneous its four properties. Finally, experimental results were compared with the results obtained from a finite element model.

2. **Identification of dynamic characteristics**

Dynamic Response and behaviour of structural systems may be studied from response observation during earthquakes, experimental results on reduced scaled or actual size models of the structures and finally from analytical or numerical modelling of structures. Performing experimental investigation is very useful in complex structures such as offshore platforms to verify the numerical result. The use of experimental techniques has been widely applied to detect dynamic response of structural systems subjected to dynamic loading. These techniques are being investigated in several fields such as mechanical engineering (Mohiuddin and Khulief, 2002; Sabnavis et al., 2004), aerospace applications (Ghoshal et al, 2001) and the offshore industry (Idichandy and Ganapathy, 1990; Mangal et al. 2001 and Ruotolo et al., 2000).

Experimental dynamic investigation offers the opportunity to obtain information about the whole system dynamic characteristics based on small number of measurements. Usually, dynamic tests lead to determination of system modal characteristics. Experimental modal analysis is the term used for determination of modal properties such as natural frequencies, mode shape and modal damping experimentally. Two common methods of the structural modal testing are the force vibration and ambient vibration (Salawu and Williams, 1995). In ambient vibration tests, the excitation is not under the control and it is usually considered as a stationary random process. Ambient excitations are from different sources such as wind, pedestrian or vehicular traffic, earthquakes, waves or similar excitation. For very large and massive structures, ambient excitation is often the only practical choice. Structural identification through ambient vibrations has been successful in numerous cases (Ivanovic et al., 2000 and Ventura et al., 2003). Usually, experimental test of full-scale structures under dynamic loads is not practical. Experimental measurement of laboratory scale model of the structure is one of the alternative methods for comparison and investigation of the performance of existing and new systems. In this paper, scaled model of a jacket type offshore platform is fabricated and experimental forced dynamic test is performed on it.

2.1. **Description of Scaled Model**

Scaled model of a newly installed jacket type offshore platform in Persian Gulf SP1 is considered for this study. The laboratory model is a welded-steel space frame with six legs, horizontal and vertical braces, two-story decks and eight skirt piles. The details of the model are presented in Figure 1. Due to available pipes and laboratory facilities, the geometric scale of 1:15 is used. The modulus of elasticity and yield stress of steel piles are determined as 2x108 KN/m² and between 265-285 MN/m² (respectively).
For considering real boundary condition in the experimental model, a square cubes hole with approximately 7.00 m dimension is excavated in the yard of civil engineering faculty of K.N.Toosi University of Technology. In order to simulate the stiff bedrock in the bottom of the hole, a thick concrete layer with compression strength of 28MPa is constructed. The hole is filled with homogenous sand with a volume of about 320 m3. The process of filling the hole with sand is done in 10 months before performing driving skirt piles and installing jacket. The soil profile consisted of a monolayer uniformly graded sand with an angle of internal friction $\phi$ of 38° and the undrained shear strength, $c_u$ of 9.8 KN/m2. Young’s modulus for the sand is varied between 12,000-25,000 KN/m2 along the depth of the pile. The installation process of the scaled platform is conducted by driving eight piles through their sleeves using pile driving tool. Figure 2 shows picture of the scaled model of the SP1 platform installed on 8 skirt piles.

Figure 1. General view of scaled model SP1
In the forced vibration tests, one vibration generating system having an eccentric mass shaker is used to excite the structure. This system can apply harmonic excitation across a wide frequency range in one or two horizontal directions and can induce weak to strong forced vibration to structures. The eccentric mass shaker is capable to impose and hold a frequency in the range 0.0 to 10 Hz within 0.1 Hz intervals. The shaker is installed in the second story of the platform deck and it is fixed to rigid plates of deck. The response of the scaled model of SP1 platform to the frequency sweep kind of excitation is measured using six two-dimensional accelerometers, four linear variable differential transformers (LVDT's) and TMR-200 portable digital central recording systems. The response of the scaled model of SP1 platform in two directions (Rows A&C and Rows 1&2) is measured in several stages. The first stage of the test is conducted by increasing the input frequency from 1 Hz to 4 Hz by 0.2 Hz intervals. In this stage, the approximate modal frequency values are evaluated. In the next stage of force vibration testing program, the exact value of natural frequencies and corresponding mode shapes is evaluated. In these stages, the frequency of excitation is increased around the preliminary resonant frequencies by a 0.1Hz intervals and the response of the platform is measured using accelerometers.

![Figure 2. Picture of scaled model, SP1 installed on soil-pile-supports.](image)

### 2.2. Description of Test Cases

In order to change vertical bracing members of SP jacket, these members are fabricated using flange type connection plates. Four different vertical bracing configurations are selected for performing forced vibration tests. First case is the base case in which members configuration is same as main design configuration of platform. In case No. 2 four vertical braces are added to top bay of jacket as shown in figure 3. In cases No. 3&4 vertical bracing of third and second bay of the jacket was removed as shown in figure 3 in order to simulate damages may occur during platform life.
Figure 3. Four bracing configuration cases used in force vibration test

2.3. Numerical Modelling Description

Dynamic characteristics of the scaled platform SP1 is also computed numerically using three- Dimensional modelling with ABAQUS software. The superstructure elements, including legs, vertical and horizontal bracing members and deck beams are modelled using two nodes beam elements. Three dimensional solid elements are applied to model piles and soil media. Mohr-Coulomb geotechnical constructive model is assumed for modelling soil material behaviour. The soil-pile interfaces are assumed as a frictional interface where soil-pile slipping and gapping may occur. Generally, Coulomb’s law of friction is used to model slipping and gapping in the soil and pile. If interface surface is in contact, full transfer of shear stress is ensured and separation occurs when there is tension between the soil and pile interface. Thus, in model using ABAQUS, the contact
constraint is applied between two surfaces of pile and soil. The surfaces are separated when the contact pressure between them becomes zero or negative, and the constraint is removed. As the system is subjected to a small force which does not induce slip, for the tangential component, rough interaction is assumed between surfaces. Figure 4 is shown 3D model of the prototype in ABAQUS.

Figure 4. Three-Dimensional Model of SP1 in ABAQUS

3. Results

In this section, results of experimental and numerical analyses are presented in term of dynamic characteristics. Response of scale model to excitation is derived from experimental data and ABAQUS model analysis result. To identify modal characteristics of the scaled platform SP1, signal processing method was used based on the power spectral density function. Modal frequencies and mode shapes are also obtained numerically using ABAQUS outputs.

3.1. Natural Frequencies of the Platform in different cases

Natural frequency of the scaled platform, SP1 is obtained using power spectral density (PSD), cross correlation spectrum (CPS), phase relationship, and the Coherence Spectrum (CS), (Equation 1 through 4). The CPS, phase relationship and CS are estimated between all response measurement points and one reference point. The segment averaging method (also known as Welch’s method) was used for better correlation and minimizing errors. The method consists of dividing time-series data into
(possibly overlapping) segments, computing a modified spectrum of each segment, and then averaging the PSD and CPS estimates. Therefore, PSD and CPS are estimated by dividing each acceleration data to eight segments and using a Hanning window with 50% overlap. To distinguish the spectral peaks representing the platform vibration modes from those corresponding to peaks in the input spectrum, the advantage concurrency of the CPS peak and the orthogonality condition of mode shapes are used. That is, all points of the platform in a lightly damped mode of vibration are in-phase or 180 out-phase with each other, depending only on the shape of the normal mode. Moreover, the large amount (approximately 1) must be occurred in the value of the coherence spectrum at the candidate frequency. A MATLAB subroutine is coded for this aim.

\[
\text{PSD} : \quad S_{xx}(f) = \int_{-\infty}^{\infty} R_{xx}(\tau)e^{-j2\pi ft}\,d\tau
\]

(1)

\[
\text{CPS} : \quad S_{xy}(f) = \int_{-\infty}^{\infty} R_{xy}(\tau)e^{-j2\pi ft}\,d\tau
\]

(2)

\[
S_{xy}(f) = C_{xy}(f) - jQ_{xy}(f)
\]

(3)

\[
\theta_{xy}(f) = \tan^{-1}\left[\frac{Q_{xy}(f)}{C_{xy}(f)}\right]
\]

(4)

\[
\gamma_{xy}^2 = \frac{|S_{xy}(f)|^2}{S_{xx}(f)S_{yy}(f)}
\]

(5)

In the above equation \(S_{xx}\) and \(R_{xx}\) are power spectral density and the auto-correlation of a measurement point of the structure respectively. \(S_{xy}\) and \(R_{xy}\) are cross correlation spectrum and the cross-correlation between two response measurement points of the structure respectively. Cross correlation spectrum, \(S_{xy}\) is a complex value that is shown by the real value \(C_{xy}\) and imaginary value \(Q_{xy}\). The phase spectrum of the CPS is calculated from equation 2 and detect that two-point of vibrations is in-phase or out-phase. The degree of linear association between two signals is compared by ordinary coherence function. Two signals are completely correlated, and its function is shown unity value, if there is not any noise during the vibration recording and there is not any computational error in the spectral calculation. The coherence spectrum has a peak in the resonant frequency of the platform, and its value is larger than 0.5. Figure 5 shows power spectral density, cross spectral density, coherence spectrum a phase spectrum that obtained from above equations for Row A&C. Tables 1 present first and second natural frequencies of scaled model platform for four vertical bracing configurations. The result of Finite element modelling using ABAQUS software is also presented in this table. By comparing the result of natural frequencies of second case with first case, it is observed that adding vertical bracing in top bay of the jacket, increased significantly natural frequencies. This confirms efficiency of adding such an offshore installed bracing system in order to avoid soft story mechanism in top bay of such a jacket. It can be seen that removing vertical bracing in second and third bay of jacket has significant change in dynamic characteristics of platform and it can be concluded that results of dynamic measurements can be used for damage detection of such structures.
Figure 5. Power spectral density, cross spectral density, coherence spectrum and phase spectrum for Row A&C.
Table 1. Measured and computed Natural Frequency of the platform at each case

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Direction</th>
<th>Test</th>
<th>ABAQUS</th>
</tr>
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<tr>
<td></td>
<td></td>
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<tr>
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<tr>
<td></td>
<td>Torsion</td>
<td>3.83</td>
<td>11.02</td>
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</table>

3.2. Platform Mode shapes

For estimation of the mode shapes of scaled model platform SP1, the amplitude of PSD is obtained for each point, and its root is calculated. The phase difference of each point relative to the reference point is determined by phase spectrum. If the phase angle is in the first or fourth quarter of the unit circle, that point is in-phase with reference point, but if the phase angle is in the second or third quarter of the unit circle, that point is out-phase with the reference point. The mode shapes are determined according to the obtained amplitude root of PSD and the phase difference (in or out-phase). Figures 6 to 9 show mode shape of scaled model platform SP1. In these figures, results of finite element (ABAQUS) model are also shown. By comparison of the result of mode shapes for cases 1 and 2, simpler dynamic behaviour can be observed, in the other words, adding vertical bracing in top bay of such a jacket and strengthening platform leads to similar mode shapes with shear regular structures. Removing vertical bracing in second and third bay of jacket changes mode shapes configuration according to figures 8 and 9.

![Figure 6. Mode shapes of platform - case 1](image-url)
3.3. Estimation of Modal Damping

Half-power bandwidth method is used for calculating the modal damping. The damping ratio is calculated using equation 6 in which frequencies $f_a$ and $f_b$ are illustrated in figure 10. Table 2 shows damping ratio for different modes of both boundary condition cases. It can be seen that generally ratio of damping increases by decreasing the lateral stiffness of structure and the difference of damping ratios in the first mode is so significantly than the higher modes.

$$\zeta = \frac{f_b - f_a}{f_b + f_a}$$  \hspace{1cm} (6)
4. Conclusion

In this paper, dynamic system identification of a scaled model of steel jacket type offshore platform newly installed in Persian Gulf are studied using experimental and numerical simulation. The model is tested on a pile supported condition in order to simulate real boundary conditions. Strengthening of jacket type offshore platforms by adding vertical bracing members in top bay of jacket and weakness of such a platform by removing vertical bracing members also studied from experimental and numerical results. The force vibration dynamic test is conducted to identify modal properties of the structure. Signal processing is used based on power spectral density function. The numerical modelling of sample platform SP1 is performed using ABAQUS software. The result of experimental analysis shows that soil-pile-structure interaction decrease the natural frequency of structure. The same result is also observed in the other modal properties and considering SPSI is increased the relative lateral displacement at mode shapes and modal damping. The effects of SPSI are significantly illustrated at higher modes compared to first mode for all the dynamic characteristics. Efficiency of offshore installed vertical bracing members in top bay of jacket is also observed from improvement of dynamic characteristics of structure experimentally and numerically. The numerical results obtained from ABAQUS model matches more with experimental observation at first mode compared to higher modes.
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