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Study of pattern of sensor installation for analysis behavior of offshore jacket structure

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ABSTRACT

Structural health monitoring (SHM) provides an effective approach to ensure the safety of structure. Although centralized development continues on innovative sensor systems, there is still significant uncertainly in deciding on number of sensor required and their location in order to take enough information on structure behavior.

This paper introduces the process for determining the optimal sensor placement (OSP) on an offshore jacket so that structural dynamic behavior can be fully characterized. Six different optimal sensor placement technique have been investigated, including the effective independence (EFI) methods, the driving-point residue(DPR) method, the effective independence driving-point residue (EFI-DPR) method, the kinetic energy method (KEM), eigenvalue vector product(EVP) method and Non optimal driving point base (NODP) method. Then a criteria is employed that measured the information content each sensor location to investigate on the strength of the acquired signal and their ability to withstand the noise pollution keeping intact the information relative structure properties.

The result showed that the EFI method provides an effective method for optimal sensor placement to identify the characteristics of the studied offshore jacket.

1. Introduction

Structural health monitoring has attracted much attention in both research and development in academics and industries in recent years. The term “Structural Health Monitoring” refers to the use of in-situ, continuous or regular measurement with permanently installed sensors and analyses of key structural and environmental parameters under operating conditions, for the purpose of warning impending abnormal states or accidents at an early stage to avoid casualties as well as giving maintenance and rehabilitation advices (Balageas et al.2006; Li et al. 2004). A typical structural health monitoring (SHM) system includes three major components: a sensor system, a data processing system (including data acquisition, transmission and storage), and a health evaluation system (including diagnostic algorithms and information management) (Li 2011).

According to definition, Sensor system is a fundamental part of SHM, for mechanical analyses of the structure, such as parameter identification, damage detection and

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condition evaluation, totally rely on the data acquired from the sensors. Unfortunately, the number of sensors installed in a structure is intensely constrained by the cost associated with data acquisition systems, processing the in-line data as well as the initial installation of the sensors, subsequently restricting the full use of SHM for the assessment of structural integrity, durability and reliability, etc. Therefore, how to deploy the limited sensors is of crucial importance in the design and construction of an effective SHM. Hence, the fundamental problem is how many and which degrees of freedom should be taken in the fault/damage identification process.

Due to the existence of large volume of redundant information, not all of degrees of freedom (DOFs) of a structure are indispensable. OSP deals with how many and which DOFs to install sensors from the set of infinite DOFs of a structure, and correspondingly the objective can be interpreted as eliminating the unnecessary DOFs as many as possible while giving sufficient information to describe the behavior of a structural with sufficient accuracy (Meo and Zumpaon 2005).

Sensor locations must be individually determined for each structure to be estimated. Normally, the selection is based purely on the engineering judgment. In order to detect structural changes within the jacket platform, a more reliable method must be developed (Meo and Zumpaon 2005).

2. Jacket platform structure

The different optimal sensor placement techniques were tested on a SPD2 jacket platform. A general configuration of SPD2 jacket platform located in South Pars Gas Field Phase 1 in the Persian Gulf is displayed in Fig. 1. Since the jackets located in this region of the Persian Gulf have similar configurations and heights, the SPD2 jacket can be an appropriate representative. The SPD2 jacket located in 65 m water depth consists of six legs and three battered faces. The jacket plan dimension is about 16.0m×27.5m at topside elevation and 23.4m×37.7m at mud line. The jacket is fixed to the ground by 6 through-leg grouted piles.

Fig. 1 SPD2 jacket platform

In order to provide input data for the OSP methods a two-dimensional model of the jacket platform was built in OpenSees software. The two-dimension model is shown in Fig. 2.

By performing a modal analysis the vibration properties were calculated. The sampling theory (Nyquist theorem) states that the maximum measurable frequency has to be less than half of the sensor sampling rate (5 Hz) (Meo and Zumpaon 2005). Therefore, according to the modal frequencies, the first four global modal properties (Table 1, Fig.3) were used as input data to find the optimal sensor locations. Hence, the OSP methodologies considered and described, in the next paragraph, employed only the first four mode shapes and the candidate sensor positions were those defined by the jacket platform nodes. The objective of the OSP selection was to identify the best locations of the available sensors in such a way to capture the dynamic response of the structure.

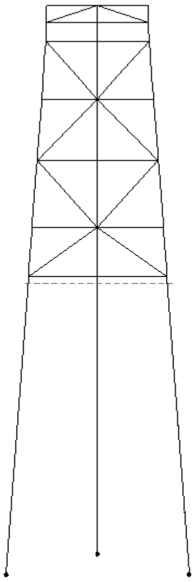

Fig. 2 SPD2 jacket platform OpenSees model

Table 1 Modal frequencies

Mode number	Period(s)	Frequency (Hz)
1	1.933	0.517
2	0.721	1.39
3	0.313	3.19
4	0.242	4.13
5	0.192	5.21
6	0.184	5.43
7	0.174	5.75
8	0.156	6.41
9	0.142	7.04
10	0.129	7.75

Six different optimal sensor placement technique have been investigated, including the effective independence (EFI) methods, the driving-point residue(DPR) method, the effective independence driving-point residue (EFI-DPR) method, the kinetic energy method (KEM), eigenvalue vector product (EVP) method and Non optimal driving point base (NODP) method. A comprehensive description of OSP methods that are used is given in the next sections.

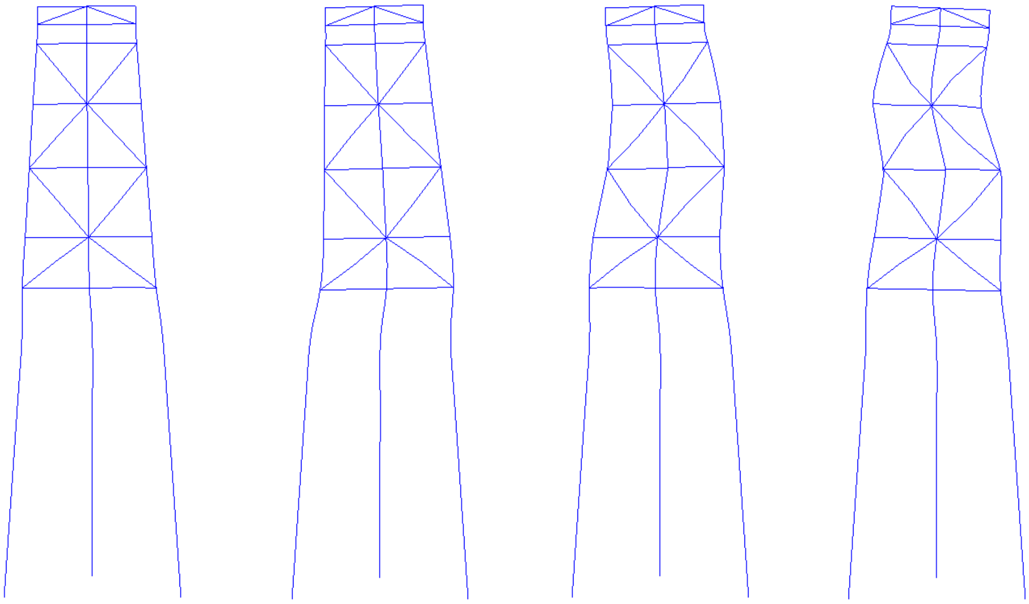

Fig. 3 First four mode shapes

3. The effective independence method

The Effective Independence (EFI) Method is one of the most influential and commonly used methods, as shown in its highly cited record. The EFI sensor placement method (Kammer and Brillhart 1996) was developed to maximize both the spatial independence and signal strength of the targeted mode shapes by maximizing the determinant of the Fisher information matrix.

The vector of the measured structural responses denoted by *ys* can be estimated as a combination of *N* mode shapes through the expression

$$y_s = \emptyset q + w = \sum_{i=1}^{N} q_i \emptyset_i + w \tag{1}$$

were ∅ is the matrix of target mode shapes, q is the coefficient response vector, w is a sensor noise vector that assumed stationary random with a mean value zero, *N* is the column number of ∅ (n by N matrix, n being the number of the candidate sensor positions), $\emptyset_i$ is the *i* th column of $\emptyset$ that is the *i* th target mode shape selected. The EFI takes the covariance matrix of the estimate error for an efficient unbiased estimator as follow

$$E(q-\hat{q})(q-\hat{q}) = [\frac{1}{\sigma^2}\emptyset^T\emptyset]^{-1} = A^{-1} \tag{2}$$

In which A is the Fisher information matrix (FIM) (Dowski 1995), E denotes the expected value, $\hat{q}$ is the vector of an efficient unbiased estimator of q. Hence, the best estimation of q occurs when A is maximized, therefore the procedure for selecting best sensor placement to unselect candidate sensor positions such that the determinant of the Fisher information matrix is maximized. Maximizing A will result in the best state estimate of q. In practice, the analysis begins by solving the following eigenvalue equation

$$[\emptyset^T\emptyset \text{ -}\lambda I]\psi = 0 \tag{3}$$

were ψ is the eigenvector matrix of A and λ is the associated eigenvalue matrix. The effective independence coefficients of the candidate sensors are then computed by the following formation

$$E_D = [\emptyset\psi]^{\wedge 2}\lambda^{-1}\{1\}_k \tag{4}$$

In which $\{1\}_k$ is the sum of all coefficients belonging to row *k*. Alternatively, the E_D index can be computed as the diagonal of the following matrix:

$$E_D = diag\ (\emptyset[\emptyset^T\emptyset]^{-1}\emptyset^T) \tag{5}$$

E_D indices represent the fractional contribution of each sensor location to the independence of the target modes. Therefore, to ensure the maximization of the *A* determinant, an iterative algorithm is developed: at each step, the smallest term in E_D is removed, and then corresponding elements in $\emptyset$ are also deleted until the required number of sensors is obtained. The results obtained from this OSP technique is shown in Fig. 4.

4. Driving point residue method

The Driving Point Residue (DPR) is a mechanic optimum criteria (Worden and Burrows 2001). The DPR for the *i th* DOF can be evaluated by using this expression

$$DPR = \sum_{j=1}^{N} \frac{\emptyset_{ij}^2}{w_j} \tag{6}$$

where w_j is the *j th* target mode frequency and $\emptyset_{ij}^2$ is the *i th* nodal displacement of the *j th* mode shape. In this case, sensors will be placed where the DOF is characterized by the highest average response over all of the target modes. The results obtained from this OSP technique is shown in Fig. 5.

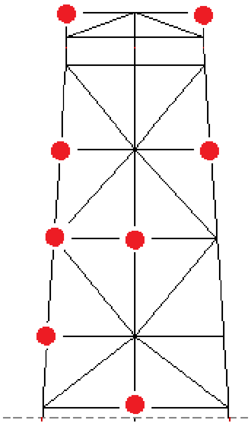

Fig. 4 EFI sensor location

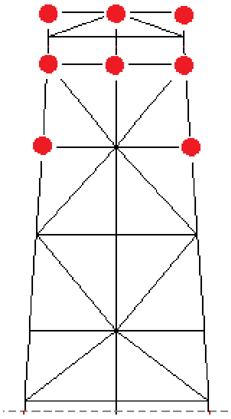

Fig. 5 DPR sensor location

5. The EFI-DPR method

A limitation of the EFI method is that sensor locations with low energy content can be selected with a consequent possible loss of information (Meo and Zumpano 2005). The EI-DPR (driving-point residue) method (Immanivic 1998) can avoid this drawback by weighting the E_D indices with the corresponding driving point residue (DPR):

$$E_{Di} = [\emptyset\psi]^{\wedge 2} \lambda^{-1} \{1\}_i DPR_i \tag{7}$$

The results obtained from this OSP technique is shown in Fig.6. As Fig.6 shows, this methodology approximately gets a similar result to the EFI method.

6. The kinetic energy method

In kinetic energy method (KEM) (Heo et all 1997) the objective is to maximize the measure of the kinetic energy of the structure. In fact, The KEM method examines the mode shapes of significance and selects locations with high amplitudes of responses as follows

$$KEM_{pq} = \emptyset_{pq} \sum_{k} M_{pk} \emptyset_{kp} \tag{8}$$

where KEM_{pq} is the kinetic energy associated with the *p* th dof in the *q* th target mode, $\emptyset_{pq}$ is the *p* th coefficient in the corresponding mode shape that is normalizes with respect to the mass matrix, M_{pk} is the term in the *p* th row and *k* th column of the mass matrix, and $\emptyset_{kp}$ is the *k* th coefficient in the *q* th normalized mode shapes.

The optimal sensor process is to select the sensors with the largest KEM. In fact, the KEM helps to select those sensor positions with possible large amplitudes. The results obtained from this OSP technique is shown in Fig. 7.

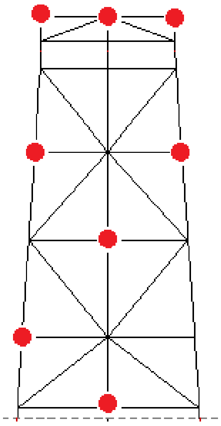

Fig. 6 EFI-DPR sensor location

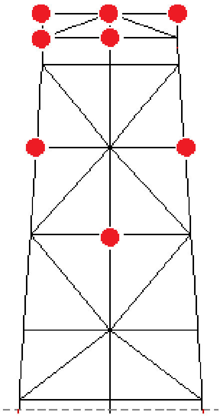

Fig. 7 KEM sensor location

7. Eigenvalue vector product

Eigenvalue Vector Product (EVP) is a mechanic type criteria (Doebling 1995). This criteria forms an indicator consisting in the absolute value of the product of every eigenvector. This product can be written for the *i th* structural DOF over the measured modes as

$$EVP_i = \prod_{j=1}^{N} \left|\emptyset_{ij}\right| \qquad (9)$$

This technique selects the sensors with the largest EVP values in order to prevent the choice of sensors placed on nodal lines of a vibration mode and to maximize their vibration energy. The results obtained from this OSP technique is shown in Fig. 8.

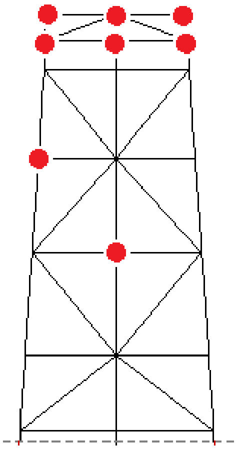

Fig. 8 EVPsensor location

8. Non-optimal driving point based method

Non-optimal driving point based method (NODP) (Immanovic 1998) is an energy-based method, generally used to find the optimal location for actuators. It is based on the well-known concept that the amount of vibration energy of any mode shapes depends on the relative positions of the excitation sources. The methodology consists in an iterative algorithm that unselects the candidate sensor position having the smallest target mode shape displacement that is:

$$NODP_i = \min_j \left|\emptyset_{ij}\right| \qquad (10)$$

The results obtained from this OSP technique is shown in Fig.9.

9. OSP comparison

In order to compare OSP methods Fisher information Matrix were used. The criterion of Fisher information matrix originates from estimation theory by sensitive analysis of the parameter to be estimated.

A comparison between OSP methods is based on the strength of the acquired signals. In fact, in order to reduce the noise, it should be as high as possible. Hence, the Fisher information matrix determinant is a useful and efficient performance index.

The Fisher information matrix determinant in term of its percentage of its initial value against the number of deleted sensors was calculated and displayed in Fig. 10.

Note that the goal was to place sensors on joints of the structure and the number of joints was 24.

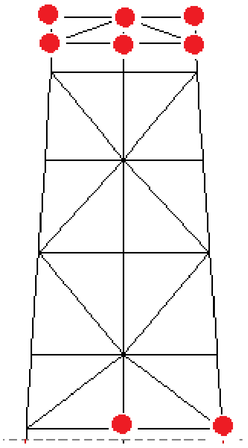

Fig. 9 NODO sensor location

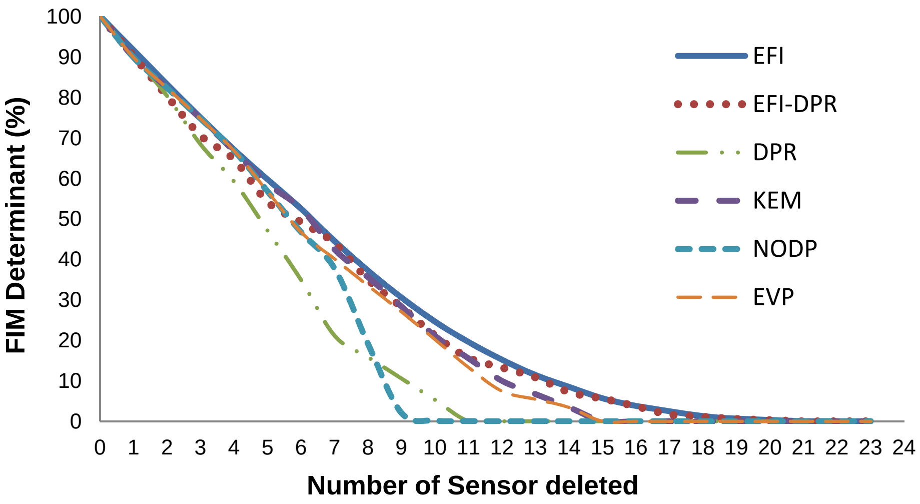

Fig. 10 Fisher information matrix determinant

The diagram shows that the worst results are obtained with NODP and DPR. The EFI and EFI-DPR behave very well in comparison to the others criteria for a wide number of deleted sensors. Intermediary performances are achieved by using KEM and EVP.

These techniques and their results are reliable for deciding number and location of the sensors. However, in evaluating the economic efforts, it should be noted that not only the number of sensors but also their location are important, since jacket platforms are located in seas and installing sensors in depth wants itself especial techniques.

10. Conclusions

In this paper, six optimal sensor placement methods were studied for a SPD2 jacket platform. The sensor locations should be able to give proper information in the reconstruction of modal and dynamic characteristics of the Jacket platform. Furthermore, the strength of the signal acquired had to be able to withstand the noise presence without introducing any appreciable change in the jacket platform properties of interest.

In order to compare OSP methods Fisher information Matrix were used. The comparison criterion results showed the better performance of the EFI and EFI-DPR methods compared to other OSP methods. In fact, they showed the better performance of EFI based techniques compared to the KEM and energy based methods.

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