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A new method of optimal sensor placement for modal identification of offshore platform structure

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ABSTRACT

A new method of optimal sensor placement for platform structures, which is based on genetic algorithm (GA), GUYAN reduction method and structural subsection technique, is proposed to capture complete and accurate modal information.Numerical simulation is conducted on a reduced scale platform model. With the hypothesis of treating the master coordinates of the FEM as the measurement locations for modal testing,two parameters are defined to evaluate the effectiveness of the proposed method. The optimal sensor locationsgot from the present method are in the high dynamic response regions, which can guarantee and improve the signal noise ratio (SNR) effectively. Furthermore, it is also found that thesensor distribution is fairly uniformalong the model, benefiting for capturing accurate and completevibration modes.

Keywords: Optimal sensor placement (OSP), Genetic algorithm (GA), GUYAN reduction method, Modal kinetic energy (MKE), Modal assurance criterion (MAC)

1. INTRODUCTION

Offshore structures continuously accumulate damage during their service life due to environmental forces such as waves, winds, current and seismic actions (Brincker 1995). These may result in crooking or buckling of some members, thus reducing their load bearing capacity and potentially affecting the safety and the integrity of the whole platform structures(Jin 2005). Therefore, many researches have been conducted with respect to structural health monitoring (SHM) by measuring vibration signals of offshore structures. Due to the large scale and complicated external environment, it is impossible to arrange sensor on every single degree of freedom (DOF) in the structure. So, how to arrange a certain amount of sensors on the structure reasonably and get the actual vibration information has a great significance.

The simplest optimal sensor placement (OSP) method is according to the engineering experiences of engineers, which is effective for some simple structures.However, it is necessary for engineers to have plenty of prior knowledge and deep analysis of structural properties (Xie 2006).Modal assurance criterion (MAC) technique (Carne 1995) aimed to match the vibration modes of finite element model (FEM) with the dynamic tests results as far as possible. The traditional method, which was dependent on the engineers' experiences,was developed (Papadopoulos

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1998;Udwadia 1994) by fitting sensors on DOFs with high amplitude responses. Effective independent (EFI) method was presented to select a group of locations which contributed significantly to the linear independence of the target modal partitions (Kammer 1991). GUYAN reduction technique(Guyan 1965) was also applied to OSP. Based on GUYAN reduction technique, it was pointed that it was reasonable to postulate the master coordinates served as the measurement locations (Penny 1994). The variance method (Meo 2005), which was as effective as independence driving-point residue (EFI-DPR) technique for OSP,wasalso able to indicate the optimal number of sensors.In the last decades, plenty of studies on OSP techniques have been conducted, most of which were based on simple structures(e.g. beams, plates, trusses and shells). For complicate structures like ocean offshore platforms, lots of works need to be conducted.

A method of OSP for platform structures, based on genetic algorithm (GA), GUYAN reduction method and structural subsection technique, is presented in the paper. The simulation analysis is conducted on a platform model to validate the effectiveness and applicability of the proposed method.

2. The OSPALGORITHM

2.1 The optimal method

For offshore platform structures, slave DOFis defined to be the DOF on diagonal and horizontal bracings, of which damages have little impact on the structural dynamic properties. DOFs on vertical bracings are defined as master DOFs, which usually affect the structural mechanical characterssignificantly. Due to economic cost and complicated external environment, DOFs on vertical bracings are chosen as the candidate DOFsin the OSP process.

In order to guarantee the integrity of tested modes, structural subsection techniqueis introduced. According to the number of sensors (NOS) N and the number of vertical bracings (NOVB) M, the model is divided into several sub-regions. The optimal procedure is shown in Fig. 1.

2.2 The theory of the algorithm

GUYAN model reduction can be expressed as shown in Eq. (1):

$$\begin{bmatrix} K_{mm} & K_{ms} \\ K_{sm} & K_{ss} \end{bmatrix} \begin{bmatrix} \Phi_m \\ \Phi_s \end{bmatrix} = \omega^2 \begin{bmatrix} M_{mm} & 0 \\ 0 & M_{ss} \end{bmatrix} \begin{bmatrix} \Phi_m \\ \Phi_s \end{bmatrix} \quad (1)$$

where$\Phi_m$is the mode information of the master DOFs; K_{mm}, M_{mm} is the stiffness and mass matrix of master DOFs; $\Phi_s$is the mode of the slave DOFs; K_{ss}, M_{ss} is the stiffness and mass matrix of slave DOFs, $M_{ss}\approx 0$.

Then, the characteristic equation can be simplified as Eq. (2):

$$(K_{mm} - K_{ms} K_{ss}^{-1} K_{sm}) \Phi_m = \omega^2 M_m \Phi_m \quad (2)$$

The whole mode Φ can be formulated by the master DOFs' mode:

$$\Phi = \begin{bmatrix} \Phi_m \\ \Phi_s \end{bmatrix} = \begin{bmatrix} I \\ -K_{ss}^{-1}K_{sm} \end{bmatrix} \Phi_m \tag{3}$$

It is seen that, in GUYAN reduction process, locations of master DOFs determine the accuracy of modal analysis based on GUYAN reduction. Therefore, treating OSP process as the procedure of choosing master DOFs for modal analysis is reasonable.

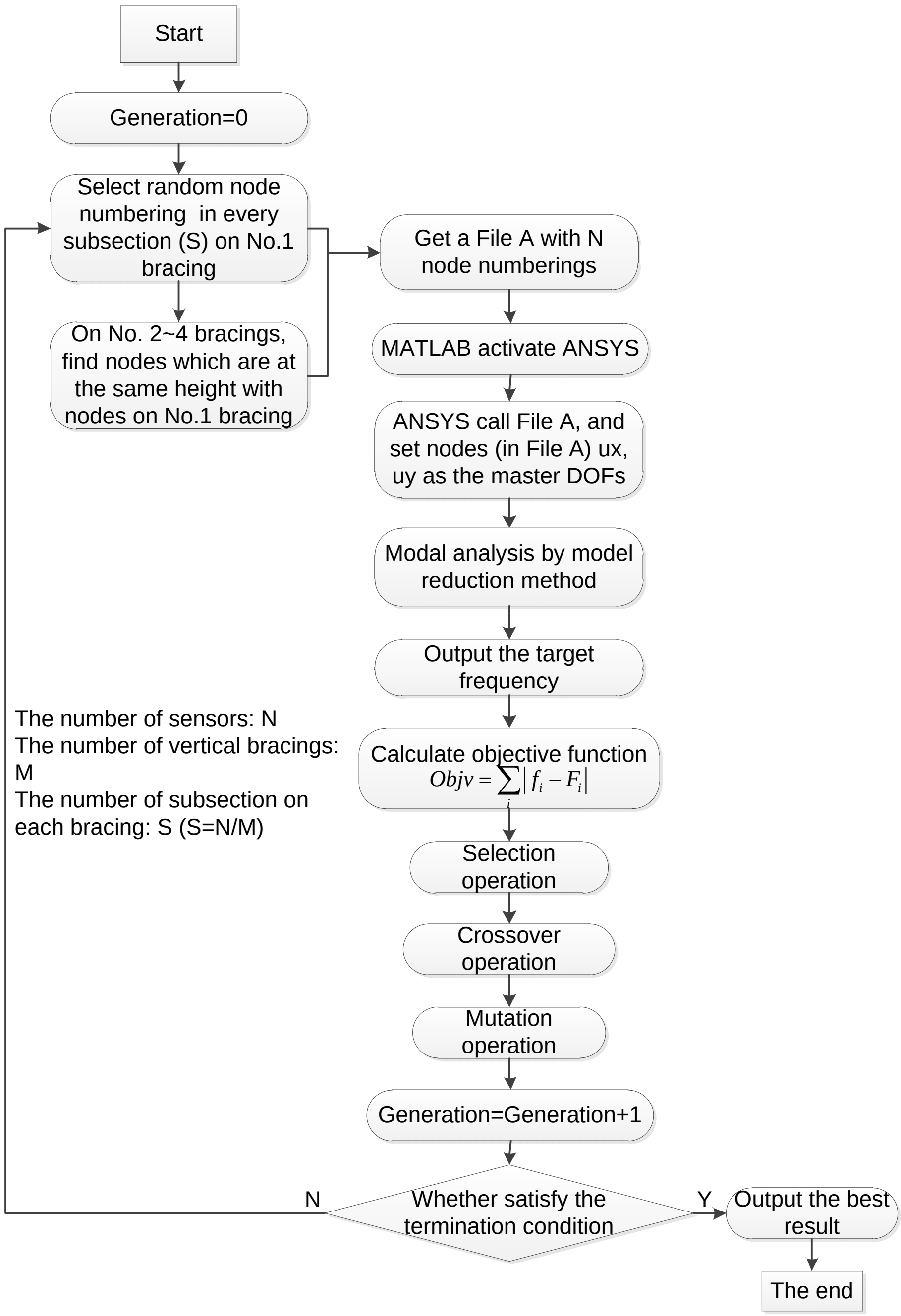


Fig. 1 The optimal procedure

3. NUMERICAL SIMULATION

3.1 Model description

The FEMmodel ofscaled platform at the height of 1.56m is as shown in Fig.2. The model included 12 diagonal bracings, 12 horizontal bracings, 4 vertical bracings and a deck plate. Diagonal bracings and horizontal bracings used25×25×3mm angle iron material, while, vertical bracings adopted40×40×4mm angle iron material. The deck platewith dimension of 0.5×0.5×0.008mwas divided into 784 SHELL63 elements. The whole model was made of stainless steel with Young's modulus of 195 GPa, Poisson ratio of 0.30, and mass density of 7850 kg/m^3. The structure was fixed on the ground by 4 bottom supportswith dimension of 0.25×0.25×0.014m.

The frequency information and vibration modes of the first sixorders, obtained from FEM analysis, are listed in Table 1. The 1^{th}, 2^{nd}, 3^{rd} and 6^{th} modeswereglobal vibration modes, yet, the 4^{th} and 5^{th} modeswere the local vibration modes. So the 1^{th}, 2^{nd}, 3^{rd} and 6^{th} modeswere chosen as the objective modes.

Table 1 First six orders of modes

Mode order	Frequency（Hz）	Vibration mode
1^{th}	27.191	First flexible（X -45°direction）
2^{nd}	27.343	First flexible（X +45°direction）
3^{rd}	42.214	First torsion
4^{th}	71.968	Deck plate vibration
5^{th}	95.910	Slave bracings vibration
6^{th}	102.88	Coupling vibration

3.2 Simulation analysis

Circular strategy was added to the optimal GA, through setting NOS as loop variable. The cycle genetic algorithm programme is made by MATLAB, increasingfour sensors in each cycle. The optimal NOSwas determined bythe NOS vs.minimal objective function (ObjV) (Eq. (4))values curve obtained by cycle calculations.

As described in Section 2.1, all nodes on the vertical bracings were set as candidate nodes, of which $U_x$and $U_y$weredefined as master DOFs. Through GA,an optimal group of master DOFs, which madeObjV smallest,were determined.

$$Objv = \sqrt{\sum_{i=1}^{2,3,6} \left| f_i - F_i \right|} \tag{4}$$

where, f_i, $F_i$is the *i-th* orderfrequency calculated by mode reduction method and Block-Lanczos method respectively; F_i is set as the standard frequency.

The NOS vs.minimal ObjVvalues curve is shown in Fig. 3. It is seen that as NOS increases, the minimalObjV value decreases. When the NOS is 24, the ObjVvalue almost stays the same as the NOS increases. Therefore, the optimal NOS is set as 24, with locations shown in Fig. 4. From Fig. 4, it is seen that the distribution of sensorsis fairly uniform along the vertical direction.

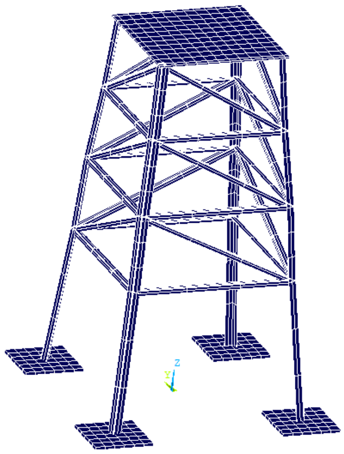


Fig. 2 FEM model of platform

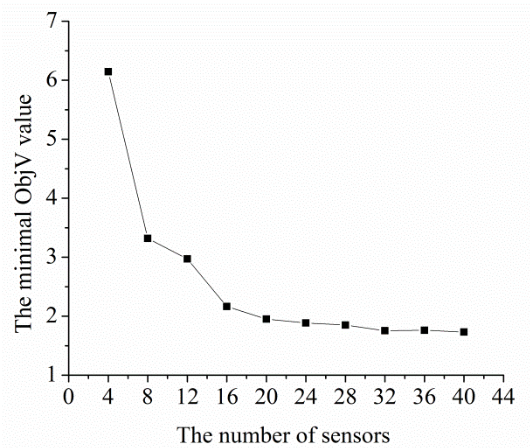


Fig. 3 NOS ~ the minimal ObjVvalue curve

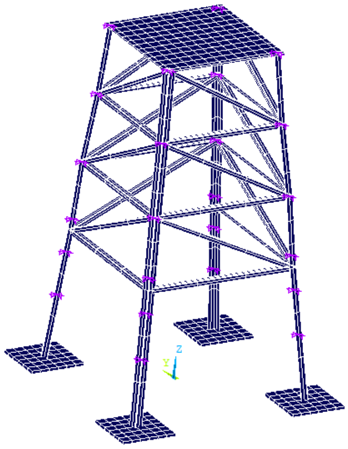


Fig. 4 Optimal sensor locations (N=24)

3.3 Method evaluation

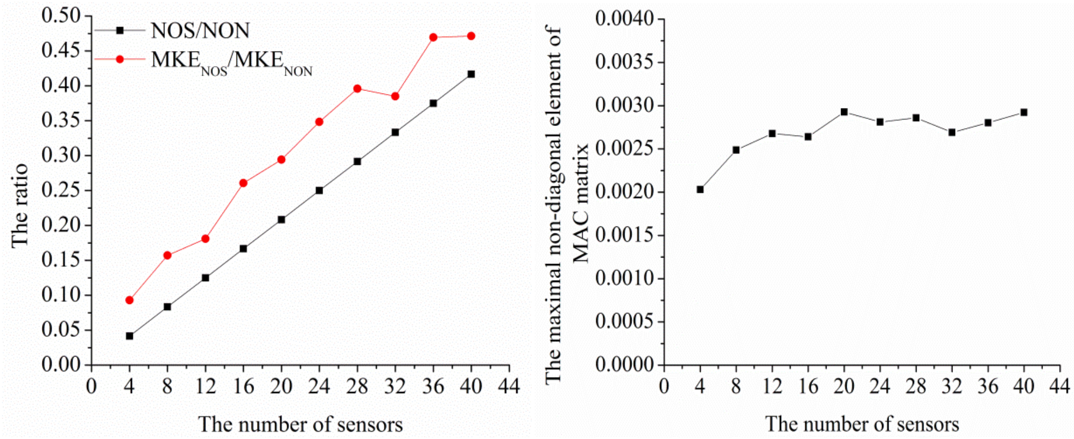
In order to validate quantitatively the optimal sensor locations,the modalkinetic energy (MKE) (Eq. (5)) and the maximal non-diagonal element of MAC matrix (Eq. (6)) wereadopted, with results shown as Fig. 5 (a) and (b)respectively.

$$E=\sum_{i=1}^{N}\sum_{k=1}^{K}E_{ik}=\sum_{i=1}^{N}\sum_{k=1}^{K}(\Phi_{ik}\sum_{j}M_{ij}\Phi_{jk}) \tag{5}$$

where E_{ik} is MKE of the *i-th* DOF in the *k-th* target mode;$\Phi_{ik}$is the *i-th*coefficient in the *k-th* mode;Φ_{jk} is the *j-th*coefficient in the *k-th* mode, $M_{ij}$is the term in the*i-th* row and *j-th* column of the FEM mass matrix; N=48; K=1,2,3,6.

$$MAC_{ij}=\frac{\left(\Phi_i^T\times\Phi_j\right)}{\sqrt{\left(\Phi_i^T\times\Phi_i\right)\times\left(\Phi_j^T\times\Phi_j\right)}} \tag{6}$$

where$\Phi_i$and Φ_j are the *i*-th and *j*-th modal vector respectively.



(a) (b)

Fig. 5 Method evalution: (a) NOS ~ the ratios information; (b) NOS ~ the maximal non-diagonal element of MAC matirx

The number of nodes (NON) on the vertical bracings, of which the MKE sum was defined as MKE_{NON}, was 96. The ratio of NOS to NON was NOS/NON, meanwhile, the ratio of sensors' MKE sum to total MKE sumwas set as MKE_{NOS}/MKE_{NON}, as shown in Fig. 5(a).

It can be seen that, at the same NOS,the ratio of MKE,MKE_{NOS}/MKE_{NON}, is higher than the ratio of number, NOS/NON, demonstrating that the optimal sensor locations got by GUYAN reduction method have relatively high vibration energy.As is known to all, in GUYAN reduction process, DOFs having high mass and low stiffness areusually chosen as the master DOFs.It demonstrates that the master DOFs have high vibration energy, which benefits for improving signal noise ratio (SNR). Therefore, OSP got by GUYAN reduction method usually have high vibration energy.

Besides, the maximal non-diagonal element of MAC matrix (Fig. 5(b))also meets the requirement proposed in reference (Carne 1995).

4. CONCLUSION

By analyzing the vibration characters of offshore platform structures, an effective OSP method, based on GA, GUYAN reduction method and structural subsection technique, is presented. Numerical analysis has been conducted to yield following conclusions:

1. The optimal locations got by the method have high vibration energy.
2. The mode integrity is guaranteed effectively by the structural subsection technique.
3. The method doesn't need any complicated operations (e.g. complicated programs, lots of operation steps), which impliesconvenience in engineering applications.

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