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Structural model updating of an offshore platform using the cross model cross mode method: An experimental study

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ABSTRACT

The present paper validates a recently developed cross model cross mode (CMCM) model updating method for an offshore platform structure by using experimental data. First, the CMCM model updating method, where a modal expansion technique is used to overcome the spatial incompleteness problem, is briefly summarized. One particularly novel development is that a simplified added-mass model of the surrounding water is proposed, and the updating coefficients are directly incorporated into the CMCM procedure. Next, a small-scale offshore platform is fabricated. Model tests are experimentally conducted for four cases, including two cases in air with and without deck mass and two cases in water under hammer and wave excitation. Finally, the first three orders of modal parameters are identified. The CMCM method in combination with the modal expansion technique is used to update the structural models. The results demonstrate that the present method is effective for the model updating of offshore platform structures with a minimal amount of lower-order, spatially incomplete experimental modal data.

1. Introduction

The increasing depth of water in offshore oil exploitation has complicated efforts to inspect oil platforms visually for structural damage. This problem has led to the development of simpler monitoring techniques for damage identification by inspecting changes in the modal characteristics of offshore structures. Such monitoring techniques have been under development since the early 1970s (Viero and Roitman, 1999). Recently, a significant amount of research has been conducted on damage detection using the modal information of a structure and many methods have been proposed (Doebling et al., 1998; Fan and Qiao, 2011). For most of these methods, an accurate theoretical structural model, which is usually a finite element (FE) model, is often required as a reference for changes in modal characteristics. Any uncertainty associated with the modeling would cause structural damage to be incorrectly located or estimated. Thus, the baseline model must to be verified and, if necessary, updated for further applications. In certain cases, model updating itself is also a damage detection procedure, with updating parameters indicating the presence and location of damage (Li et al., 2008), and baseline model updating is required to eliminate modeling errors.

Structural model updating corrects an analytical finite element model using test data to produce a refined model that better predicts the dynamic behavior of a given structure. Many papers and even a complete book (Friswell and Mottershead, 1995) have been devoted to the subject. The existing prediction methods can be broadly classified into two groups (Hu et al., 2007): (i) direct matrix methods and (ii) indirect physical property adjustment methods. Direct matrix methods are generally non-iterative methods, all of which are based on computing changes made directly to the mass and stiffness matrices. Such changes may succeed in generating a modified model, but these updated models cannot be interpreted in a physical manner. By contrast, indirect physical property adjustment methods seek to find correction factors for each finite element or for each design parameter relating to each finite element, which more closely approximate physically realizable quantities. However, these methods are all iterative, indicating that they require greater computational effort. Adopting an approach that is completely different from the traditional methods, Hu and Li (2007) and Hu et al. (2007) recently developed the cross model cross mode (CMCM) model updating method for the simultaneous updating of the stiffness, mass and damping matrices. This method is a non-iterative method and therefore highly cost-effective in computational time and also has the advantage of preserving the initial model configuration and physical connectivity of the updated model. By applying model reduction or modal expansion schemes, the method can also be used with incompletely measured data. The CMCM method has been investigated and demonstrated to be effective in numerical studies

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(Hu et al., 2007; Li et al., 2008). However, no experimental study has yet been applied to validate this method's practicability.

Despite these research efforts, many problems related to structural model updating still warrant further investigation. Several of these problems involve selecting updating parameters, boundary conditions and solutions of updating equations in the presence of noise pollution and the spatial incompleteness of measurements. Another problem is estimating the added mass of offshore structures. It is widely known that added mass has a significant effect on the natural frequency of offshore platform structures. Therefore, many investigators have evaluated added mass using the classical theory of hydrodynamics for rigid-body vibration. Using this concept, these investigators have obtained accurate results for the fundamental frequency of vibration only. Maheri and Severn's (1992) research on the added mass of cylinders vibrating in water demonstrated that the added mass of the first mode is equal to the fluid mass displaced by the cylinder, but this relation does not hold for higher modes. Han (1996) proposed a simple added-mass model for a cantilevered cylinder vibrating in water and proposed a formula for estimating the natural frequencies of the cylinder. Yadykin et al. (2003) reviewed investigations of added mass and found that added mass decreases as the vibration mode increases and decreases as the aspect ratio decreases. Li et al. (2011) reported that the mode shape of a structure determines the added mass, and the added mass also affects the mode shape. Although the added mass of flexible structures has drawn considerable attention, no appropriate added-mass models have been developed for finite element modeling.

In this paper, we present an experimental study of structural model updating of an offshore platform using the CMCM method, which represents the first experimental validation of this approach. The paper is structured as follows. In Section 2, the CMCM model updating method is briefly summarized, and a modal expansion technique is used to overcome the spatial incompleteness problem. Furthermore, a simplified added-mass model of the surrounding water is proposed, through which the added-mass coefficients can be easily estimated by the CMCM procedure. A detailed description of the physical experiment is presented in Section 3, in which model tests are conducted under different cases, including two cases in air with and without deck mass and two cases in water under hammer and wave excitation. Section 4 reports and discusses the experimental results of structural model updating by using the identified lower order of spatially incomplete modal data. Finally, concluding remarks are presented in Section 5.

2. Cross model cross mode method for model updating

2.1. CMCM method

The free vibration of an undamped dynamic system can be described by the following equation:

$$M\ddot{\mathbf{x}}+\mathbf{K}\mathbf{x}=0 \tag{1}$$

where $\mathbf{M}$ and $\mathbf{K}$ are the mass and stiffness matrices of the structure, respectively, which are obtained from a finite element (FE) model. The eigen-analysis for the structure is expressed as

$$\mathbf{K}\Phi_i=\lambda_i\mathbf{M}\Phi_i \tag{2}$$

where λ_i and Φ_i denote the ith eigenvalue and eigenvector, respectively. This paper is intended to update the stiffness and mass matrices based on modal measurements, including those of a few mode shapes and their corresponding frequencies.

Assuming that the stiffness matrix $\mathbf{K}^*$ and mass matrix $\mathbf{M}^*$ of the actual (experimental) model are modifications of $\mathbf{K}$ and $\mathbf{M}$, these matrices can be formulated as

$$\mathbf{K}^*=\mathbf{K}+\sum_{n=1}^{N_K}\alpha_n\mathbf{K}_n \tag{3}$$

$$\mathbf{M}^*=\mathbf{M}+\sum_{n=1}^{N_M}\beta_n\mathbf{M}_n \tag{4}$$

where the matrices $\mathbf{K}_n$ and $\mathbf{M}_n$ are the stiffness and mass matrices of the nth substructure. N_K and N_M are, respectively, the numbers of substructure stiffness and mass matrices to be updated. α_n and β_n are the corresponding correction coefficients, which could be chosen as updating parameters. When every element of the structure is required to be corrected, $\mathbf{K}_n$ and $\mathbf{M}_n$ are the stiffness and mass matrices corresponding to the nth element, respectively; N_K and N_M are both equal to the number of the elements N_e. Throughout this paper, the superscript "*" is used to denote the model associated with measured data, whereas terms without a superscript denote the analytical baseline model.

The jth eigenvalue and eigenvector associated with $\mathbf{K}^*$ and $\mathbf{M}^*$ are expressed as follows:

$$\mathbf{K}^*\Phi_j^*=\lambda_j^*\mathbf{M}^*\Phi_j^* \tag{5}$$

where λ_j^* and Φ_j^* are the jth eigenvalue and eigenvector, respectively associated with the actual structure, which are obtained from modal tests.

Premultiplying Eq. (5) by Φ_i^T (the transpose of Φ_i) yields

$$(\Phi_i)^T\mathbf{K}^*\Phi_j^*=\lambda_j^*(\Phi_i)^T\mathbf{M}^*\Phi_j^* \tag{6}$$

Substituting Eqs. (3) and (4) into Eq. (6) yields

$$\sum_{n=1}^{N_K}\alpha_nC_{n,ij}^{\dagger}+\sum_{n=1}^{N_M}\beta_nE_{n,ij}^{\dagger}=f_{ij}^{\dagger} \tag{7}$$

where $C_{n,ij}^{\dagger}=(\Phi_i)^{\mathrm{T}}\mathbf{K}_n\Phi_j^*$, $E_{n,ij}^{\dagger}=-\lambda_j^*(\Phi_i)^{\mathrm{T}}\mathbf{M}_n\Phi_j^*$ and $f_{ij}^{\dagger}=-(\Phi_i)^{\mathrm{T}}\mathbf{K}\Phi_j^*+\lambda_j^*(\Phi_i)^{\mathrm{T}}\mathbf{M}\Phi_j^*$. After using a new index "m" to replace "ij", Eq. (7) yields

$$\sum_{n=1}^{N_K}\alpha_nC_{n,m}^{\dagger}+\sum_{n=1}^{N_M}\beta_nE_{n,m}^{\dagger}=f_m^{\dagger} \tag{8}$$

when N_i modes are taken from the FE model and N_j modes are measured from the corresponding actual structure, then $N_m=N_i\times N_j$ CMCM equations can be formed from Eq. (8). One of these equations can be expressed in a matrix form as follows:

$$C\boldsymbol{\alpha}+E\boldsymbol{\beta}=\mathbf{f} \tag{9}$$

where $\mathbf{C}$ and $\mathbf{E}$ are $N_m\times N_K$ and $N_m\times N_M$ matrices, respectively; $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ are column vectors of size N_K and N_M, respectively; and $\mathbf{f}$ is a column vector of size N_m. Furthermore, one can rewrite Eq. (9) as

$$\mathbf{Ax}=\mathbf{f} \tag{10}$$

where

$$\mathbf{A}=\begin{bmatrix}\mathbf{C} & \mathbf{E}\end{bmatrix} \tag{11}$$

and

$$\mathbf{x}=\begin{Bmatrix}\boldsymbol{\alpha}\\ \boldsymbol{\beta}\end{Bmatrix} \tag{12}$$

One can apply a singular value decomposition (SVD) approach to solve for $\mathbf{x}$ when the system is either under-determined, over-determined, or mixed-determined.

$$\mathbf{x}=\mathbf{A}^{-g}\mathbf{f} \tag{13}$$

where $\mathbf{A}^{-g}$ is the generalized inverse of matrix $\mathbf{A}$.