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MODAL ANALYSIS OF AN OFFSHORE STRUCTURE

MODEL FOR DAMAGE EVALUATION

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ABSTRACT

An overview of damage evaluation of offshore structures using vibration measurements is presented. The modal analysis theory is reviewed and different modal testing methods are discussed. A scaled typical jack type laboratory model was constructed and was submerged in a water tank. An electro-magnetic shaker was fixed at the top of the structural model to cause the dynamic excitation on the structure. Twenty-four accelerometers attached at each corner of the structure records the response of the structure. A data acquisition and control system controls the tests and process the acceleration responses to give system frequency response functions of the model. A multiple degree of freedom curve fitting technique is used to extract the structural modal parameters. Twenty-four modes and eighteen modes when the tank was empty and when the tank was filled with water were extracted, respectively. To study the influence of damage on the structural dynamic characteristics, a damage was inflicted on the structure. More modes were extracted due to the inflicted damage. The modal shapes were identified with respect to those of undamaged structure. The modal assurance criteria was used for the identification of modes.

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CHAPTER 1

INTRODUCTION

Offshore structures are routinely subjected to extreme environmental loadings. Therefore, there is a high probability of structural failure. The importance of the detection of damage in offshore platforms is for safety and economic reasons. If the structural damage can be detected at the early stage, and with the development of undersea welding technology, the damage can be repaired long before the overall structural integrity is affected. Generally, the inspection of offshore structures is performed by underwater inspection and by ultrasonics. These techniques are very expensive and may not be accurate. As offshore platforms are erected in progressively deeper water, the problem of undersea inspection becomes more difficult. The use of divers is generally hampered by poor visibility, poor lighting and hazardous conditions. These obstacles worsen rapidly with the increase in depth. In addition, marine growth and corrosion may conceal structural defects.

Using vibration measurements to detect the damage of offshore structures is a new technique developed in recent years. This technique provides a way to confirm possible structural damage, including damage below the walter lines which is often difficult to detect. The main advantage that

an effective vibrational method may offer over other inspection methods is that once a system is installed, underwater diving may not be as routinely required.

1.1 Background Of Vibrational Damage Evaluation Of Offshore Structures

Using vibration measurements to evaluate the structural damage is based on the principle that any structure has its own modal parameters (natural frequencies, modal shapes and damping ratios). These modal parameters depend on the mass, stiffness and geometry of the structure, but are generally independent of the excitation. If a structure is damaged, the stiffness and mass of that structure will change [1-4]. The changes of stiffness and mass will cause changes of structural dynamic characteristics, therefore damage can be detected from the changes of the structural modal parameters.

Offshore structures have been frequent subjects of vibrational damage evaluation studies [5-13]. In most of these studies, structural damages have been assessed from changes in the vibrational characteristics. Vandiver[11] was among the first researchers to investigate the detection of structural failure on fixed platforms by measurements of the dynamic response. He used statistical energy analysis to interpret results of a computer model. Loland and Dodds [12] reviewed and discussed experiences in developing and operating

structural monitoring system. Other investigators such as Wojnarowski et al [8] and Stevenson and Rubin [13] have presented descriptive papers on the subject. Kenley and Dodds [6] showed that complete severance of a member can be detected from vibration measurements. Crohas and Lepert [5] field tested a damage-detection monitoring system by comparing transfer functions at specific braces of a platform before and after damage. They concluded that the method can detect and locate a flooded or damaged brace.

This review has revealed a significant variation in experimental approaches and procedures. In experimental methods, the approaches used by Crohas and Lepert [5] and Nataraja [7] consisted of mechanical excitations of the platform to generate frequency response functions. The method used by Yang and co-workers [9,10] relied on the random forces of wind, waves and currents to provide the excitation. In all cases the motion was sensed using accelerometers.

The analytical procedures to analyze the transduced signal were equally varied. These procedures included the Random Decrement method [9,10], Fast Fourier Transform [5], spectral energy analysis [6,11] and engineering judgement [8]. In each case, the analytical procedure yields a vibrational signature of the damaged structure that is compared to either the signature of undamaged platform [5,7,9,10] or to the vibrational characteristics of a finite element model [6,8].

Each method makes a different claim regarding the effectiveness and practicality of the structural integrity technique. For example, Nataraja [7] concluded that such technique comprising of accelerometers can only detect global changes but cannot locate the damage. Yang and co-workers [9,10] claimed that the Random Decrement technique was able to detect damage and non-damaged situations. Crohas and Lepert [5] concluded that their detection technique has considerable capabilities for integrity monitoring and design of offshore platforms.

It can be noted from the above review that there are broad variations on the damage prediction techniques. What's needed is a sound theoretical basis for structural damage evaluation that provides changes in the dynamic properties of a structure as a function of related changes in the mass, damping and stiffness of that structure. This deterministic formulation was initially reported by Stubbs [14] and Stubbs and Osegueda [15]. The formulation relates the changes of eigenvalues to changes of the stiffness properties of locations of a structure, it is generally called eigenvalue sensitivity detection method. This formulation has been analytically verified and successfully used to detect inflicted damage on Cantilever beams [16], two-dimensional trusses [17], three-dimensional laboratory Cantilever truss with six bays [18], and offshore platforms [19,20].

1.2 Problem Statement

The major problem of using the sensitivity detection method to evaluate the damage of offshore structures is that the structures are massive, and that shakers and other natural methods of excitation fail to excite but few modes. The number of possible damage locations will be significantly larger than the number of experimentally extracted eigenfrequencies. Since the variables of possible damage locations is larger, the system of equations relating the frequency changes to damage is underdetermined. One solution to solve this problem is to use least squares technique to give the best estimates and to place constrains on the damaged variables. For example, the stiffness changes at particular locations must be negative, if it is positive, then variables to be zero. This is because the increase of stiffness in real structure is almost impossible. Although these techniques work well to detect the damage to some simple structure, they may fail to provide the damage location for complex structures.

To overcome the above limitation, the formulation was expanded by Osegueda [21]. This expanded formulation includes relationships between the changes of modal shapes to structural damage as a function of location.

This study is a small part of a research project to investigate detection of damage in offshore structure. The

thrust of the project consists of a damage evaluation a scaled model of an offshore platform.

1.3 Objectives

The objectives of this study are:

1) To study the modal analysis theory and to report on a multiple-degree-of-freedom curve-fitting techniques that are suitable to dynamically test an offshore structure model.

2) To provide an overview of existing damage detection methods.

3) To provide a full description of the offshore structural model to be tested.

4) To perform modal analysis test on the structural model and to verify the implementation of the modal analysis theory and the MODF curve fits.

5) To study the influence of an inflicted damage on the structural dynamic characteristics.

1.4 Scope Of Study

This study is limited to an experimental offshore platform submerged in a watertank. Current and wave influence on the modal testing is not considered in this work. In the modal analysis, the structure was assumed to be linear and time invariant. Damage studies were limited to analyze the influence of an inflicted damage on the structure dynamic

characteristics. The damping was measured but ignored during the analyses.

CHAPTER 2

BACKGROUND OF MODAL ANALYSIS

This chapter reviews the basic theory of modal analysis. Two modal testing methods are described, one is a frequency domain method and the other is a time domain. This chapter also discusses a multiple degree of freedom curve-fitting technique which is used to extract modal parameters. The discussion is based on information collected from references [22-31]. The modal assurance criterion to identify and compare extracted mode shapes is also discussed in this chapter.

2.1 Introduction

Modal analysis is a very popular and widely accepted tool for analyzing the dynamic behavior of various kinds of structures and mechanical systems. Modal analysis can be classified into analytical modal analysis and experimental modal analysis. The aim of analytical modal analysis is to establish a mathematical model that represents the relationship between the dynamic excitation and the response of the structure. This mathematical model is known as the system transfer function of the structure.

Experimental modal analysis (also called modal testing) is normally referred to the experimental determination of

modal parameters of a structural system. In this chapter, the modal testing theory is introduced, and a theoretical expression of transfer function of a N-degree-of-freedom vibration system is deduced. If in the frequency domain, the system transfer function is also called frequency response function. This response function can be measured using modal testing theory. The dynamic characteristics of the structure, which include natural frequencies, modal shapes, modal masses, modal stiffness, and damping ratios, can be extracted from the frequency response functions by using curve-fitting techniques.

2.2 System Transfer Function

From vibration theory, the governing equation of motion of a N-degree-of-freedom elastic structural system can be expressed by the following differential equation [22]:

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{f(t)\} \tag{2.1}$$

Where [M], [C] and [K] are the mass, damping, and stiffness matrices, respectively, and {f(t)} is the dynamic force matrix.

Taking the Laplace transform of equation (2.1), so that

$$\mathcal{L}\left[\ [M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\}\ \right] = \mathcal{L}\{f(t)\} \tag{2.2}$$

and assuming that the initial displacement and velocity of the system are zero, then the following arises:

$$([M]S^2 + [C]S + [K])\{X(s)\} = \{F(s)\} \tag{2.3}$$

Where, X(s) and F(s) are the Laplace transforms of the displacement and the force, respectively, and $S=\sigma+j\omega$.

Equation (2.3) can be expressed in compact form as follows:

$$[Z(s)]\{X(s)\} = \{F(s)\} \tag{2.4}$$

Where $[Z(s)] = [M]S^2+[C]S+[K]$, and is called the impedance matrix of the system in the S-domain. For a restrained system, [Z(s)] is a non-singular symmetric matrix. Thus, its inverse always exists. Hence, the Laplace transform of the displacements is given by[22]:

$$\{X(s)\} = [Z(s)]^{-1}\{F(s)\} = [H(s)]\{F(s)\} \tag{2.5}$$

Where, H(s) is the transfer function and is given by:

$$[H(s)] = [Z(s)]^{-1} = \frac{adj[Z(s)]}{\det[Z(s)]} = \frac{N(s)}{D(s)} \tag{2.6}$$

In the above equation, D(s) and N(s) are the determinant and the adjoint of the impedance matrix, respectively. The determinant D(s) can be expressed as a polynomial expression as follows:

$$D(s) = b_0 + b_1S + b_2S^2 + \cdots + b_{2N}S^{2N} \tag{2.7}$$

The matrix [N(s)] is of order N by N and is symmetric. Its elements $N_{ij}(s)$ can also be expressed as polynomial expressions of the form:

$$N_{ij} = a_0 + a_1 S + a_2 S^2 + \cdots + a^{2N-2} S^{2N-2} \qquad (2.8)$$

Hence, the coefficients of the transfer function $H_{ij}(s)$ can be expressed as follows:

$$H_{ij}(s) = \frac{N_{ij}}{D(s)} = \frac{a_0 + a_1 S + a_2 S^2 + \cdots + a_{2N-2} S^{2N-2}}{b_0 + b_1 S + b_2 S^2 + \cdots + b_{2N-2} S^{2N}} \qquad (2.9)$$

Because the determinant D(s) is a polynomial with real coefficient, a value of D(s)=0 will produce N pairs of conjugate roots. Thus, equation (2.9) can be written as follows[23]:

$$H_{ij}(S) = \frac{N_{ij}(S)}{\prod_{r=1}^{N} (S-S_r)(S-S_r^*)} = \sum_{r=1}^{N} \left[\frac{A_{ijr}}{S-S_r} + \frac{A_{ijr}^*}{S-S_r^*} \right] \qquad (2.10)$$

Where, S_r and S^*_r form a pair of complex conjugate roots when D(s)=det[Z(s)]=0, A_{ijr} and A^*_{ijr} are the corresponding residues at pole points S_r and S^*_r . The residue can be determined by:

$$A_{ijr} = U_{ijr} + jV_{ijr} = H_{ij}(S)(S-S_r)|_{S=S_r} \qquad (2.11)$$

Letting $S=j\omega$, then equation (2.10) or equation (2.6) turns into the transfer function in the frequency domain.

The system transfer function in the frequency domain can be measured through modal testing. Since the transfer function is an N by N matrix, there are N^2 elements. It can be shown, however, that only one row or one column of the transfer function is needed to completely determine a