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Comparison between Field Test and Numerical Analysis for a Jacket Platform in Bohai Bay, China

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KEY WORDS: Jacket platform, Modal parameters identification, Dynamic testing, Modal analysis, Finite element model, Vibration, Structural health monitoring

ABSTRACT: *This paper presents a comparison between numerical analysis and field test on a real offshore platform in Bohai Bay, China. This platform is a steel jacket offshore platform with vertical piles. The field testing under wave-induced force and wind force etc. was conducted, in order to obtain the dynamic parameters of the structure, including the frequencies of the jacket platform, as well as the corresponding damping ratios and mode shapes. The natural excitation technology (NExT) combined with eigensystem realization algorithm (ERA) and the peak picking (PP) method in frequency domain are carried out for modal parameter identification under operational conditions. The three-dimensional finite element model (FEM) is constructed by ANSYS and an analytical modal analysis is performed to generate modal parameters. The analytical results were compared with experimental results. A good agreement was achieved between the finite element and analysis and field test results. It is further demonstrated that the numerical and experimental modal analysis provide a comprehensive study on the dynamic properties of the jacket platform. According to the analysis results, the modal parameters identification under ambient excitation can calibrate finite element model of the jacket platform structures, or can be used for the structural health monitoring system.*

1. Introduction

The technology of experimental modal analysis has been used extensively in mechanical engineering, civil engineering for the last decades. In the classical modal parameters identification approach, the modal parameters are found by fitting a model to the so-called frequency response function (FRF), a function relating input loading and output response. In fact, large civil engineering structures such as offshore platform, bridges, high-rise buildings suffer various kinds of loading, in many cases, the loading of large structures are not easily measured under operational condition. On the other hand, these structures are difficult to excite artificially. Therefore, the modal parameters identification process will need to only base itself on output response data (Peeters and De Roeck, 1999). The modal parameter identification under ambient excitation could be very useful to calibrate finite element models (FEM) of the building, or can be used for the development of structural health monitoring (SHM), online control technology, and so on. Thus, it is very attractive to develop a technology of modal parameter identification under ambient excitation for the continuous monitoring of civil structures, especially for offshore platforms (Li and Yang, 2004).

In recent years, structural health monitoring of civil structures using dynamic properties of structures has received significant attention by researchers (Hoon et al., 2003). Ambient excitation is the most practical type of excitation for the testing of large civil engineering structures and for an automated, modal based health monitoring system designed to assess the deterioration of offshore platforms (Yang and Li, 2003). Also, an automated health monitoring system for an offshore platform would undoubtedly use ambient excitation so that the data could be taken periodically and possibly remotely, without taking the platforms out of service. This technology is cheap and fast, since equipment for excitation is not needed, less time is spent on testing.

The purpose of this research is to apply the available data identify the modal parameters, and compare with analytical modal analysis of a real jacket platform. The modal identification of the jacket platform has been done through ambient vibration measurements. It has been shown how the modal parameters can be extracted from ambient vibration

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data only by using the peak picking method and the natural excitation technique(NExT). The natural excitation technique (NExT) was applied in conjunction with the eigensystem realization algorithm to identify structural modal parameters (natural frequency, damping ratio, mode shape), with limited acceleration information. Analytical work involves the development and modal analysis of a three-dimensional finite element model. Results of the FEM modal analysis are compared with those obtained from the field experimental modal analysis.

The offshore platform addressed in this paper located at a mean water depth of 11.2 m in Bohai Bay, China. It consists of two decks and four tubular piles penetrating the seabed and a jacket with four main legs which are revised from the temporarily used piling facilities (Huang et al., 2002). Fig. 1 is the picture of the jacket platform configuration.

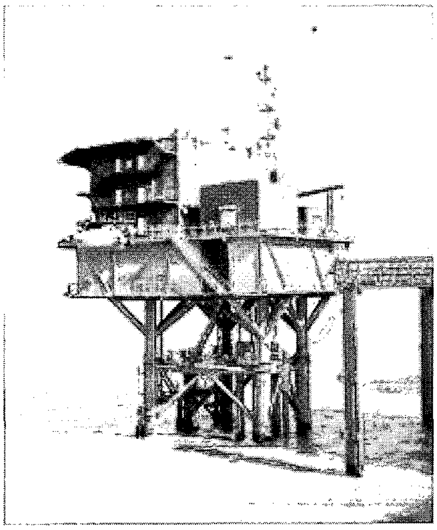


Fig. 1 Jacket platform configuration

2. Theoretical Aspects

As we all know, the ambient excitation are not measurable, so the structural modal parameters can only be extracted from output response data. The first is the very simple peak picking method (PP). It has some theoretical drawbacks, but it is very practical: the method is very fast and can be used on site allowing a quality check of the acquired data. The second method is the natural excitation technique (NExT).

2.1 Acquiring free response data

James et al.(1993) showed that the matrix of cross-correlation functions between the responses of the structure and a response selected to be the reference response is a solution to the homogeneous equation of motion. We refer to this step as application of natural excitation technique (NExT).

Consider the equation of motion for an N degree of freedom classically damped linear structure:

$$[M]\{\ddot{x}(t)\}+[C]\{\dot{x}(t)\}+[K]\{x(t)\}=\{f(t)\} \tag{1}$$

where $[M]$, $[C]$ and $[K]$ are the mass, damping, and stiffness matrices, respectively, $\{\ddot{x}(t)\}$, $\{\dot{x}(t)\}$, $\{x(t)\}$ is the vector of acceleration, velocity and displacements, $\{f(t)\}$ is the vector of forces acting on the structure.

For stationary force inputs, the correlation function between two measured displacement responses can be shown to be:

$$R_{mn}(\tau)=\sum_{r=1}^{N}\frac{\Phi_{mr}G_{nr}}{m_r\omega_{dr}}\exp(-\xi_r\omega_{nr}\tau)\sin(\omega_{dr}\tau+\theta_r) \tag{2}$$

where Φ_{mr} is the matrix of mode shapes, G_{nr} is a constant which corresponds with reference point and mode shapes number, ξ_r, ω_{nr} and ω_{dr} are the damping ratio, natural frequency and damped frequency of the r^{th} mode. The free response solution of Eq. (1) for some initial conditions is shown to be:

$$X_{ml}(t)=\sum_{r=1}^{N}\frac{\Phi_{mr}\Phi_{lr}}{m_r\omega_{dr}}\exp(-\xi_r\omega_{nr}t)\sin(\omega_{dr}t) \tag{3}$$

Note that the modes of the acceleration responses are identical to those of the displacements, so the acceleration responses can be used as well. The cross-correlation function Eq. (2) is a sum of decaying sinusoids of the same form as the impulse response function in Eq. (3). So the similarity allows the use of time-domain modal parameter identification such as eigensystem realization algorithm (ERA).

To implement this method, one of the responses is identified as the reference signal $x(t)$ the cross spectral density functions between the reference signal and each of the response signals are obtained, and an inverse fast Fourier transform is performed to determine the cross correlation functions. The reference channel should be selected such that all of the modes are observed in the responses at that location. If the reference channel location corresponds to a node of one of the modes, that mode will not be observed. This method allows the cross spectral density functions to be averaged over a number of samples. Windowing should be used to minimize the effects of leakage (Pappa et al., 1993).

2.2 Eigensystem realization algorithm (ERA)

Once the time domain free response data is obtained, there are numerous techniques available for identifying the modal parameters, such as Ibrahim time domain technique (ITD), least squares complex exponential method (LSCE), eigensystem realization algorithm (ERA). Here the ERA (Juang and Pappa, 1985) is adopted because it is quite effective for identification of lightly damped structures and is applicable to multi-input/multi-output systems. The ERA realization finds the linear least squares solution to minimize the error in the shift in the Hankel matrix of system model and the data according to:

$$H_{rs}(k-1)=\begin{bmatrix} y(k) & y(k+1) & \dots & y(k+s-1) \\ y(k+1) & y(k+2) & \dots & y(k+s) \\ \dots & \dots & \dots & \dots \\ y(k+r-1) & y(k+r) & \dots & y(k+r+s-2) \end{bmatrix} \tag{4}$$

where $y(k)$ is the response vector at the k^{th} time step. The parameters s and r correspond to the number of columns and rows (of response vectors) in the matrix. For good, r should be selected to be approximately 10 times the number of modes to be identified, and m should be selected to be approximately 5 times r (Juang and Pappa, 1986). This matrix is evaluated for H(0) and a singular value decomposition is performed as follows:

$$H_{rs}(0)=P_r S_{rs} Q_s^T \tag{5}$$

If the Hankel matrix is formed from the data, then the factors V_r and W_s are obtained from the 0^{th} Hankel matrix according to:

$$V_r=P_r S_{rs}^{0.5}\ ,\ W_s=S_{rs}^{0.5} Q_s^T \tag{6}$$

The model order is selected in principle by examining the numerical rank of $H_{rs}(0)$. From this, the system realization problem is solved by:

$$\begin{aligned} A &= S_{rs}^{0.5} P_r^T H_{rs}(1) Q_s S_{rs}^{-0.5} \\ B &= S_{rs}^{0.5} Q_s^T (1:n_x, 1:m) \\ C &= P_r(1:l, 1:n_x) \end{aligned} \tag{7}$$

where $H_{rs}(1)$ is a matrix of the same form as $H_{rs}(0)$ but its data are shifted in time by one additional sample.

Peterson(1992) discusses the computationally more efficient approach to calculate the factors of Eq. (5) and Eq. (6). By only computing the largest n_x eigenvalues and vectors of the Hankel matrix product, it is possible to determine realizations using very large values of r and s without calculating the entire spectral decomposition.

Transforming the realization into modal coordinate by use of the eigenvalues Z and eigenvector matrix Ψ and A yields

$$A' = \Psi^{-1} A \Psi = Z\ ,\ B' = \Psi^{-1} B,\ \ C' = C\Psi \tag{8}$$

The modal damping rates σ_i and damped modal frequencies ω_i are the real and imaginary parts of the eigenvalues after transformation back to the continuous domain.

$$s_i = \sigma_i \pm j\omega_i = ln(z_i)/\Delta t \tag{9}$$

where Δt is the sampling interval. The modal participation factors and mode shapes are the corresponding rows of B' and columns of C', respectively.

3. Experimental and Numerical Modal Analysis

3.1 Description of ambient vibration testing

Field testing of a jacket platform provides an accurate and reliable description of its current dynamic global characteristics. Compared with forced vibration testing, ambient vibration testing does not affect the production of the jacket platform because it uses the environment forces as excitation. Obviously, this method is less costly than forced vibration testing since no extra equipment is needed to excite the structure.

The platform has a trapezoidal section conductor and four vertical piles, as shown in Fig. 1 and Fig. 2. The pile has a diameter of 1400 mm and a wall thickness varies 34 mm. In order to avoid grouting work on the sea, ring devices are used along the main legs to guide the pile and ensure the load transfer. The level of connection point and the mud line are 7.8 m and 11.2 m respectively.

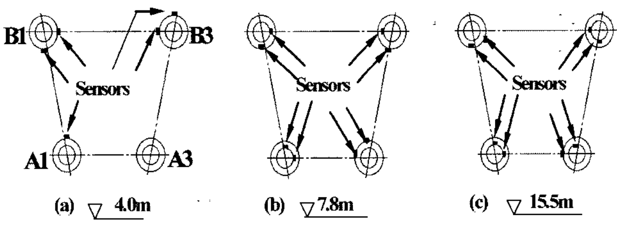


Fig. 2 Location of the accelerometers installation

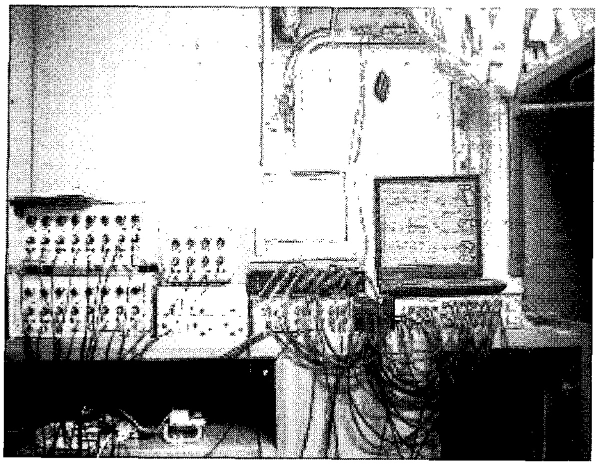


Fig. 3 Acquisition equipment

In this experiment the accelerometers were placed on the X transverse and Y transverse directions, as shown in Fig. 2. In order to identify the mode shapes of the jacket platform, a total of twenty-one of these sensors have been mounted on the plies and the main legs of the platform respectively.

The equipment used for the tests included accelerometers, signal cables, and a 32-channel data acquisition system with signal amplifier and conditioner, as shown in Fig. 3. Accelerometers convert the ambient vibration responses into electrical signal conditioner. The signal conditioner unit is used to improve the quality of the signals by removing unit is used to improve the quality of the signals by removing undesired frequency contents (filtering) and amplifying the signals. The amplified and filtered analog signals are converted to digital data using an A/D converter. The signals converted to digital form are stored on the hard disk of the data acquisition computer, these ar the data for modal parameter identification.

3.2 Finite element analysis

A complete finite element modal analysis of the jacket platform is used as starting point for the experimental survey. This step of the process is very important, because the goal is to limit the number of measurements, and not to do unnecessary, time consuming, installation work. To perform the analytical modal analysis of the jacket platform, a three-dimensional finite element model has been developed using the commercial finite element code, ANSYS. The advantage is that the FEM analysis gives a lot valuable information for creating the best modal test model.

In this paper, a finite element model of an actual offshore platform is shown in Fig. 4. The main structural parameters of the platform are listed in Table 1.

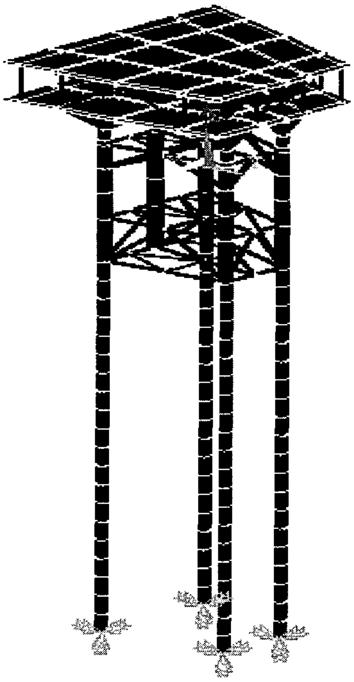


Fig. 4 Three-dimensional finite element model of the jacket platform

Table 1 Parameters of the jacket platform

	Parameters	
Pile	Length (mm)	69300
	Section (mm)	$\phi 1400 \times 34$
Jacket	Jacket leg (mm)	$\phi 1716 \times 20$
Braces	Slant (mm)	$\phi 609 \times 12$
	Horizontal (mm)	$\phi 457 \times 12$
	Horizontal (mm)	$\phi 406 \times 9$

Several special kinds of elements to account for various physics have been utilized, including the simulation of external forces due to ocean wave and current, the buoyant effect of the water, and the element mass containing added mass of the water and the pipe internals, etc. Additionally, the buildings and equipments at the top of the offshore platform are also modeled accordingly.

The modeling of the jacket platform boundary condition is an important issue in the modal analysis. In the current model, the supports are considered fixed in vertical direction and interacted with soil in the horizontal direction for piles. To simulate the actual behavior, the soil-pile interaction is included in the analysis by special spring element.

3.3 Identification of modal parameters

The sampling frequency on site was 200Hz. The ambient vibration measurements were simultaneously recorded for 20 minutes at all channels. The typical acceleration time history records are as shown in Fig. 5.

In order to cut off the noise from the test data and to obtain stationary vibration signals, it is necessary to design a suitable digital filter and to choose the passband and stopband edge frequencies correctly before modes were identified. The cut-off frequency of the anti-aliasing filter was set at 20Hz. The Hanning window has been used in this study.

For the NExT method in frequency domain, the raw cross spectral densities for part measurement data without decimating are shown in Fig. 6

The classical modal parameter identification techniques that involve frequency- or time-domain analysis of dynamic response to forced vibration cannot be directly applied to the output-only vibration data because the input excitations are not measured in the test. Two complementary modal parameter identification techniques are implemented in this work. They are the rather simple peak picking (PP) method in the frequency-domain and the more advanced natural excitation technique (NExT) combined with eigensystem realization algorithm (ERA). The ERA is an analysis of system parameters based on the relationship of the Hankel matrix of Markov parameters to the state-space matrices that define the system.

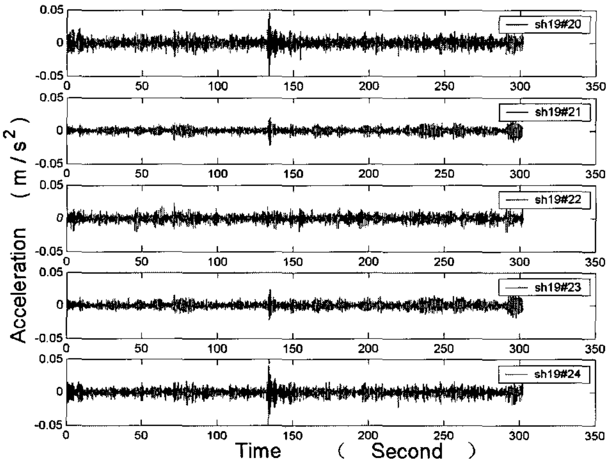


Fig. 5 Raw acceleration time history data

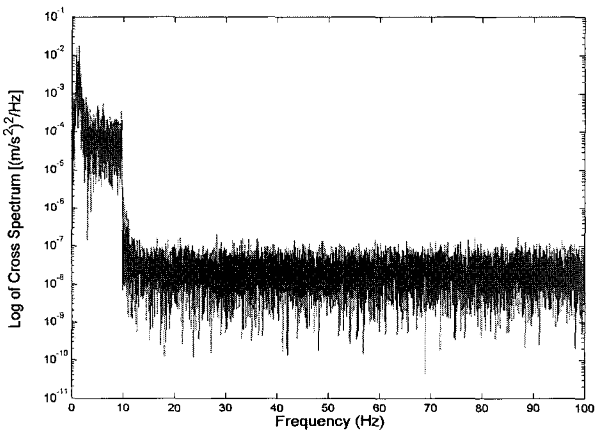


Fig. 6 Raw cross spectral density

The procedures and main results obtained for the ambient vibration tests are described below. The flowchart of ERA is shown in Fig. 7.

The correlation between modal parameters identified from the test and those calculated numerically can be evaluated by comparing the values of modes. Table 2 shows the comparison of the numerically calculated frequencies form the finite element analysis and experimentally identified

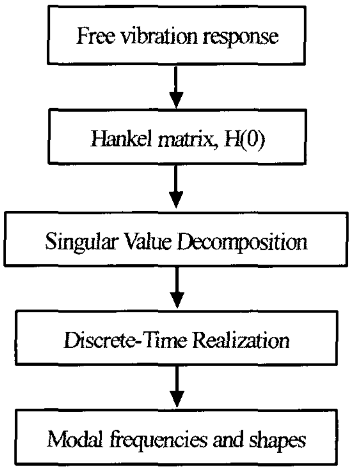
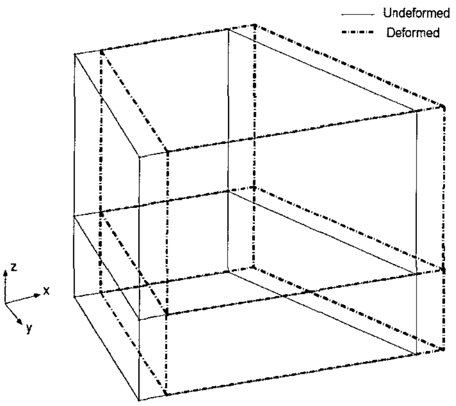


Fig. 7 Flowchart of eigensystem realization algorithm

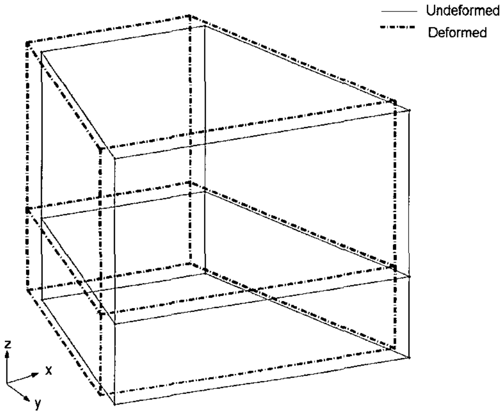
Table 2 Comparison of identified from the test and calculated modal frequencies by FEM

Mode	Analytical frequency [Hz]	NExT & ERA		Peak picking
		Frequency [Hz]	Damping [%]	Frequency [Hz]
1	0.926	0.943	1.3	0.96
2	1.532	1.469	2.1	1.50
3	2.472	2.350	1.6	2.40
4	3.176	3.232	0.4	3.15
5	5.545	5.387	0.2	5.25
6	7.996	7.205	0.1	7.10

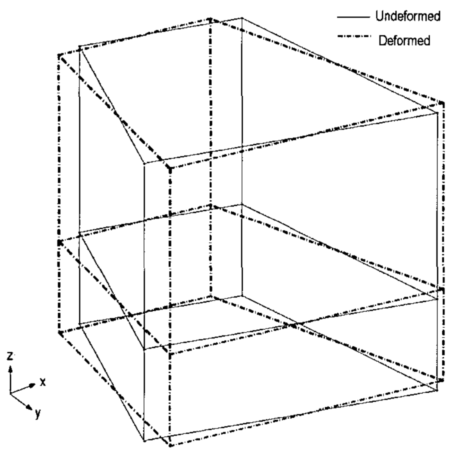
frequencies from the field ambient vibration tests. It is observed that the frequencies agree well between identified with the peak picking, natural excitation technique (NExT) and calculated with FEM.



(a) 1st x-direction transverse mode (0.943Hz)



(b) 2nd y-direction transverse mode (1.469Hz)



(c) 3rd torsional mode (2.35Hz)

Fig. 8 Mode shapes obtained from the field testing data

Vibration mode shapes of the jacket platform have been identified by the NExT combined with ERA. Fig. 8 gives the most dominated extracted mode shapes in the first x-direction transverse, second y-direction transverse and torsion. The obtained results have demonstrated that the ambient vibration response measurements are sufficient enough to identify the most significant modes of the jacket platform. It is also demonstrated that the identified mode shapes by NExT technique is better.

4. Conclusion

In this paper the modal identification of a real jacket platform has been done through ambient vibration measurements. Both the NExT and peak picking analysis of ambient vibration measurements are implemented to identify the jacket platform in Bohai Bay, China. The case study shows that both methods are effective to identify the structural modal parameters. For the PP method, if the mode are well separated, this is no major drawback. The weak point of the PP method is also its strong point: the identification is very fast and it can be used on site to verify the quality of the measurements.

The analytical and experimental modal analysis provides a comprehensive investigation of the dynamic properties of the jacket platform. The analytical modal analysis through three-dimensional finite element modeling gives a detailed description of the modal characteristics, while the experimental modal analysis through the field dynamic tests offers a valuable source of information for validating the finite element model. An ambient vibration testing is a convenient, faster and cheaper way to perform the jacket platform. The output-only modal parameter identification of the jacket platform can be effectively carried out by using two independent numerical techniques : the peak picking and the natural excitation technique (NExT).

The experimentally determined frequencies showed a good correspondence with the numerical results from a finite element model, as far as the lowest frequencies are concerned. For real applications, it is suggested that the peak picking technique could be used on site to judge the overall dynamic characteristics of the structure. And then, the NExT could be applied afterwards to detail or to ensure the results.

According to the analysis results, the modal parameters identification methods can be very useful to calibrate finite element models (FEM) of the building, or can be used for the structural health monitoring (SHM), or maintenance of civil infrastructure.

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References

Aktan, E., Beck, J. and Cornwell, P. (1999). "The State of the Art in Structural Identification of Constructed Facilities", Report by the ASCE Committee on Structural Identification of Constructed Facilities.

Farrar, C.R., Doebling, S.W., Cornwell, P.J. and Straser, E.G. (1997). "Variability of Modal Parameters Measured on the Alamosa Canyon Bridge", The 15th International Modal Analysis Conference, Orlando.

Hoon, S., Farrar, C.R., Hemez, F.M., Shunk, D.D., Stinemates, D.W. and Nadler, B.R. (2003). A Review of Structural Health Monitoring Literature: 1996 - 2001, Los Alamos National Laboratory, Los Alamos.

Huang, W.P., Jiang, J.T. and Li, H.J. (2002). "Measurement of Excessive Vibration of a Jacket Platform". Proc. of International Symposium on Safety Science and Technology, ISSST, Tai'an, China, Vol 3, pp 502-506.

Li, H.J. and Yang, H.Z. (2004). "Research Progress on Modal Parameter Identification and Damage Diagnosis for Offshore Platform Structures", Engineering Mechanics, Vol 21, pp 116-138.

James III, G.H., Carne, T.G. and Lauffer, J.P. (1993). "The Natural Excitation Technique (NExT) for Modal Parameter Extraction from Operating Wind Turbines," SAND92-1666, UC-261, Sandia National Laboratories.

Juang, J.N. and Pappa, R.S. (1985). "An Eigensystem Realization Algorithm for Modal Parameter Identification and Model Reduction", Journal of Guidance, Control and Dynamics, Vol 8, No 5, pp 620-627.

Juang, J.N. and Pappa, R.S. (1986). "Effects of Noise on Modal Parameters Identified by the Eigensystem Realization Algorithm", Journal of Guidance, Control, and Dynamics, Vol 9, No 3, pp 294-303.

Peeters, B. and De Roeck, G. (1999). "Reference Based Stochastic Subspace Identification in Civil Engineering", Proc. of the 2nd International Conference on Identification in Engineering System. Swansea, pp 639-648.

Peterson, L.D. (1992). "Efficient Computation of the Eigensystem Realization Algorithm", Proc. of the 10th International Modal Analysis Conference, San Diego, CA, pp 1122-1131.

Pappa, R.S, Elliott, K.B. and Schenk, B. (1993). "A Consistent-Mode Indicator for the Eigensystem Realization Algorithm", Journal of Guidance, Control and Dynamics, Vol 16, No 5, pp 852-858.

Yang, H.Z. and Li, H.J. (2003). "Damage Localization of Offshore Platform under Ambient Excitation", China Ocean Engineering, Vol 17, No 4, pp 307-316.

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