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Structural monitoring of offshore platforms using impulse and relaxation response

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Abstract

Monitoring offshore platforms, long span bridges, high rise buildings, TV towers and other similar structures is essential for ensuring their safety in service. Continuous monitoring assumes even greater significance in the case of offshore platforms, which are highly susceptible to damage due to the corrosive environment and the continuous action of waves. Also, since a major part of the structure is under water and covered by marine growth, even a trained diver cannot easily detect damage in the structure. In the present work, vibration criterion is adopted for structural monitoring of jacket platforms. Artificial excitation of these structures is not always practicable and ambient excitation due to wind and waves may not be sufficient for collecting the required vibration data. Alternate methods can be adopted for the same purpose, for example, the application of an impact or a sudden relaxation of an applied force for exciting the structure. For jacket platforms, impact can be applied by gently pushing the structure at the fender while relaxation can be accomplished by pulling the structure and then suddenly releasing it using a tug or a supply vessel in both cases. The present study is an experimental investigation on a laboratory model of a jacket platform, for exploring the feasibility of adapting vibration responses due to impulse and relaxation, for structural monitoring. Effects of damage in six members of the platform as well as changes in deck masses were studied. A finite element model of the structure was used to analyze all the cases for comparison of the results as well as system identification. A data acquisition and analysis procedure for obtaining the response signatures of the platform due to the impulse and relaxation procedure was also developed for possible adoption in on-line monitoring of offshore platforms. From the study, it has been concluded that both impulse and relaxation responses are useful tools for monitoring offshore jacket platforms. The present work forms the basis for the development of an automated, on-line monitoring system for offshore platforms, using neural networks. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Many researchers have investigated the possibility of using vibration characteristics for monitoring structures for their integrity Shahrivar and Bouwkamp (1984), Shyamsundar and Ting (1985), Idichandy (1986), Idichandy et al. (1987), Kondo and Hamamoto (1994), Chiostrini and Vignoli (1994), Osegueda and Dsouza (1992) and Rubin and Coppolino (1983). Difficulty in adapting this method in large structures is due to the problem of artificially exciting them at different frequencies. Collacot (1985) has suggested alternate methods like impact and relaxation responses for determining vibration characteristics of structures. Kung et al. (1989) has investigated structural integrity monitoring using impulse loading. Other applications have been documented by Raghavendrachar and Atkan (1992) for bridge diagnostics and Koh et al. (1995) for building frames. Most of the work in this area is for simple structures, the results of which may not be directly applicable to complex structures such as offshore platforms. Research work applying impulse or relaxation techniques for monitoring offshore platforms has not been found in the literature, although these two methods can be easily used for offshore jacket platforms, unlike the case for high-rise buildings and towers. In order to establish the feasibility of these techniques for monitoring offshore platforms, a detailed experimental and analytical investigation has been initiated. The ultimate aim of this study however is to suggest an on-line monitoring system for offshore jacket platforms. At present structural monitoring of offshore platforms depends on the reports of divers.

In the present work, a scaled down model of an existing platform is used to study the feasibility of using impulse and relaxation methods for monitoring. The changes in the response signatures due to damages in the structure and variation of deck mass are studied to isolate vibration parameters which depend only on structural damage. The present work also includes the development of software for data acquisition and processing which can be used for on-line structural integrity monitoring Mangal et al. (1996b).

2. Methodology

The main objective of the present work is to investigate the feasibility of impulse and relaxation techniques for monitoring offshore jacket platforms. An impulse is defined as a force of very high magnitude applied over a very short period of time whereas relaxation is the instantaneous release of the structure from an initially displaced position. Both methods cause the structure to undergo damped free vibration, the characteristics of which may depend on the shape, duration and magnitude of the impulse or on the initial displacement. The transient response of the structure will contain energy over a frequency range, which is used for determining those vibration parameters helpful in detecting possible damage in the structure and hence it's structural integrity. Initially, system identification is necessary to identify the most suitable analytical model representing the structural system, and this is accomplished by comparing the natural frequencies and mode shapes determined using finite element analysis with those obtained from the physical model. The mode shape vectors for six nodes on one leg in the X and Y directions were used for identification.

For the impulse response study, impacts were applied on one of the main legs of the platform model and acceleration responses were recorded in both the X and Y directions for two diagonally opposite legs. The transient time domain responses were converted to the frequency domain using the Discrete Fourier Transform (DFT) method. The vibration signatures representing the magnitude of the displacement vector at different levels of the platform for different modes were obtained from the frequency domain plots. For the relaxation response study, relaxation was applied in one direction. Analysis procedure for the collected data was similar to that of the impulse test. The impulse and relaxation tests were conducted for six cases of structural damage with different deck masses in order to study the effect of damage and deck mass changes on vibration signatures.

3. The physical model

The physical model fabricated of polyvinyl chloride (PVC) tubes represented an existing platform in service, in a water depth of 88 m. The geometric scale used was 1:35. It had four main legs and four skirt legs, which were rigidly fixed to the base. The details of the model are as shown in Fig. 1. The main legs had a diameter of 40 mm and a wall thickness of 1.5 mm. All bracings in the vertical plane were 20 mm in diameter and 1.2 mm thick and the diagonals in the horizontal plane were 16 mm in diameter and 1 mm thick. Tubes were cut to the exact dimensions and joined using an adhesive used for joining PVC, to ensure proper load transfer. The upper and lower decks were fabricated using Perspex plates.

As previously stated the first step in the study is the system identification or the identification of a finite element model, which exactly represented the structure. For this, a finite element model of the physical model of the platform was formulated. Three dimensional beam elements having six degrees of freedom were used for the FE model. Nodes were located at the centroidal axes of the intersecting members. The final model had 74 nodes and 170 beam elements. The model was assumed to be fixed at eight points representing the ends of four main and four skirt legs. The structural analysis program SAP IV was used for dynamic analysis. Natural frequencies and mode shapes were determined from the analysis. These were compared with the measured values of the physical model for system identification.

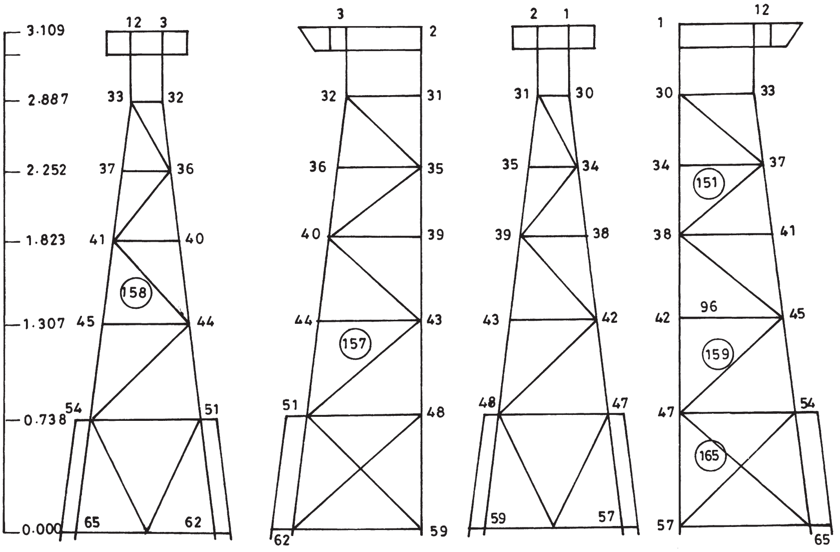

Fig. 1. Different frames of the jacket platform model.

4. Experimental set-up and instrumentation

Forced vibration was used to determine the dynamic parameters of the model. For this purpose external excitation was applied by means of an electro-dynamic exciter (type 4801) with a mode study head (type 4814) driven by a power amplifier (model 2707), all manufactured by Bruel and Kjaer, Denmark. The excitation signal to the power amplifier could be applied using either a function generator or a time series generated by a personal computer. The exciter was rigidly fixed on a frame close to the model fixed to the ground such that the excitation force was applied at the still water level of the jacket.

The instrumentation consisted of six accelerometers for response measurement and a load cell for measuring the excitation force. Inductive spring-mass type accelerometers (B12/200, HBM, Germany) were used for the testing. A ring type load cell made of stainless steel was fixed onto the rod connecting the exciter to the model. Fixtures were provided such that the accelerometers could be fixed in both X and Y directions on two diagonally opposite legs. The accelerometers as well as the load cell were connected to a multi-channel carrier frequency amplifier (KWS 673.A7, HBM, Germany). The output from the carrier frequency amplifier was connected to the PC based data acquisition system, which also drove the vibration exciter.

5. Data acquisition system

The data acquisition system was a PC with a high speed, 12 bit 16 channel data acquisition card (PCL-818, Advantech). Each channel had a software switchable range from ±0.5 V to ±10 V. An interactive program was developed using BASIC (Quick BASIC Version 4.0) and assembly language routines supplied by the manufacturer. The salient features of the data acquisition software are given below:

1. The ability to set the sampling frequency, start channel and end channel and duration of data collection
2. Separate calibration constants for each channel
3. Provision of an individual voltage range for each channel
4. An automatic zero error adjustment with zero error display for all channels (this ensures that the maximum/minimum range is not exceeded)
5. Simultaneous operation of analog to digital and digital to analog, if required
6. Graphical display of data acquired on any/all channel/s, two channels at a time before storing, which enables the inspection of the acquired data before storing.
7. Titles for each set of data stored in the file.
8. An auto triggering facility for automatic starting of data acquisition when a particular threshold voltage is reached in any specified channel.
9. A means of saving settings for repeated measurements.
10. Provision for specifying the start time for storing data in simultaneous A/D and D/A operations thereby avoiding the storage of unnecessary data.

This program was developed as a compact and stand-alone module for studying the impact and relaxation responses in cases where the auto-triggering facility is required for data acquisition.

6. Identification of natural frequencies

The natural frequencies in the range 0–60 Hz (first 9 frequencies) were investigated. Initially a sweep sine wave signal was used to excite the structure such that the responses at different frequencies could be studied with a single test. Data was acquired on all seven channels and recorded. A fast Fourier Transform (FFT) was done on the data and the peaks were identified which gave the approximate values of the natural frequencies. After determining the approximate frequencies, the structure was excited at these frequencies and fine adjustment of the frequency was made such that the maximum response was obtained. This frequency was accurately measured using a digital storage oscilloscope.

A program was written in C language for displaying the mode shapes of the structure. This program reads the output of the finite element program (SAPIV) and creates an AutoCAD script file, which when loaded displays the mode shapes, and can be viewed from any angle. This program is very useful in identifying the mode shapes. The frequencies obtained from both finite element and experimental analyses are given in Table 1. It may be noted that the natural frequencies agreed within very close ranges. Mode shapes also gave similar results. This validated the selected FE model as a true analytical representation of the structural system used.

Table 1
Comparison of natural frequencies FEM and experiment

FEM analysis	Experiment		Remarks
	X-direction	*Y*-direction	
4.300	4.427		1st mode in *X* direction
4.541		4.531	1st mode in *Y* direction
18.722	19.30	18.55	1st torsional mode
22.499	22.37		2nd mode in *X* direction
24.050		23.10	2nd mode in *Y* direction
34.720	34.87	34.14	2nd torsional mode
39.170	41.08	40.48	Vertical mode
45.590		45.28	3rd mode in *Y* direction
53.470	54.78		3rd mode in *X* direction

7. Impulse response

The experimental setup for the impulse response studies is shown in Fig. 2. A very sensitive servo-type accelerometer (model LBSC-1, Lucas-Schaevitz, USA) was used for the lower three nodes and an inductive type displacement transducer (model W20k, HBM, Germany) was used to measure the displacement time history at node

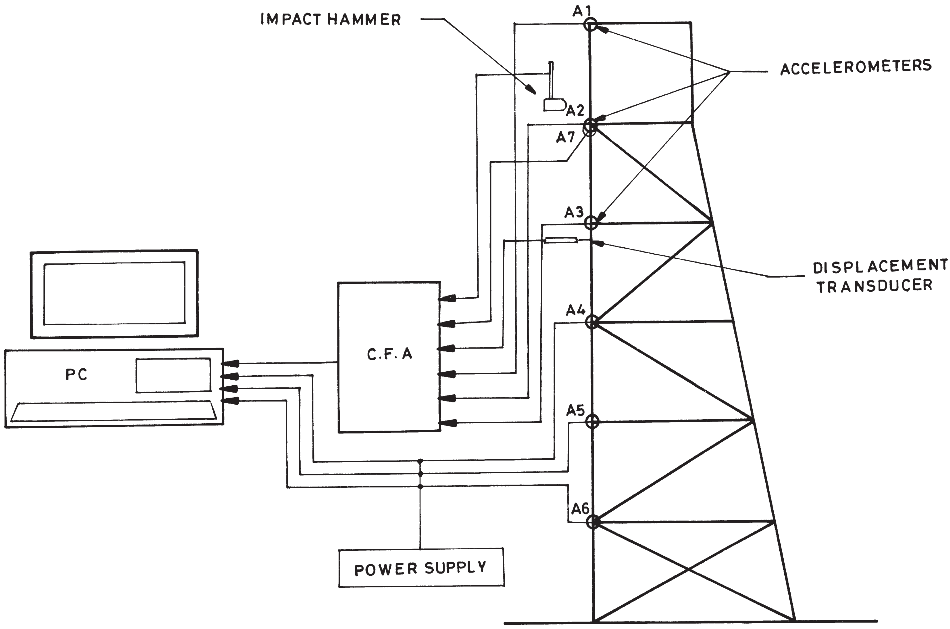

Fig. 2. Experimental set-up for the impulse response study.

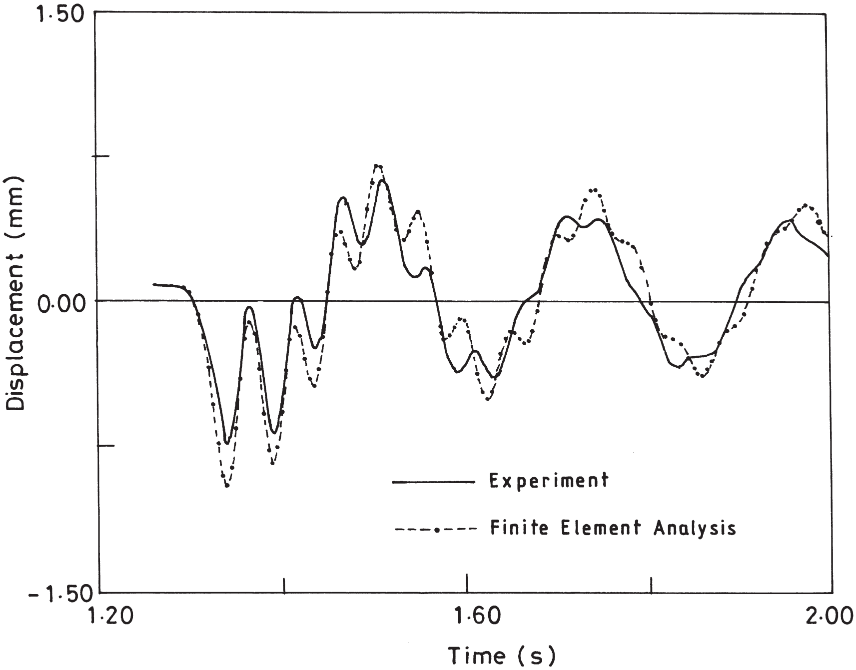

Fig. 3. Comparison of displacement time history for impulse response for node 34.

34 in the X-direction in addition to the other instrumentation already explained. The impulse was applied using an instrumented hammer designed and fabricated at the Ocean Engineering Centre for a similar project carried out by Padmaprabha (1991).

The impact hammer used for the present work consisted of an impact head connected to a beam type force transducer fixed to the body wall. A handle was secured to the body for convenient use of the hammer. The entire hammer was fabricated out of stainless steel. Four strain gauges in full bridge configuration were used for maximum sensitivity. The size of the beam element was 2 mm $\times$ 5 mm in cross section and the span was 34 mm. The natural frequency of the beam was found to be 2.1×10^5 Hz, which was sufficiently high to measure the applied impact. Hitting the hammer against a standard load cell with a soft material (hard sponge) in between was used for calibrating the hammer for impact loads. Several trials were done for different magnitudes of impacts. A calibration curve was drawn and it was found to be linear. Calibration of the impact hammer was necessary for accurately defining the load in the FE analysis of the structure. A soft material was placed at the point where the impact was applied on the model such that the duration of the impulse transferred was capable of exciting the first few natural frequencies of the model.

8. Experimental procedure

The impact in both the X and Y directions was applied at the second node from the top on one of the main legs (node 30). The responses due to these impulses were studied on six nodes on this leg and the diagonally opposite leg. Since only six accelerometers were used, the responses of one leg in one of the directions only could be acquired at a time. The displacement transducer output was used to verify the actual response with that obtained using finite element analysis. To study the effect of variations in deck mass, the experiment was repeated for various deck masses from 9 kg to 11.5 kg at 0.5 kg intervals (normal deck mass=10 kg). In some cases, a seventh accelerometer was also used to measure the response in the perpendicular direction at the second node. Altogether six damage cases were studied (member nos. 159, 151, 165, 96, 156 and 157 severed) of which four were on the same frame on one side. For each damage case, the member was cut and the responses due to impact in both the X and Y directions were recorded. After testing, the member was rejoined and the response of the structure was compared with that of the undamaged structure before further damage was induced. This ensured that

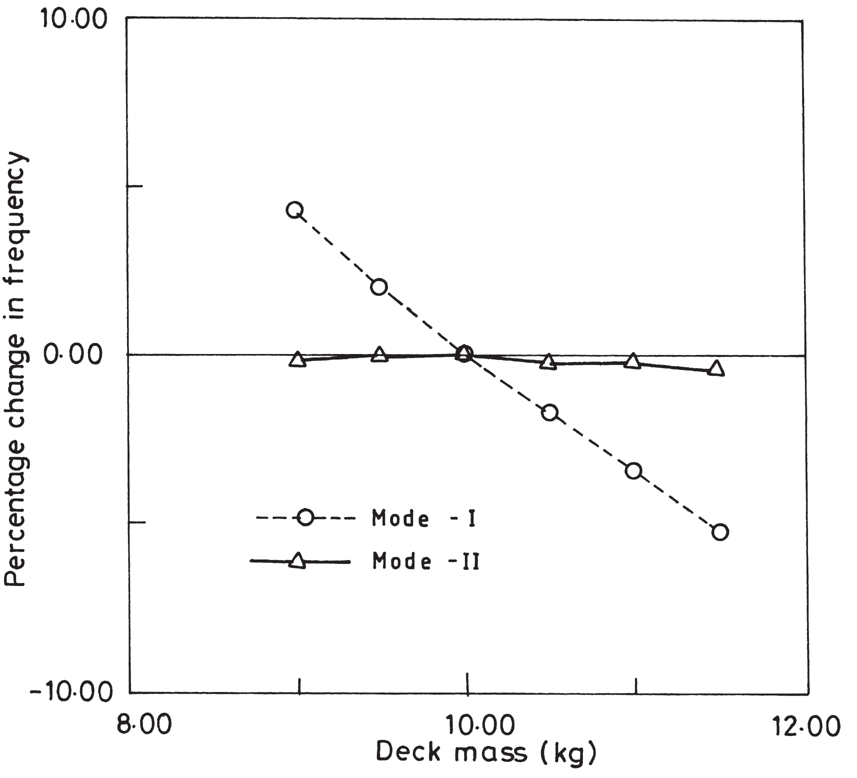

Fig. 4. Variation in natural frequency due to change in deck mass.

the cut member was properly rejoined and structurally sound. A test case was also done with the impact applied at an angle of 45° diagonal to the X and Y directions.

9. Processing of data

The response history obtained was processed to find the impulse response signature, found by collecting the peaks of the Fourier Transforms of the responses of all six nodes at the vicinity of the first two natural frequencies, and normalizing the vector obtained. A FORTRAN program was developed for processing the file containing the time series to evaluate the vibration signatures. The program used the DFT method to acquire the complex frequency component given by the formula

$$X_m = \sum_{k=0}^{k=n-1} x_k^{e^{-j(2\pi mk/N)}}$$

Where X_m is the amplitude of the frequency component m and x_k and is the time series having N points. The DFT method is much slower than the usual FFT tech-

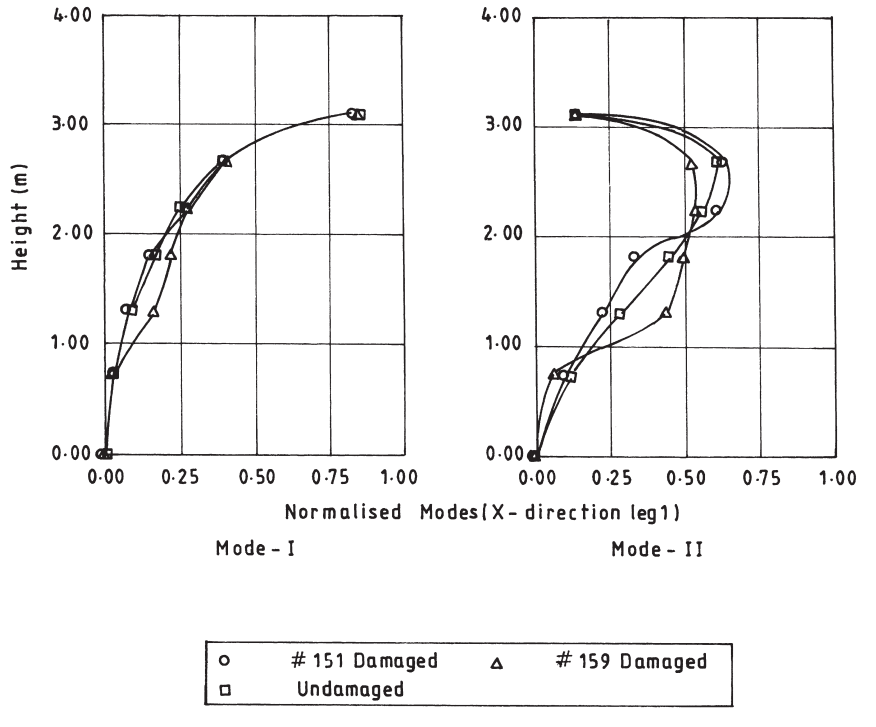

Fig. 5. Changes in vibration signatures due to damage in members 151 and 159.

nique, but gives any number of frequency points at any desired interval, whereas in FFT analysis the number of frequency points is restricted to $N/2$. The processing time depends on the number of ordinates required. In the DFT, there are no restrictions on the number of points in the time series, whereas in FFT the number of points should be a power of two. Since the objective was the identification of peaks in the vicinity of the natural frequencies, only those portions were scanned with a resolution of 0.01 Hz for collecting the peak value. The vectors of the peaks for all six accelerometers were normalized to unit length to get the response signature for that frequency. This program would be extremely useful for the on-line monitoring of structures.

10. Results and discussion

The time history of the response of node 34 of the structure is presented in Fig. 3 along with the results of the finite element analysis. It is seen that both responses agree reasonably well. The vibration signatures for various deck masses are given in Table 2. As anticipated, it is observed that the normalized signatures are insensitive to the changes in deck mass. This means that if one uses the changes in the response signatures for monitoring and detection of damage in the platform, the deck mass variations will not influence the damage detection process. However, the changes in deck mass have some effect on the natural frequencies. The variation of frequencies with change in deck mass for the first and second modes are shown in Fig. 4. Studies were conducted for damage in six members. They can be classified into three groups: highly sensitive members (151 and 159), redundant members (165 and 96), and members which were not connected to the instrumented leg (156 and 157). The changes in the response signatures for the first and second modes for severance of members 151 and 159 are given in Fig. 5. For the redundant members (165 and 96), the

Table 2
Changes in 1st and 2nd modes for different deck masses

Deck mass	9 kg	10 kg	11 kg
Mode I	0.8614	0.8616	0.8623
	0.3844	0.3831	0.3833
	0.2676	0.2682	0.2662
	0.1693	0.1702	0.1696
	0.0935	0.0929	0.0926
	0.0336	0.0337	0.0337
Mode II	0.0945	0.0901	0.0599
	0.5887	0.5852	0.5925
	0.6056	0.6083	0.6051
	0.4292	0.4316	0.4294
	0.2791	0.2782	0.2813
	0.1241	0.1248	0.1242

changes in the signatures are not as significant as those for the first case, but are still detectable as evident from Fig. 6. For the third group, even though the members are sensitive, the changes in their signatures are smaller in comparison to the first case, since they are not connected to the instrumented leg. For the second and third cases, the detection of the damage is possible, but identification may be difficult. If the diagonally opposite leg (leg 2) was also instrumented, additional data would be available, as presented in Figs. 7 and 8 for better detection of damage. Therefore, for effective monitoring, it is suggested that the diagonally opposite legs be instrumented at all panels.

In all the cases discussed above, the responses used were in the same direction in which the member was oriented. The changes in the signatures in the perpendicular direction due to damage were observed to be much less when compared with those changes in the same direction. It may be noted that for all the studies, the responses were taken in the same direction as that of the impulse. The response in a direction perpendicular to that of the impulse is observed to be negligible and was not used in this study. Moreover responses in the perpendicular direction did not match those obtained by finite element analysis.

Some tests were conducted by applying the impact in a direction inclined at 45° to the *X* and *Y* directions. The signatures in the *X*-direction for severed member 159

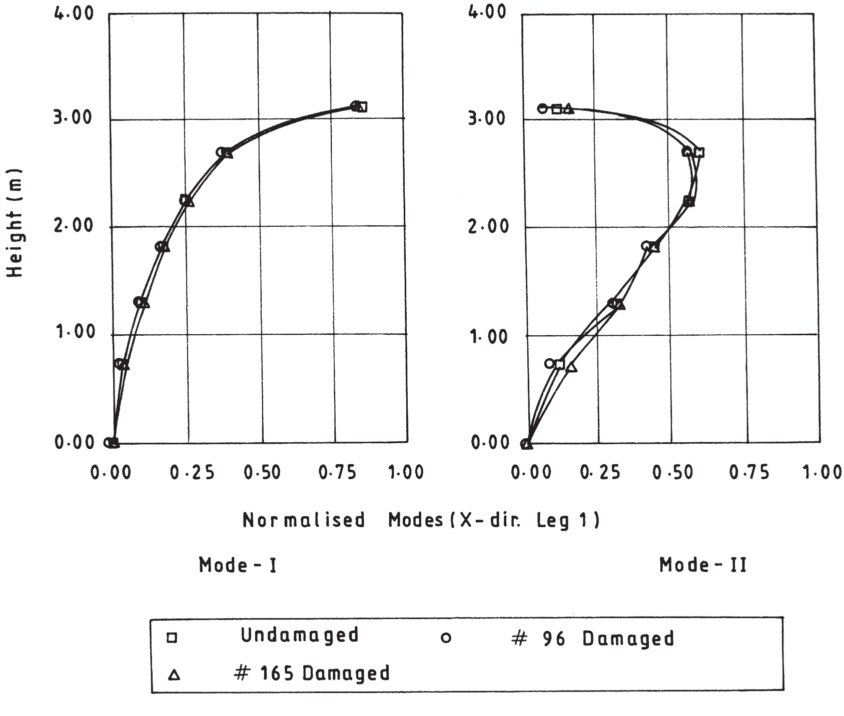

Fig. 6. Changes in vibration signatures due to damage in members 165 and 96.

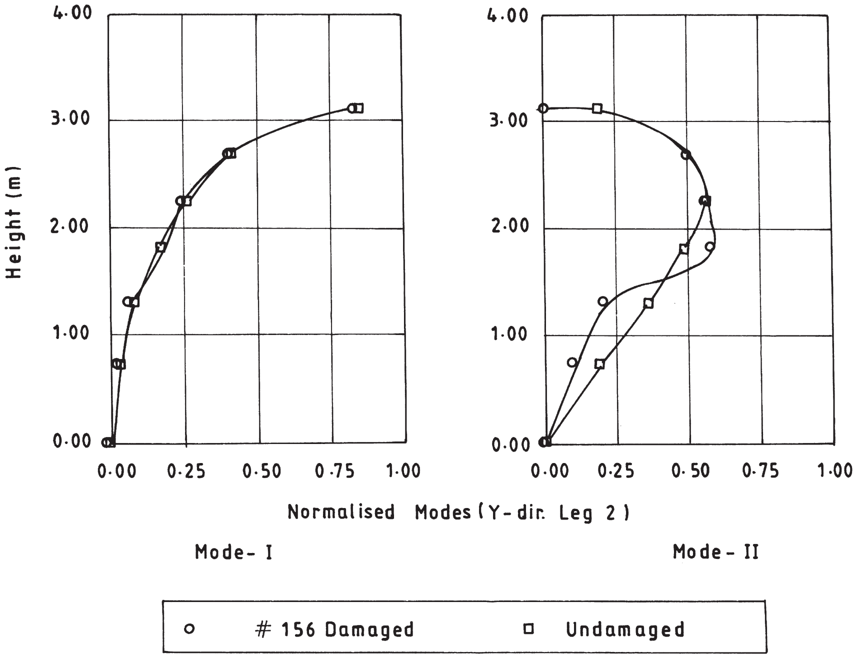

Fig. 7. Changes in vibration signatures due to damage in member 156, leg 2.

are given in Fig. 9. These signatures are not identical to the signatures of impacts applied in the *X* direction, nevertheless are found to be effective in damage detection as evident from the figures. Impact at an angle is a better alternative since the responses in both the *X* and *Y* directions can be obtained simultaneously in a single test.

11. Relaxation response

A relaxation response study was also performed to explore the suitability of this method of monitoring. This consisted of pulling the structure from one side and then suddenly releasing it so that the oscillation induced due to this sudden relaxation could be used for damage detection. The experimental setup was the same as that for the impulse response study except for the arrangement used to apply the sudden relaxation. A horizontal force was applied through a string tied to the structure at node 30. The string passed over a pulley and a pan was attached at the free end. A total weight of 23 N was placed on the pan. The string was cut using a sharp knife for suddenly releasing the load. The acceleration and displacement data were acquired for 2.5 s and an automatic triggering facility initiated the data acquisition system. Relaxation response was obtained also by finite element analysis. Load was slowly increased from zero to a value of 23 N and maintained at that level for 0.2

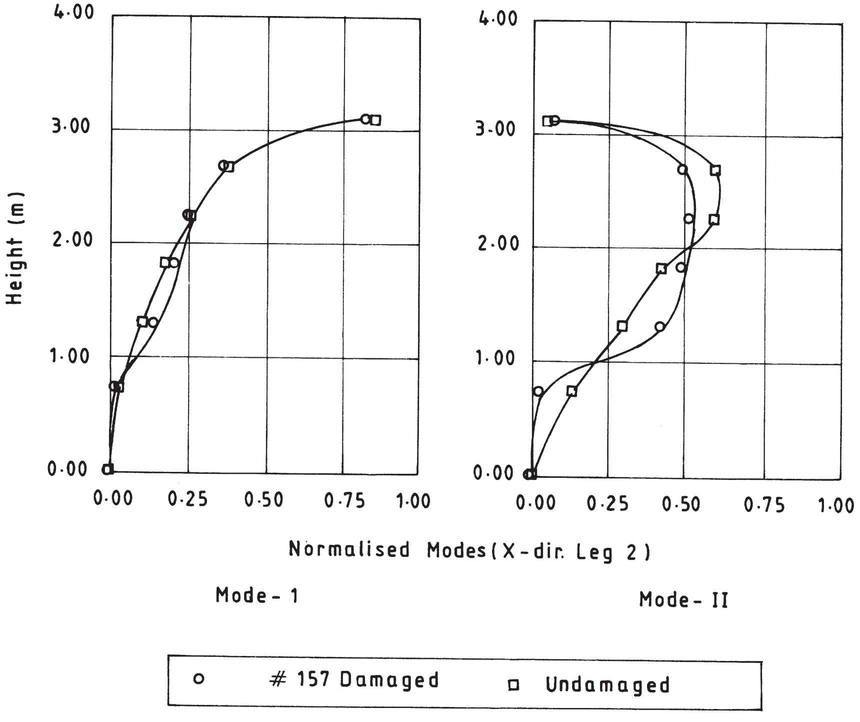

Fig. 8. Changes in vibration signatures due to damage in member 157, leg 2.

s. It was suddenly reduced back to zero in 0.001 s and retained at zero for the rest of the data acquisition period. The comparison of the responses from the finite element analysis and those observed are given in Fig. 10. The same data processing program used for the impulse response study was used for the relaxation response study. The plots of the response signatures due to different damage for the first and second modes are shown in Fig. 11. These signatures compared well with those obtained by impulse response and established that the relaxation test was also an effective method for structural integrity monitoring similar to the impulse response method.

12. Neural networks in monitoring

Neural networks are artificial intelligence based information processing systems. These systems can be used for interpreting the vibration data for detecting structural damages. Some of the work in this area has been reported by Elkarody et al. (1994), Wu et al. (1992), Hsu and Yeh (1993) and Branceleoni et al. (1993). The authors have adopted neural networks for damage detection of offshore structures Mangal et al. (1995, 1996a). The results from the present work can be used for validating

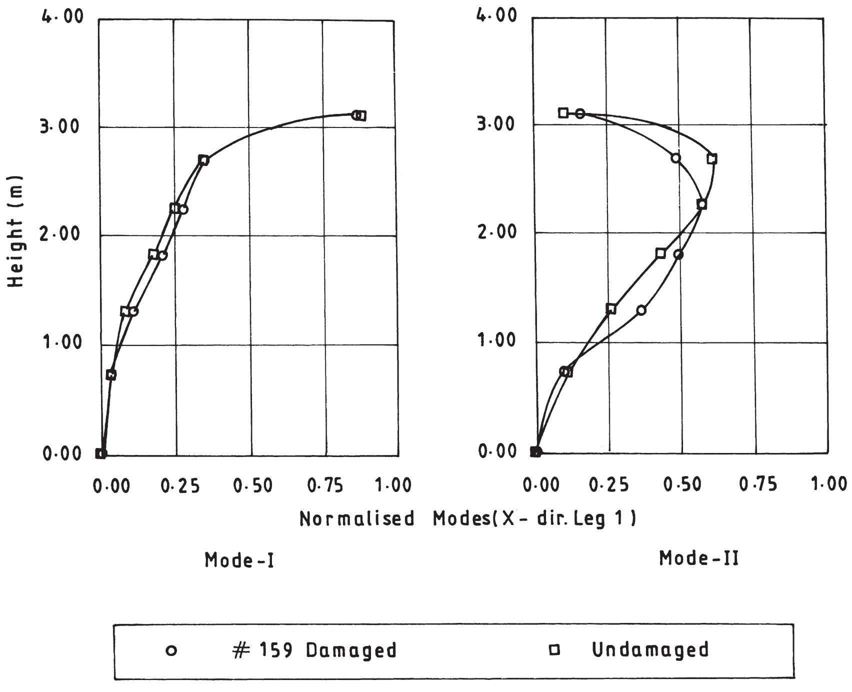

Fig. 9. Changes in vibration signatures in the *X*-direction due to damage in member 159 for an impulse at 45°.

the method. Since the experimentally obtained results correlated well with the results of the finite element analysis, the latter can be used to train the neural networks. This is necessary since the actual structure cannot be damaged in acquiring the data used for training these networks. Consequently, system identification assumes greater importance in developing an on-line monitoring system for offshore structures.

13. Conclusions

The study proposes the use of vibration parameters realized from impulse and relaxation methods for monitoring the integrity of offshore structures. The changes in deck mass which affected the natural frequencies of the structure were found to have no effect on vibration signatures (minimum change was less than 1%). Both the impulse response method and the relaxation method were found to be very effective in the detection and location of structural damage. The changes in response signatures are larger for critical members and smaller for redundant members. (Maximum change was approximately 30% for critical members and 10% for redundant members.) The response in a direction perpendicular to the impact was negligible and that requires further investigation before adopting it into practice. For

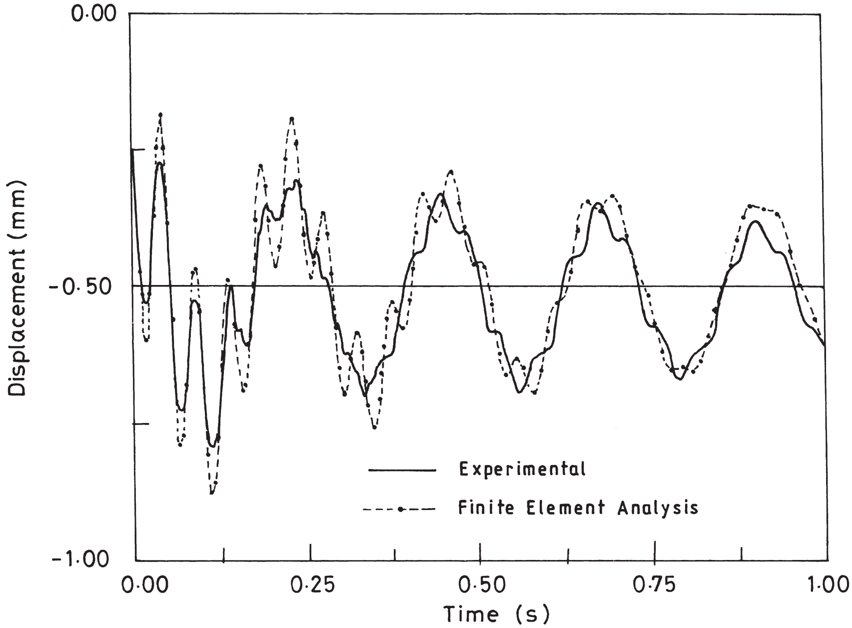

Fig. 10. Comparison of displacement time history for relaxation response of node 34.

efficient monitoring, the diagonally opposite legs in all panels should be instrumented. An impulse at 45° to both the *X* and *Y* directions is also effective in concurrently obtaining vibration signatures in the *X* and *Y* directions. The results of these studies will go a long way in designing an on-line structural monitoring system for offshore platforms.

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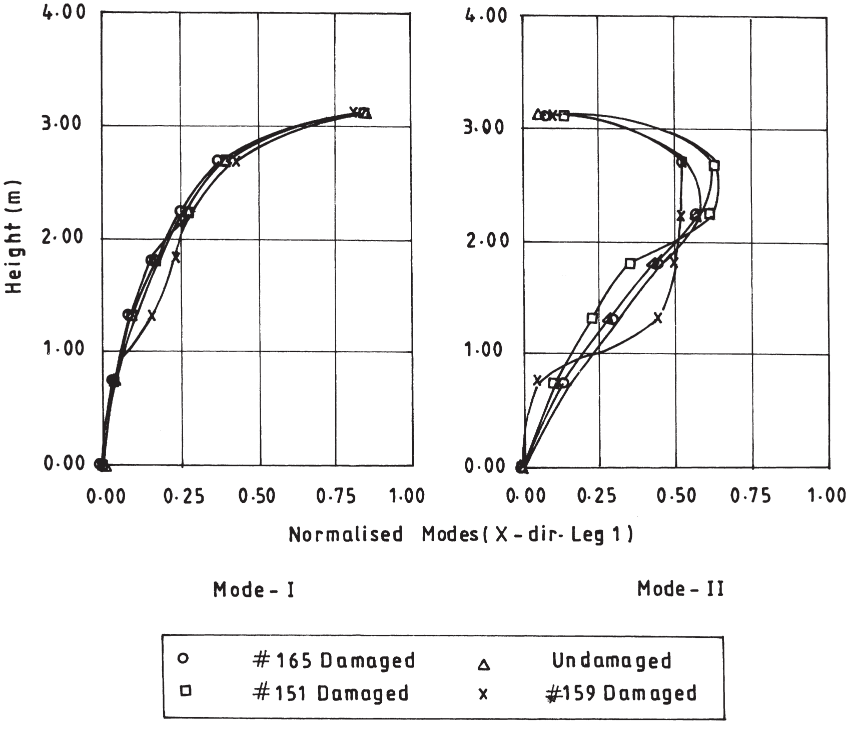

Fig. 11. Changes in vibration signatures due to various damage by the relaxation method.

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