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Experimental Modal Test on a Scale Model of Floating Structure

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Abstract : *Identification of the modal properties of a structural system has received much attention over the years because of its importance in structural model updating, structural health monitoring and structural control. This paper presents experimental modal test results such as natural frequencies and mode shapes of a scale model of floating structure. A modal testing is performed on the structure and modal parameters for the structure are extracted from the measured data. The results are compared to a finite element model and the correlation between the measured and analytical modal parameters is investigated.*

Key words : *modal test, floating structure, natural frequency, mode shape, forced vibration*

1. Introduction

Dynamic characteristics of a structural system, such as natural frequency, damping, and mode shape have been widely used for structural model updating, structural health monitoring, and structural control. In the early period of structural health monitoring, studies have focused on the possibility of using modal properties, e.g., shifts in resonant frequencies as indicators of structural damage. Many researchers have investigated and applied vibration monitoring to offshore structures (Vandiver, 1977; Kenley and Dodds, 1980; Osegueda et al., 1992).

The consequence of seismic events and failure of bridge have resulted in attempts to monitor the integrity of bridges (Biswas et al., 1990; Choi et al., 2004). The use of sensitivity approaches based on the relationship between the eigenfrequencies, modal stiffness, modal mass, and modal damping have focused on the development of methods that predict the location and magnitude of any damage in the structure (Stubbs and Osegueda, 1990). In addition, Park et al. (2006) presented blind test results of damage detection by using the simulated time domain data from a four-story steel frame. They reported the results of modal analysis and also reported damage locations and estimation of damage severities for two damage cases using only mode shapes of undamaged and damaged structures.

Recently, the possibility of monitoring the structural integrity of a containment structure in the nuclear power plant was explored by utilizing modal properties from an ambient vibration measurement (Choi et al., 2010). In this study, the modal parameters, i.e., resonant frequencies and corresponding mode shapes, were extracted using the peak picking and the frequency domain decomposition methods. A sensitivity-based structural identification technique with the finite element model was used to identify the elastic modulus of the concrete. Also, an application of modal parameters in damage detection for a truss structure was investigated via numerical examples (Park, 2008).

Usually the structural model updating, structural health monitoring, and the structural control methods comprise the measurement technique for recording dynamic responses, the data processing technique for extracting dynamic characteristics, e.g., resonant frequencies, damping, and mode shapes, and the system identification technique for relating the extracted dynamic characteristics to physical properties of the structural system. (Doebling et al., 1996).

To ensure the various methods mentioned above successful, the exact modal properties are essential. There are two methods available in measuring the dynamic responses of a structure: the forced vibration test and the ambient vibration test. The forced vibration test is the most popular method because of its accuracy and convenience. Since in the forced vibration method the input force is known, transfer function can be obtained directly from the measurements of input force and output response. However, in the ambient vibration test, output responses are only

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Note) This paper was presented on the subject of "Modal Properties of a Scaled Model of Floating Structure" in 2010 International Offshore and Polar Engineering Conference proceedings(Beijing, China, June 20-25, 2010, pp. 554-559) measurable. So the process of identifying the transfer function and modal parameters is more complicated than the forced vibration test.

Few researches have been conducted for the identification of the ship vibration modes and their modal properties (Riska and Kukkanen, 1994; Thomas et al., 2003; Rosenow et al., 2007). Recently, some researchers investigated the dynamic behavior of floating structures (Tang et al., 2011; Tajali and Shafieefar, 2011), however, their studies were related to rigid body motion of the structure. Although many vibration tests have been applied to various types of structures, the study on application to the floating structure is still pending.

The objective of this paper is to present the modal properties, e.g., resonant frequencies and the corresponding mode shapes of a scale model of steel box structure which is floating on the water. In order to achieve the stated goal, the following tasks are performed. First, an impact modal testing is performed on the scale model of selected structure. Second, the modal parameters including resonant frequencies and corresponding mode shapes are extracted from the measured data by utilizing the peak picking method in the frequency domain. Third, a finite element model is constructed and the analytical modal parameters are computed. Finally the correlation between the experimental and analytical modal parameters is investigated.

2. Experimental modal test in the laboratory

2.1 Description of the test structure

The structure of interest in this test is a steel-box which is floating on the water. Fig. 1 depicts a view of the structure in a water tank. The size of water tank is 1.5m (length) × 1m (width) × 0.5m (height). The water is filled in the tank with the height of 0.3m from the bottom of the tank.

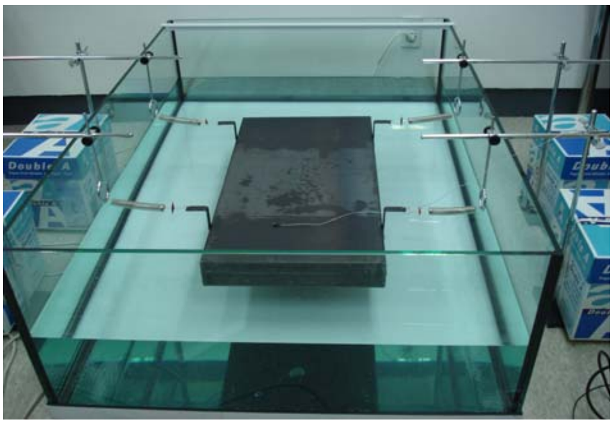


Fig. 1 Photograph of the test structure in a water tank

The steel box, a hexahedron that the inner-space of the box is empty, is made of six steel plates which consist of an upper plate, a bottom plate, and four side plates. The thickness of all plates is 0.0029m and the outer dimension of steel box is 0.8m (length) × 0.4m (width) × 0.1m (height). To make the inner space of box void, all edges of the box are fully welded. The material properties of the modulus of elasticity and the mass density for steel plate are E = 210 GPa and ρ = 7,850 kg/m^3, respectively. The total weight of steel box is 193.17 Newton.

As depicted in Fig. 1, the steel box has been submerged into the water about 6.2 cm from the surface of the water. The calculated value of submerged length for 193.17 N of buoyant force is 6.15 cm. To simulate a real floating structure, the steel box is moored to four mild springs connected to some holding devices. The mooring points, as shown in Fig. 1, are located 15 cm from each corner of long side of the box.

2.2 Measurement methodology and instrumentation

Active excitation and ambient noise are commonly used to excite a structural system. Ambient vibration methods have been actively pursued by many researchers (Gentile and Bernardini, 2008; Brincker et al., 2000; Carder, 1937) and are applicable to large structures where measurement of excitation source is impractical or expensive. Forced excitation methods are mainly used on smaller civil, aerospace, and mechanical structures. Excitation sources include swept harmonic input, random excitation, and impulse excitation.

The measurement technique used here is a modal impact testing (impulse excitation) for laboratory data collection. Fixed-point response measurement testing with roving

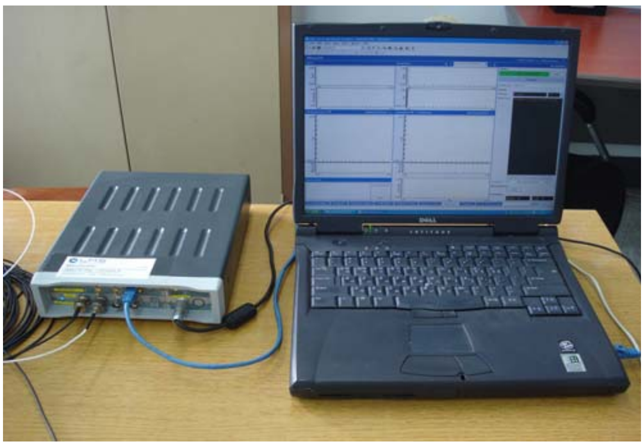


Fig. 2 Experimental instruments

hammer impacts is performed to collect data. The experimental instruments used in the modal testing on the steel box specimen are shown in Figs. 2 and 3. Instrumentation used to conduct the modal testing consists of an impact hammer, an ICP accelerometer (Kistler 8778A500), a 4-channel dynamic signal analyzer (LMS SCM V-4), and a portable computer.

A response accelerometer is glued to the upper plate of steel box as shown in Fig. 3. A total of 45 impact points are marked on the upper plate to insure positional repeatability during the test. The impact and sensor locations are depicted in Fig. 4. The parameters of test settings used for the modal test are summarized in Table 1.

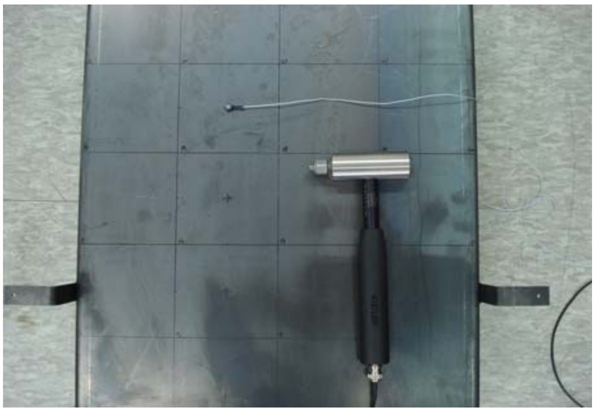


Fig. 3 Impact hammer and accelerometer

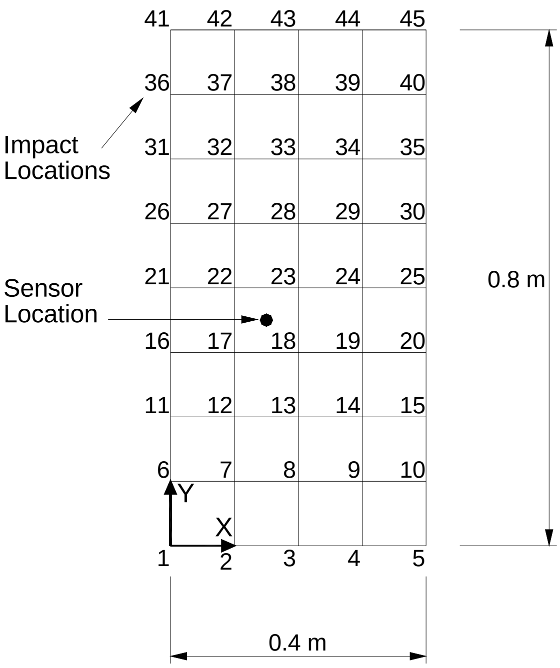
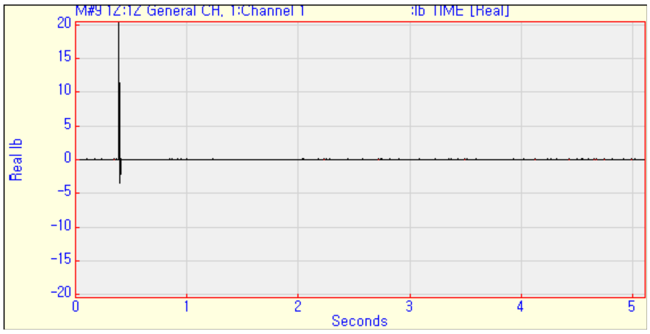


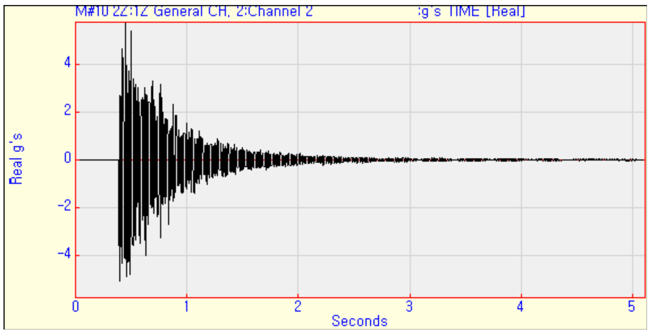
Fig. 4 Impact and sensor locations

Table 1 Parameters of test setting

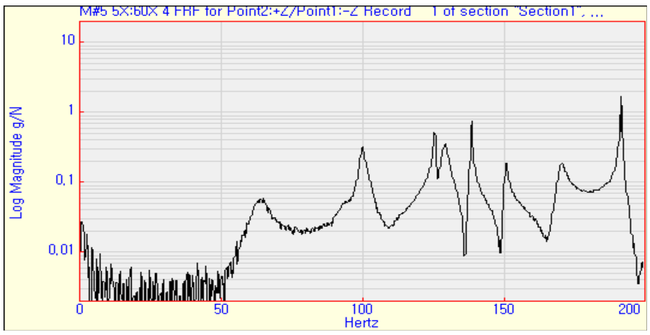
Test Parameter	Value	Notes/Units
Sample frequency	400	Hz
Sample length	2048	Samples per channel
Spectral resolution	0.195	Hz
Number of repetitions	3	Linear average
Channel gain	Varied	Adjusted for overloading
Trigger method	+2% hammer FS	Pre-trigger save all channels
Accelerometer window	Exponential	80% down at end
Hammer window	Rectangular	8% window width



(a) Time series of impact hammer



(b) Time series of acceleration response



(c) Frequency response function

Fig. 5 Typical measurement data

2.3 Experimental data and modal analysis

A total of 45 frequency response functions (FRFs) are measured using a fixed response-roving input test method. The FRFs measured at each impact location are derived from an average of three impacts and response measurements. Time series from the response accelerometer and the impact hammer are transformed to the frequency domain and the associated frequency response functions are generated. Fig. 5 presents a typical time series of impact hammer, acceleration response, and the corresponding frequency response function. Fig. 6 shows the superposition of all measured FRFs.

It is possible to extract modal parameters (i.e., frequencies and mode shapes) directly from the FRF data because of the low damping, sharp peak, widely spaced frequencies, and simple geometry of the test configuration. ME'scope Version 5.0 (2009) is used to analyze the FRFs derived from time data collected during the test. The modal parameters are obtained from the plot of frequency response function using the peak picking method (Ewins, 1984). The mode shapes of the upper plate of steel box are drawn by measuring the magnitude and phase angle of frequency response functions corresponding to impact location 1 through impact location 45 at specific frequencies (e.g., resonant frequencies of the first five modes). The measured resonant frequencies of the steel box are presented in Table 2. The resultant mode shapes are depicted in Fig. 7.

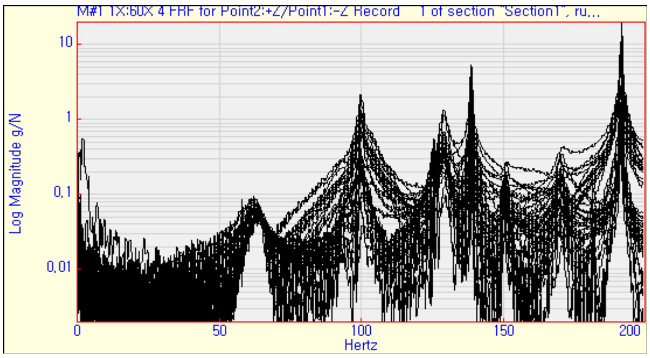
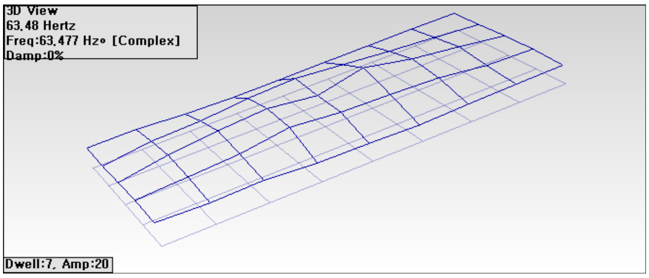


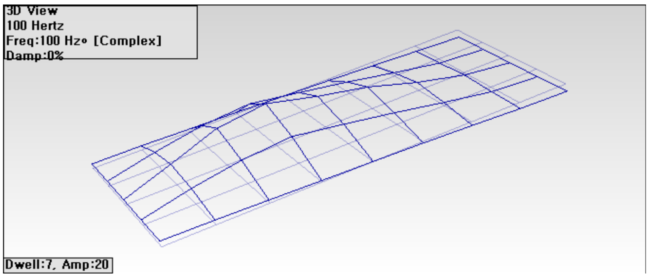
Fig. 6 Superposition of 45 FRFs

Table 2 Measured frequencies of the steel box

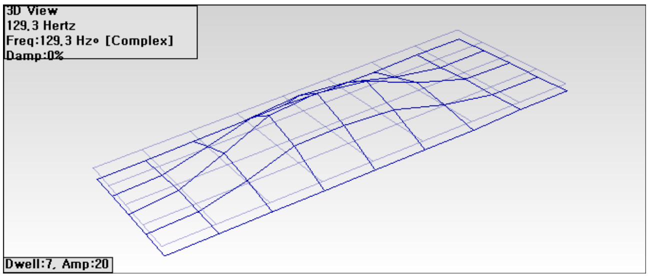
Mode	Frequency (Hz)
1	63.48
2	100.00
3	129.30
4	138.87
5	191.80



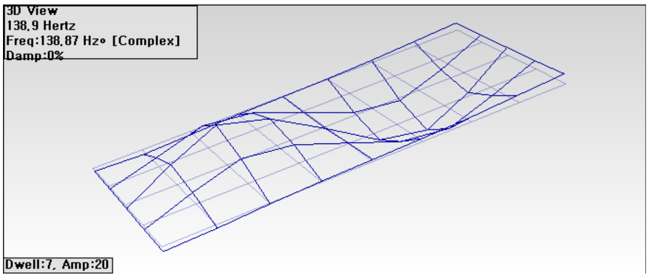
(a) Mode 1



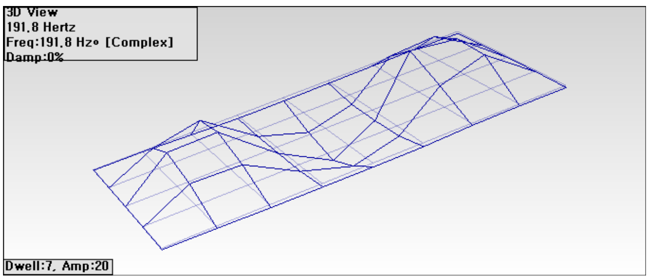
(b) Mode 2



(c) Mode 3



(d) Mode 4



(e) Mode 5

Fig. 7 Experimental mode shapes

3. Comparison of modal properties between experimental and numerical data

A finite element (FE) model of the steel box is developed using commercial software (ABAQUS, 2001) for the comparison of measured modal parameters. A schematic of the FE model for the steel box is shown in Fig. 8. Six sides of the steel box and four mooring devices are modeled using 2228 plate elements. The size of each plate element is 2 cm × 2 cm. The interaction between the bottom of steel box and the water is modeled using 861 axial springs (distributed in the bottom plate of steel box) in the Z direction. Two axial springs in the Y direction and two axial springs in the X direction are used to represent the mooring system at each moored point. In all, the FE model contains 3105 elements and 13452 degrees of freedom.

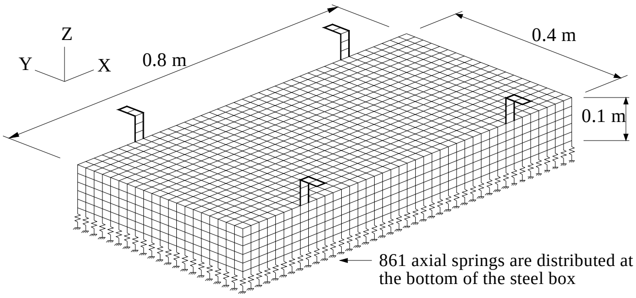


Fig. 8 Schematic of the finite element model

Table 3 Calculated frequencies from the FE model

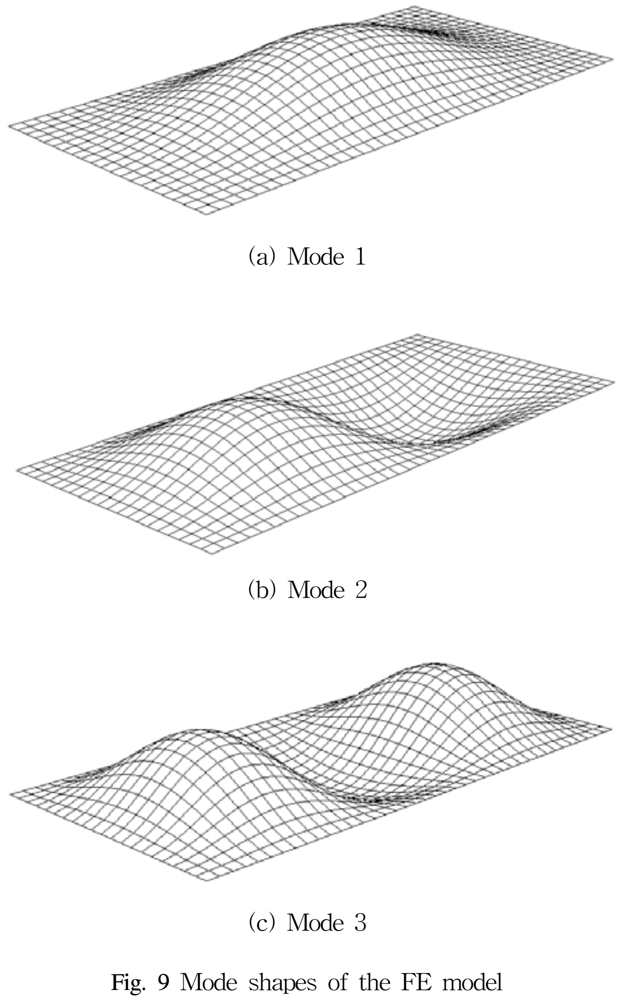
Mode	Frequency (Hz)
1	118.06
2	139.70
3	189.79

The material properties for the finite element model are generated as follows: (1) all steel plates are assumed to have a mass density of ρ = 7,850 kg/m^3, Poisson ratio of ν = 0.3, and the elastic modulus of E = 210 GPa; (2) the spring constant for structure-water interaction is assumed to be k_s = 3,646 N/m. Note that the whole spring stiffness for the steel box is obtained from buoyancy dividing by submerged length and the each spring constant is calculated from whole spring stiffness dividing by number of nodes.

A free-vibration analysis is performed to obtain the natural frequencies and the corresponding mode shapes. The results are shown in Table 3 and Fig. 9, respectively. Note that in Fig. 9 only the shapes of upper plate of the steel box are depicted.

The mode shapes extracted from measured FRFs and calculated from the FE model are compared in this section. To investigate the similarity between the modes, MAC (Modal Assurance Criteria) is calculated by Eq. 1 (Ewins, 1984).

$$MAC(E,F) = \frac{\left| \sum_{k=1}^{N} (\Phi_E)_k (\Phi_F)_k \right|^2}{\left(\sum_{k=1}^{N} (\Phi_E)_k (\Phi_E)_k \right) \left(\sum_{k=1}^{N} (\Phi_F)_k (\Phi_F)_k \right)} \qquad (1)$$



(a) Mode 1

(b) Mode 2

(c) Mode 3

Fig. 9 Mode shapes of the FE model

where Φ_E is the experimental mode shape from FRFs, Φ_F is the mode shape from FE model, and N is the number of degrees of freedom. If two modes are correlated, MAC value should be close to unity.

MAC values for five experimental mode shapes versus three FE mode shapes using the matching 45 degrees of freedom are presented in Table 4. As shown in the table, the first FE mode is almost identical to the third experimental mode with MAC of 0.9891, and the second and the third FE modes are highly correlated with the fourth and the fifth experimental modes with MAC of 0.9168 and 0.8640, respectively. These values are highlighted in the table.

Table 4 Modal assurance criteria

Experimental mode	FE modes			
	Mode	1	2	3
Mode	Frequency (Hz)	118.06	139.70	189.79
1	63.48	0.0099	0.0007	0.0034
2	100.00	0.4700	0.0644	0.0192
3	129.30	0.9891	0.0001	0.0011
4	138.87	0.0046	0.9168	0.0010
5	191.80	0.0426	0.0000	0.8640

4. Discussion of results

The mode shape of floating steel box on the water, extracted from the experimental data, seems to show more complex behavior than FE model. There are several features when comparing the experimental modes to the analytical modes. The first two modes at 63.48 Hz and 100.0 Hz shown in Fig. 7 are not reflected in the finite element analysis. No pure plate bending mode exists in experimental modes. For example, modes 3, 4, and 5 show the plate bending mode combined with the rigid body motion or pitching of the structure. These phenomena can be discerned clearly when animating the mode shape. Similar behaviors are found in the analytical mode from the FE model. It should be noted that although the first FE mode is almost identical to the third experimental mode there is relatively big discrepancy in frequency value. The resonant frequency of the third experimental mode is 129.3 Hz and the calculated frequency of the first FE mode is 118. 06 Hz. There is 8.7% difference between frequencies. However, the fourth and the fifth experimental modes with the second and the third FE modes show only 0.6% and 1.0% difference, respectively. These two modes agree well with the FE modes. The main reason of this discrepancy is due to the modeling error of the FE model. Note that the interaction between the bottom of the steel box and the water is simply replaced by linear spring elements in FE model. The impact of the force of inertia, damping force, and restoring force due to the water is neglected in the model. Indeed, constructing the accurate FE model of a floating structure is a challenging task and should be addressed in the near future. Also the data processing technique for modal properties using ambient vibration test should be studied for the real massive floating structures where input force is impractical.

5. Summary and conclusions

The objective of this paper is to identify the modal properties of a steel box structure floating on the water. A laboratory impact modal testing is performed on the upper plate of steel box to obtain the resonant frequencies and the corresponding mode shapes. A total of five modes are extracted in the frequency range of 0 to 200 Hz. These results are compared to those of a finite element model.

On the basis of the results obtained in this study, the following conclusions are drawn.

First, high quality experimental data, which correlates well with FE predictions, can be obtained for the floating structures presented in this study.

Second, the correlations between the experimental and analytical mode shapes are identified using the modal assurance criteria and three modes show acceptable correlation.

Third, an ambient vibration measurement method along with the modal identification technique should be developed for the real massive floating structure.

Finally, more corroborated efforts are needed to enhance the accuracy of the finite element model which can explain the interaction between structure and water.

Acknowledgements

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