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Dynamic characteristics of a scaled floating mobile quay using ambient vibration tests under normal sea condition

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ABSTRACT: For the purpose of analyzing economical and structural feasibility and obtaining core technologies in design, fabrication, ballasting, integration and maintenance of a floating mobile quay, one-sixth scale model with 50m x 30m x 5m dimension of pontoon-type floating mobile quay was constructed. After turning out four individual modules (with 25m x 15m x 5m) on a floating dock, they were launched, ballasted, and then integrated by post-tensioning. Two times of ambient vibration tests were carried out for an individual module of floating mobile quay (with 15mx25mx5m) and for an integrated floating quay (with 30mx50mx5m) and the resonant frequencies and corresponding mode shapes and damping ratios were estimated. It was found that the global behavior of a structure is dominated by rolling and pitching motions and there is almost no heaving motion. Consequently the rolling and pitching modes can be estimated reasonably while the heaving mode could not be obtained.

1 INTRODUCTION

Recently many studies are being carried out to enhance loading and unloading capability of the existing land-based berthing system and to reduce total logistics cost by developing new-type harbor infrastructures and equipments. An indented berthing system with both sides loading/unloading capability (http://ceres.apmi.nl/indented_berth.html), a speed port (http://www.actamaritime.com), a hybrid quay wall (Chae *et al*. 2008) and an intelligent terminal operation system are recently proposed or applied systems to meet the changing market conditions of harbor logistics industries such as the increase of yearly global container throughput and the appearance of very large container ship in 15,000 TEU (twenty-foot equivalent unit) class. In the case of berthing system, which is one of main infrastructures in a container terminal, a floating-type (mobile or fixed) quay is drawing increasing interest nowadays because the floating-type quay can be easily and eco-friendly applied to expand the handling capability of an existing quay while the reclamation-based enlargement can cause severe environmental problems. To handle the increasing containership and transshipment cargos in time, a new-type floating mobile quay is being developed in this study. The floating-type mobile quay is designed to maximize the handling capability by using both sides of very large container ship and is also expected to utilize for enlargement of an existing berth eco-friendly.

The intensive feasibility tests should be carried out and the structural stability, safety and workability of floating mobile quay need to be verified theoretically and also experimentally to

equip container terminals with a new-type floating quay. For the purpose of analyzing economical and structural feasibility and obtaining core technologies in design, fabrication, ballasting, integration and maintenance of a floating mobile quay, one-sixth scale model with 50m x 30m x 5m dimension of pontoon-type floating mobile quay was constructed in the yard of Samsung Heavy Industries in Geoje, Korea. After turning out four individual modules (with 25m x 15m x 5m) on a floating dock, they were launched, ballasted, and then integrated by post-tensioning. An intensive field test at an open sea area was carried out to verify the structural stability and safety of the mobile quay and crane workability at the operating room during last December. For the field test, a ship wave driven by four successive traveling vessels was utilized as an external wave loading condition and many kinds of sensors were installed to measure dynamic motions and internal forces including MRU-5 (a gyro-system), RTK-GPS (Real Time Kinematic-Global Positioning System), Strapdown accelerometers, vision-based system, load cells and buoys. The intensive field test data are now under analysis and the results will be summarized and discussed later.

Since these kinds of intensive field experiments in open sea are very difficult to exercise due to high costs of sensor installation and ship rent, an alternative way is also adopted herein based on the ambient vibration measurements under normal sea condition. Ambient vibration test, which can be carried out with simple and economic measurement system, is quite appropriate as a preliminary tool to understand the fundamental dynamic characteristics of a large scale floating structure.

2 INTRODUCTION TO HYBRID QUAY WALL

The floating mobile quay (HQW, Hybrid Quay Wall) is consisted of a very large pontoon type floating structure with thrusters controlled by dynamic positioning technique, mooring systems, and access bridges to an existing land side berth. It has functions of both side loading/unloading and direct transshipment to feeder vessels in combination with the existing land based berth, container crane(CC), transfer crane(TC) and an intelligent operating system for the HQW.

There are various advantages and disadvantages of the HQW compared to land-based berthing structures. The advantages of using HQW includes (i) the loading and unloading capabilities can be easily expanded and accelerated, (ii) it is minimally influenced by the change of water-level by tide and storm surge, (iii) the containers and structures on a floating quay are protected from seismic shocks, (iv) not influenced by soil/seafloor condition such as sinkage, liquefaction, deposition, and scouring so it does not suffer from differential settlement due to reclaimed soil consolidation, (v) minimize the construction cost requiring no foundation work, (vi) can be easily removed or relocated if the sea space is needed in future or if it is required at a different place, (vii) minimum environmental impact on the flow/water-quality system inside a harbor, (viii) applicability to related technologies, such as floating factory plants and floating docks. On the other hand, possible disadvantages include (i) possible non-operability in relatively severe wave condition and survivability in a very severe storm condition, such as a Typhoon, (ii) operational cost related to towing may be very high, (iii) mooring design for mobile quay is highly challenging. One of the most important aspects of the HQW design is to minimize relative motions between the floater and container ship to ease the offloading operation.

Isometric view for the container terminal adopting the HQW is shown in Fig. 1. Two different applications of the HQW are considered as shown in Figure 1. One is an indented berth with adjustable width (the left in Figure 1), and the other is a mobile quay along an existing berth (the right in Figure 1).

Figure 1. Isometric view of a terminal adopting the HQW

3 AMBIENT VIBRATION TEST AND ITS APPLICATION

3.1 Ambient vibration tests

Recently ambient vibration tests are drawing a great deal of interests among civil engineers and researchers related to the management of civil infrastructures. This method can be applied to identify dynamic properties of civil infrastructures such as long-span bridges and high-rise buildings and to evaluate their structural integrities based on estimated dynamic characteristics. While many studies related to ambient vibration tests are very actively carried out for the inland civil infrastructures nowadays, ambient vibration tests and its applications were studied already in early 1980's for offshore jacket structures (Yang *et al*. 1984). Yang *et al* proposed the random decrement technique to identify modal properties of offshore jacket structures using ambient vibrations under wave loading conditions and to evaluate the structural damages. However, the related research works are not frequently reported nowadays even a number of offshore structures are being utilized to produce natural resources in ocean area. It may be due to the fact that these structures are generally private properties and the owners don't want to report their properties' integrities to the public. Recently Balaji *et al*. (2008) proposed modal parameter identification method for a floating system using impulse motion and continuous wavelet transform. And they concluded that the continuous wavelet transform were found to be accurate compared to that obtained from the time and frequency domain analysis. However, it would be very difficult to make an impact response for the very large floating structures like floating mobile quay. In such a case, ambient vibration tests can be a reasonable alternative method to identify modal properties of floating structures.

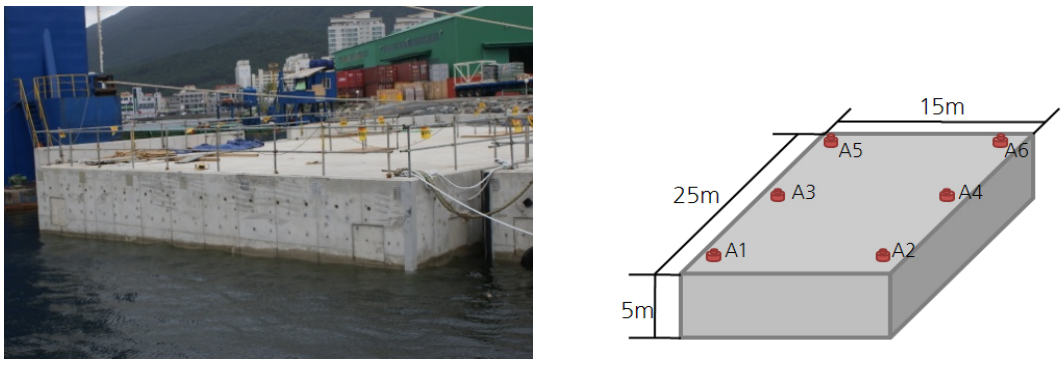
In this study, the stochastic subspace identification technique (Peeters and De Roeck, 1999), which is a relatively new modal identification technique using output-only information, is is applied to identify fundamental vibration modes (resonant frequencies, mode shapes and damping ratios) from ambient vibration data. And the identified dynamic characteristics are compared with the numerical simulation results.

3.2 Ambient vibration tests for module of mobile quay

After fabricating four individual modules on floating dock, they were launched and temporarily moored using a fixed mooring dolphin and mooring lines as shown in Figure 2. Before integrating these modules, the ambient vibration tests were carried out during 60 minutes from 12:30PM on 24 September 2008. Figure 2 shows the tested module and sensor locations, and

Figure 3 shows the initial 10 minutes' measured responses from Sensor #1. Without regular electricity, a wireless data logging system (http://www.kmbest.co.kr), which can be operated with small size of batteries, was utilized for quick sensor and cable installation. 6 ICP-type accelerometers were used and accelerations in vertical direction at the 6 points were measured in sampling rate of 20Hz.

For very large and relatively thin floating structures, a hydroelastic behavior needs to be considered, however the hydroelastic responses were ignored during the vibration tests, and just 6 rigid body motions were considered including heave, surge, sway, roll, pitch and yaw. In the case of surge, sway and yaw, they don't have any resonant (or dominant) frequencies because there is no reaction and the motions are controlled by input wave forces and (hydrodynamic) inertial and damping forces. On the other hand, the other 3 motions (heave, roll and pitch) have resonant frequencies because the buoyant forces act as a reaction force like spring elements in structural system. These resonant frequencies can be analyzed by numerical simulation and also experimental test. In this study, the resonant frequencies and corresponding mode shapes and damping ratios were experimentally estimated using ambient vibration tests and the results were compared with numerical simulation results.



(a) Test module of floating mobile quay (b) Sensor locations

Figure 2. Test module of floating mobile quay and sensor locations

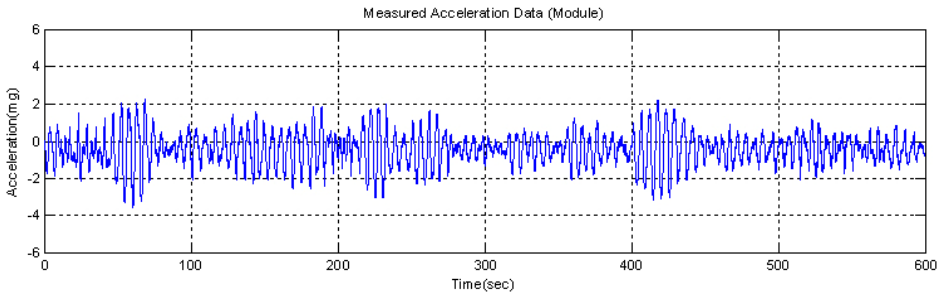


Figure 3. Measured acceleration data (for initial 10 minute at Sensor #1)

Figure 4 shows the stabilization chart (Peeters and De Roeck, 1999) that gives very useful information to identify stable and non-trivial modal properties of a structure. From this stabilization chart, the stable and non-trivial modes can be easily obtained. To enhance the precision and computational efficiency, the measured data were recollected with a sampling rate of 2Hz by low-pass (anti-aliasing) filtering and decimation because main modes were observed in frequency range lower than 1Hz. It can be observed that the main vibration modes are in the range of 0.17-0.20Hz. The estimated modal properties such as mode shapes, resonant frequencies and damping ratios are summarized at Figure 5. It was expected that the resonant

modes of all 3 rigid body motions could be easily identified by measuring ambient vibration; however, the heaving mode was not clearly obtained consequently. It may be due to the fact the structure was not in fully free floating condition (i.e. they were connected with each other by ropes and a fixed dolphin) and also the input wave forces excited just two modes (rolling and pitching modes) but heaving mode.

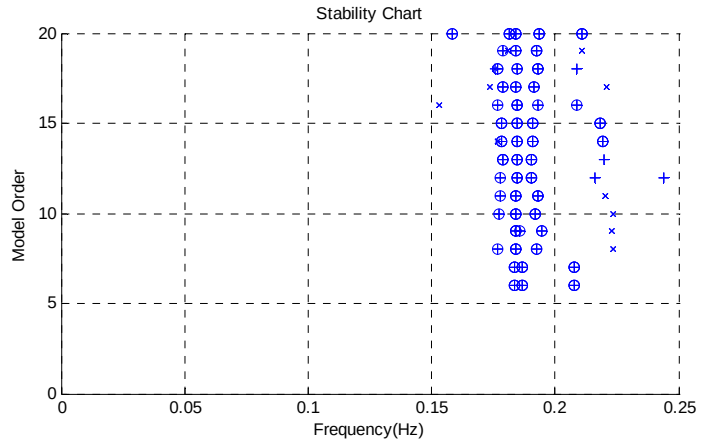
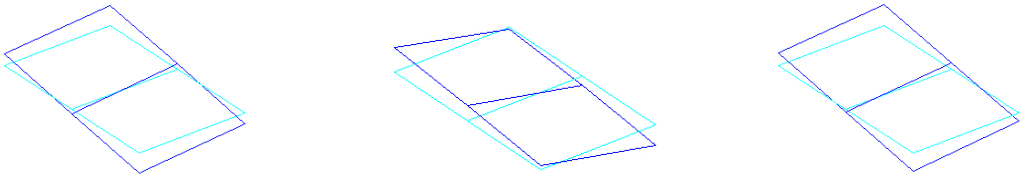


Figure 4. Stabilization chart for measuring data of one module



(a) 0.1779Hz, 4.82% (Rolling governing mode)

(b) 0.1843Hz, 1.34% (Pitching + Rolling)

(c) 0.1932Hz, 1.71% (Rolling governing mode)

Figure 5. Estimated mode shapes and corresponding resonant frequencies and damping ratios

To analyze the details of the 3 modes, the 3 motion components are recalculated using the following equations. Even though the rolling and pitching motions are rotational quantities, the distance between sensors are not considered to compare the acceleration levels related to rolling and pitching with that of heaving motion.

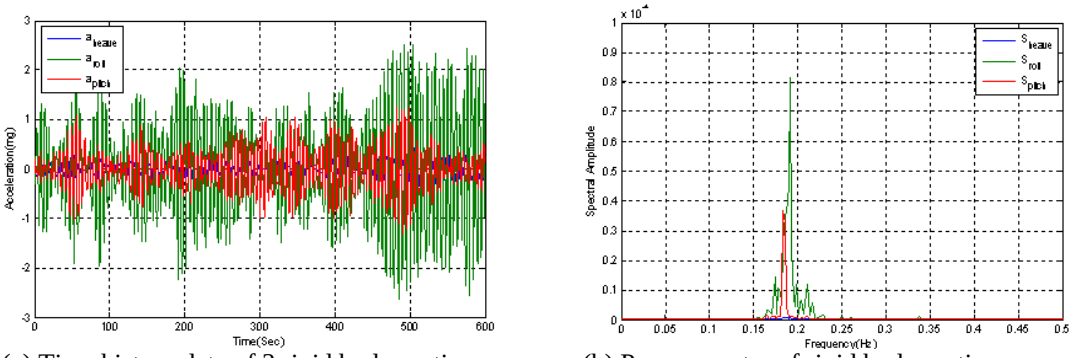
$$a_{heave}(t) = \left(a_1(t) + a_2(t) + a_5(t) + a_6(t)\right)/4 \tag{1}$$

$$a_{rolling}(t) = \left(a_1(t) + a_2(t) - a_5(t) - a_6(t)\right)/4 \tag{2}$$

$$a_{pitching}(t) = \left(a_1(t) - a_2(t) + a_5(t) - a_6(t)\right)/4 \tag{3}$$

Figure 6 shows the time history data of the 3 components and the response spectra. It can be easily found that the rolling motion is governing the global behavior of the module structure, and then the pitching motion is secondly dominant. It can be understood that there is almost no heaving motion. Moreover, it can be observed that the resonant frequencies of the rolling and pitching modes are separated with each other while the resonant frequency of heaving mode is almost same with that of rolling motion (see Figure 6(b)). It means that the heaving mode was

not sufficiently excited by the wave forces during ambient vibration tests and also the global behavior is dominated by rolling and pitching rather than heaving. There were two resonant frequencies for rolling modes (i.e. 0.1779Hz and 0.1932Hz), but the result in Figure 6(b) reveals that the latter frequency (i.e. 0.1932Hz) is the fundamental frequency of rolling mode.

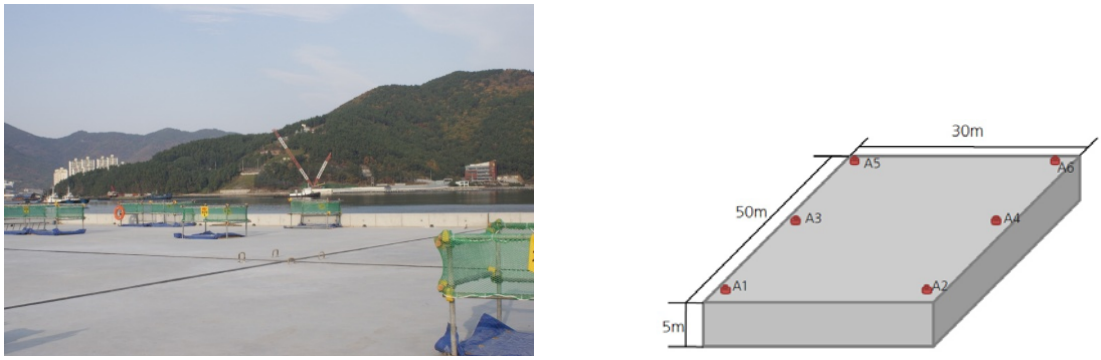


(a) Time history data of 3 rigid body motions (b) Power spectra of rigid body motions

Figure 6. Three rigid body motion components and their power spectra

3.3 Ambient vibration tests for integrated mobile quay

After integrating four modules, ambient vibration tests were carried out once again during 60 minutes from 3:30PM on 17 November 2008. Figure 7 shows the integrated floating mobile quay and sensor locations, and Figure 7 shows the initial 10 minutes' measured responses from Sensor #1. 6 ICP-type accelerometers were used and accelerations in vertical direction at the 6 points were measured in sampling rate of 20Hz.



(a) An integrated floating mobile quay (b) Sensor locations

Figure 7. An integrated floating mobile quay and sensor locations

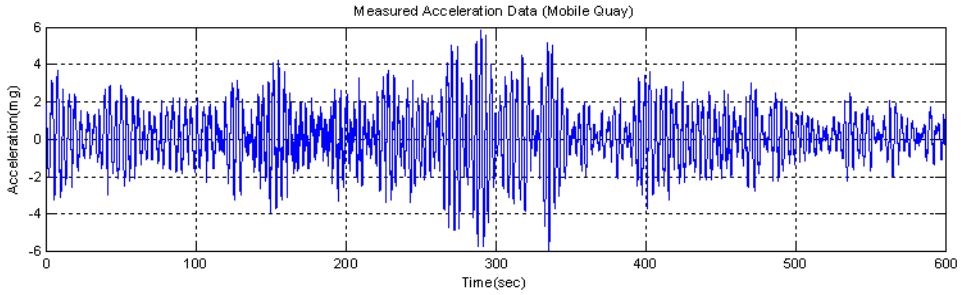


Figure 8. Measured acceleration data (for initial 10 minute at Sensor #1)

Figure 9 shows the stabilization chart and the main vibration modes are found in the range of 0.2-0.35Hz. The estimated modal properties are summarized at Figure 10. The heaving mode was not identified either due to the same reason of the former example study for the module in Section 3.2.

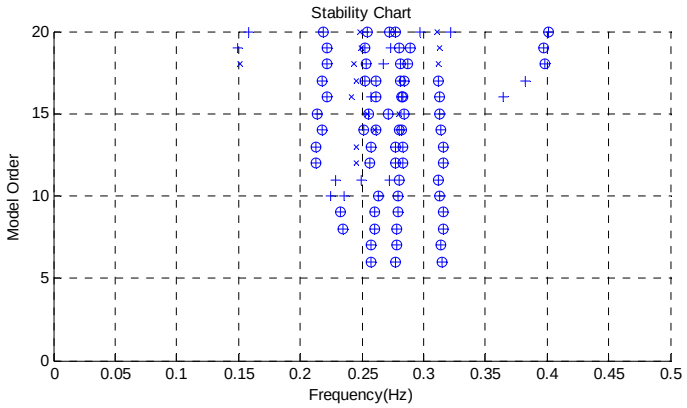
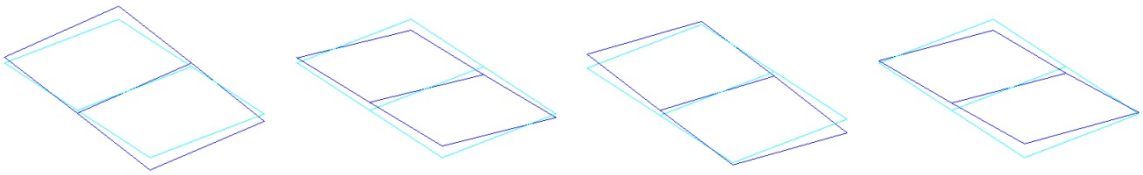


Figure 9. Stabilization chart for measuring data of integrated mobile quay



(a) 0.2175Hz 8.60% (Roll+Pitch)

(b) 0.2575Hz 5.02% Rolling

(c) 0.2789Hz 4.58% Pitching

(d) 0.3142Hz 2.00% Roll+Pitch

Figure 10. Estimated mode shapes and corresponding resonant frequencies and damping ratios

The resonant frequencies can be numerically evaluated from the RAO (response amplification operator) analysis using boundary element method or other numerical methods. For the boundary element method, the structure is modeled as rigid body for simplicity and the RAOs for just 6 vibration modes were obtained. The evaluated resonant frequencies are summarized in Table 1 and it is observed that there are significant levels of discrepancies between two results. It may be due to that the modeling errors in numerical simulation or difference of wave condition (such as wave direction). Further studies need to be carried out for more reliable comparison.

Table 1. Evaluated resonant frequencies from numerical simulation and experimental tests

	Numerical simulation	Experimental tests
Heave	0.1592Hz	-
Pitching	0.1989Hz	0.2789Hz
Rolling	0.1512Hz	0.2575Hz

4 CONCLUDING REMARKS

This paper introduces the new-type floating mobile quay (Hybrid Quay Wall, HQW) and the vibration characteristics obtained from ambient vibration tests. The results are not fully understood including the reason why the heaving modes are not sufficiently excited and the results are significantly differ from the results of numerical simulation. More precise analysis is required and also the results from ambient vibration tests can be compared with the intensive field tests later.

ACKNOWLEDGEMENTS

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