Hindawi Publishing Corporation
International Journal of Distributed Sensor Networks
Volume 2012, Article ID 597546, 9 pages
doi:10.1155/2012/597546

Research Article

Field Implementation of Wireless Vibration Sensing System for Monitoring of Harbor Caisson Breakwaters

Han-Sam Yoon,[1] So-Young Lee,[2] Jeong-Tae Kim,[2] and Jin-Hak Yi[3]

[1] *Research Center for Ocean Industry and Development, Pukyong National University, 599-1, Daeyeon 3-dong, Nam-gu, Busan 608-737, Republic of Korea*
[2] *Department of Ocean Engineering, Pukyong National University, 599-1, Daeyeon 3-dong, Namgu, Busan 608-737, Republic of Korea*
[3] *Coastal Development & Ocean Engineering Research Division, Korea Institute of Ocean Science and Technology, Sa 2-dong, Sangrok-gu, Ansan 426-744, Republic of Korea*

Correspondence should be addressed to Jeong-Tae Kim, idis@pknu.ac.kr

Received 25 September 2012; Accepted 7 November 2012

Academic Editor: Ting-Hua Yi

A wireless sensing system for structural health monitoring (SHM) of harbor caisson structures is presented. To achieve the objective, the following approaches were implemented. First, a wave-induced vibration sensing system was designed for global structural health monitoring. Second, global SHM methods which are suitable for damage monitoring of caisson structures were selected to alarm the occurrence of unwanted behaviors. Third, an SHM scheme was designed for the target structure by implementing the selected SHM methods. Operation logics of the SHM methods were programmed based on the concept of the wireless sensor network. Finally, the performance of the proposed system was globally evaluated for a field harbor caisson structure for which a series of tasks were experimentally performed by the wireless sensing system.

1. Introduction

According to a report of the Intergovernmental Panel on Climate Change [1], global warming is unambiguous. As sea surface temperature increases, water vapor in the lower troposphere also increases, and so does the energy of typhoons. The relationship between global warming and increased typhoon activity and intensity has been verified, reported by studies based on analyses of historical records and simulation results [2–4]. It was also reported that typhoons in the western North Pacific (WNP), including Korea, have become more intense as measured by their frequency in hurricane categories 4 and 5 [5] or the power dissipation index [3]. A strong typhoon usually brings strong winds and heavy rains, causes severe surge and floods, and then results in significant loss of life and property. Accordingly, the increase of typhoon intensity and frequency makes severer damages over the Pacific Ocean from the Philippine Islands to Taiwan, Japan, Korea, and the southwestern coast of China.

In general, coastlines, interfaces between ocean and land, are facing a severe state of typhoon than inland; thus, the safety of coastal structures becomes more significant under storm waves. The safety can be checked in a regular or irregular time scale, depending on the state of the target coastal structures and occurrence of extreme loading conditions such as typhoons. The safety is usually done by structural health monitoring (SHM) to identify existing damages in the target structures, gravity type or pile type, and finally to make an assessment of their healthy status. In the gravity-type coastal structures, the damages can be classified into settlement, overturning, or sliding. Local defects such as scouring and disturbance in foundation can also occurr and these defects tend to propagate into severer damages, that is, the global damages, such as partial settlement, under extreme wave forces. Thus, it is imperative to capture the local defects in time, at least just before these defects become a real threat.

In South Korea, most coastal or harbor structures have been constructed as gravity type and recently, thanks to the advances in concrete and towing and laying technology, very large caissons, a gravity type, became popular for constructing breakwaters, quays, and so forth. Considering the report [6, 7], significant damages of harbor caissons are mostly attributed to foundation-structure interface that is, foundation mound. Goda and Takagi [8] and Takahashi et al. [9] also reported that sliding at the foundation-structure interface is the primary damage of caissons. It is known that cavity in foundation mound or backfill makes harbor caissons weaker against extreme loads such as storm waves, mainly occurred from typhoon. Thus, SHM for gravel mounds for existing caisson structures is absolutely demanded.

Since as early as the 1980s, many researchers had studied SHM techniques in the field of civil engineering [10, 11] by mainly performing vibration-based damage monitoring of civil structures [12–14]. Also, many researchers have worked on developing damage detection methods such as the modal sensitivity method, modal flexibility method, genetic algorithm, and neural network [15–20]. Related to the damage detection, sensor placement techniques have been studied and evaluated by applying to the tower structure [21, 22].

Up-to-date research studies, however, have focused mostly on inland structures but only few research efforts have been made to harbor structures, which include vibration response analyses of soil-structure or fluid-soil-structure interactions in harbor caisson structures [23, 24] and SHM of a cylinder caisson using fiber grating sensing technology [25]. Considering harbor caisson structures, there exist research needs to monitor vibration responses with limited access and to identify sensitive vibration methods of a row of caisson units with respect to damage in caissons foundation and/or damage in caisson's interlocking members.

The demand to test full-scale structures has led structural engineers to develop new methods to perform such experiments, that is, input-output (forced vibration) and output-only (ambient vibration) modal identification methods. Since it is difficult to excite large and massive civil structures in a controlled manner, the performance of output-only modal identification tests became an alternative in the field of civil engineering. Bridge structures have been the representative target to verify the efficiency of output-only modal identification [26–30]. Also, other structures have been tested through the identification [31–34]. These studies show that ambient tests have been successfully applied to a number of large bridges, towers, storage tanks, and buildings. Thus, in this study, we applied vibration-based SHM on massive caisson structures that cannot be excited by forced vibration. In other words, instead of using forced vibrations, we used water wave-induced vibrations for SHM, which utilized by ambient vibration modal identification methods.

Output-only modal identification methods can be classified into two groups: parametric methods in time domain and nonparametric methods essentially developed in the frequency domain. The frequency domain methods are initiated by the construction of power spectral densities (PSDs) involving all of the measurement points in the test program. In this study, we also used PSDs and, consequently, correlation coefficient (CC) and lower control limit (LCL) to alarm the damaged states. Namely, the occurrence of damage was indicated when the standard deviation of CC values is beyond the bound of LCL. In addition, the frequency domain decomposition (FDD) method was used to extract modal parameters such as natural frequency and mode shape. These modal parameters were used to determine a reference state and, accordingly, distinguish the healthy states of the target caissons.

Recent development in wireless smart sensor node (SSN) technologies has motivated various applications in the frequency domain-based SHM of massive engineering structures. So far, numerous field works have demonstrated that wireless smart sensors can be used to construct a reliable and accurate SHM system [35–40]. In addition to the relatively lower cost than wired SHM systems, one of the great advantages for using wireless sensors is that autonomous operations for SHM can be implemented by embedding advanced system technologies. In the study, we also proposed a vibration-based wireless sensing system comprising an accelerometer, wireless data logger, wireless receiver, and laptop. Moreover, an autonomous SHM scheme was developed utilizing CC and modal parameter-based method, which were operation logics of the proposed SHM.

In summary, we present a wireless sensing system for structural health monitoring of harbor caisson structures. To achieve the objective, the following approaches were implemented. First, a wave-induced vibration sensing system was designed for global structural health monitoring. Second, global SHM methods which are suitable for damage monitoring of caisson structures were selected to alarm the occurrence of unwanted behaviors. Third, an SHM scheme was designed for the target structure by implementing the selected SHM methods. Operation logics of the SHM methods were programmed based on the concept of the wireless sensor network. Finally, the performance of the proposed system was globally evaluated for a field harbor caisson structure for which a series of tasks were experimentally performed by the wireless sensing system.

2. Wireless Monitoring System for Harbor Caisson

2.1. Vibration-Based Wireless Sensing System. Figure 1 shows the proposed vibration-based wireless sensing system. One system is comprised of accelerometers, wireless data loggers, a wireless receiver, and a laptop, as shown in Figure 1. Rechargeable battery, which supplied electric power to the data logger itself and to the accelerometer through the BNC cable, was embedded in the data logger. Electric power for receiver was supplied by external portable battery. In the system, as shown in the figure, the *i*th accelerometers captured the signals and transported the captured to the *i*th data loggers by the BNC cables, then the transported signals were wirelessly transmitted to the receiver, and finally the signal arrived to the laptop via the LAN cable. To acquire the wave-induced, micro-vibration signals, we used PCB393B03 model for the accelerometers, which have the measurable range of ± 0.5 g and sensitivity of 10 V/g. In the wireless communication, 2.4 GHz Bluetooth of transmitting frequency was used to range its communication to 1.2 km. The wireless data loggers had a programmable low pass filter

Figure 1: Schematic of wireless vibration sensing system.

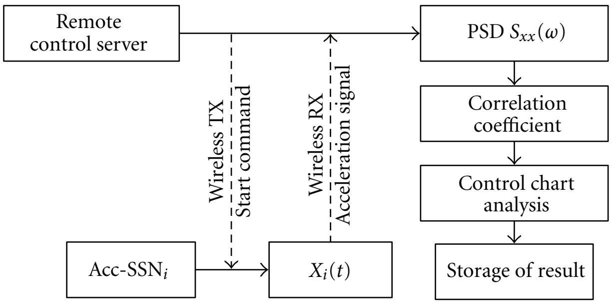


Figure 2: An autonomous SHM procedure for PSD-based method.

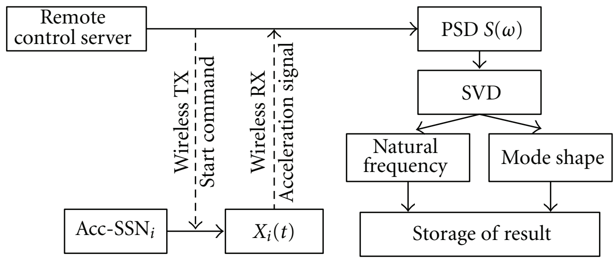


Figure 3: An autonomous SHM procedure for modal parameter-based method.

from 10 Hz to 1 kHz and resolution of 16 bits. Also, the available sampling frequency ranged from 1 Hz to 1 kHz and the accuracy of synchronization was in 10 Ms.

The wireless sensing system utilized the vibration-based SHM methods PSD–based method and modal parameter-based method. Moreover, an autonomous operation was carried out in the wireless sensing system by the operation logics based on correlation coefficient of power spectral density and modal parameter-based method. The brief introduction to the SHM methods and autonomous operation are briefly explained in the following sections.

2.2. Vibration-Based SHM Methods

2.2.1. Power Spectral Density-Based Method. Assume there are two acceleration signals, $x(t)$ and $y(t)$, measured before and after a damaging episode, respectively. The corresponding power spectral densities (PSDs), S_{xx} and S_{yy}, are calculated from Welch's procedure as [41]

$$S_{xx}(f) = \frac{1}{n_d T}\sum_{i=1}^{n_d}\left|X_i(f,T)\right|^2, \tag{1a}$$

$$S_{yy}(f) = \frac{1}{n_d T}\sum_{i=1}^{n_d}\left|Y_i(f,T)\right|^2, \tag{1b}$$

where X and Y are the frequency response transformed from correspondent acceleration signal; n_d is the number of divided segments; T is the data length of divided segment.

The correlation coefficient (CC) of PSDs represents the linear identity between the two PSDs obtained before and after a damage event, as follows:

$$\rho_{XY} = \frac{E\left[S_{xx}S_{yy}\right] - \mu_{S_{xx}}\mu_{S_{yy}}}{\sigma_{S_{xx}}\sigma_{S_{yy}}}, \tag{2}$$

where $E[\cdot]$ is the expectation operator and $\sigma_{S_{xx}}$ and $\sigma_{S_{yy}}$ are the standard deviations of PSDs of acceleration signals measured before and after damaging episode, respectively. If any damage occurs in target structure, its acceleration responses would be affected and, consequently, the decrement of CC can be a warning sign of the presence of damage.

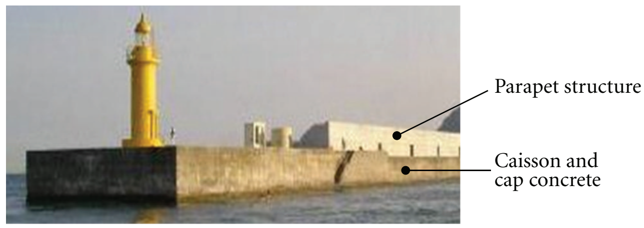


Figure 4: Oh-Ryuk-do caisson-type breakwater.

For damage alarming, control chart analysis is also performed to discriminate damage events from the CC values. The alarming threshold is determined by the lower control limit (LCL) as follows:

$$\mathrm{LCL}_\rho = \mu_\rho - 3\sigma_\rho, \tag{3}$$

where μ_ρ and σ_ρ are the mean and the standard deviation of the CC values, respectively. The occurrence of damage is indicated when the CC values are beyond (i.e., less than) the bound of the LCL; otherwise, there is no indication of damage occurrence.

2.2.2. Modal Parameter-Based Method. Frequency domain decomposition (FDD) method [42, 43] is used to extract modal parameters such as natural frequency and mode shape. The singular values of the PSD function matrix $\mathbf{S}(\omega)$ are used to estimate the natural frequencies instead of the PSD functions themselves as follows:

$$\mathbf{S}(\omega) = \mathbf{U}(\omega)^T\mathbf{\Sigma}(\omega)\mathbf{V}(\omega), \tag{4}$$

where $\mathbf{\Sigma}$ is the diagonal matrix consisting of the singular values (σ_i's) and $\mathbf{U}$ and $\mathbf{V}$ are unitary matrices. Since $\mathbf{S}(\omega)$ is symmetric, $\mathbf{U}$ becomes equal to $\mathbf{V}$. In this FDD method, the natural frequencies can be determined from the peak frequencies of the singular value, and the mode shape from

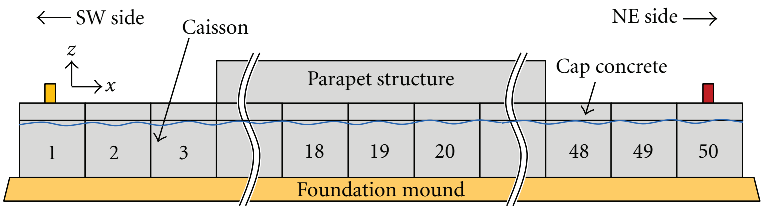


Figure 5: Test layout of Oh-Ryuk-do breakwater.

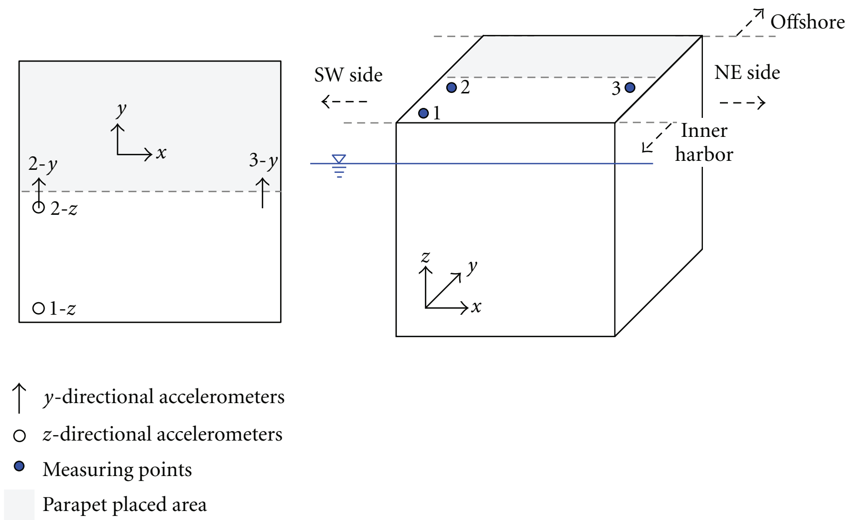


Figure 6: Schematic of wireless vibration sensing system.

any of the column vectors of $\mathbf{U}(\omega)$ at the corresponding peak frequencies. Generally the first singular value $\sigma_1(\omega)$ among σ_i's $(i = 1, \ldots, N)$ is used to estimate the modal parameters except in some special cases such as with two or more identical excitations.

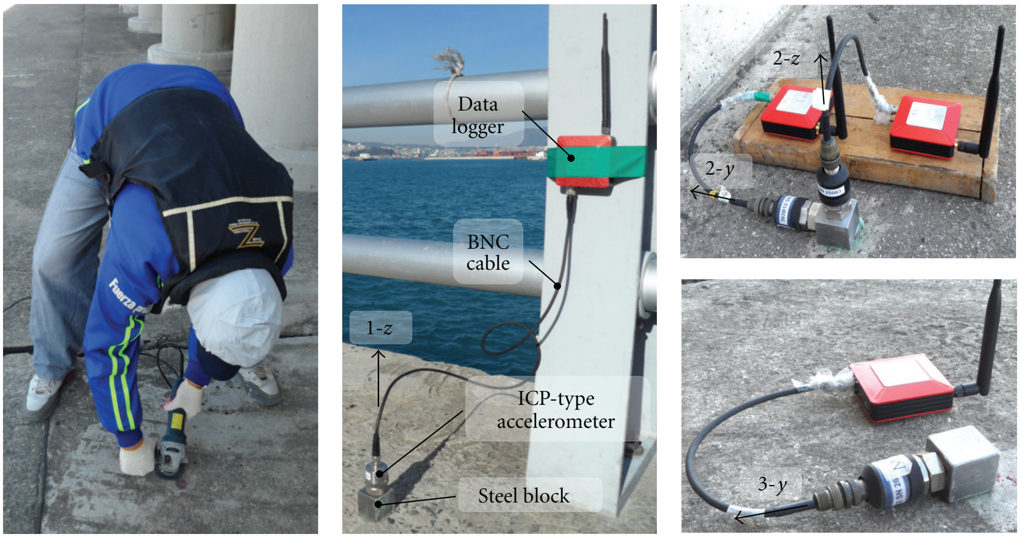
2.3. Autonomous SHM Scheme

2.3.1. Power Spectral Density-Based Method. An autonomous SHM procedure for PSD-based method is designed as shown in Figure 2. The detailed procedure is as follows: (1) transmit “start command” by remote control server to the Acc-SSN (acceleration-based smart sensor node); (2) acquire acceleration signals and store the measurement data in the Acc-SSN; (3) transmit the acceleration signal by the Acc-SSN into the remote control server; (4) compute power spectral density in the remote control server using the embedded FFT algorithm; (5) calculate correlation coefficient in the remote control server; (6) determine if damage is occurred by performing the control chart analysis.

2.3.2. Modal Parameter-Based Method. An autonomous SHM procedure for the modal parameter-based method is designed as shown in Figure 3. The detailed procedure is as follows: (1) transmit “start command” by remote control server to the Acc-SSN (acceleration-based smart sensor node); (2) acquire acceleration signals and store the measurement data in the Acc-SSN; (3) transmit the acceleration signal by the Acc-SSN into the remote control server; (4) compute power spectral density in the remote control server using the embedded FFT algorithm; (5) calculate natural frequency and mode shape using singular value decomposition (SVD) in the remote control server.

3. Field Evaluation

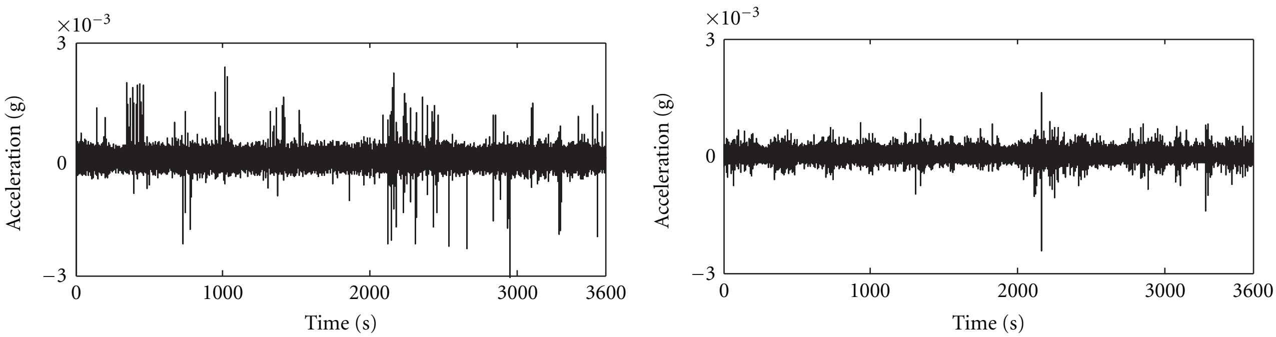
3.1. Target Caisson Structure. A real caisson-type breakwater locating in Busan, South Korea, Oh-Ryuk-do breakwater was selected to verify the applicability of the proposed vibration-based SHM technique, as shown in Figure 4. The breakwater consisted of 50 caissons and its total length was 1,004 m. Each caisson is covered by cap concrete to the height of 4 m. Parapet structure, which has 5.3 m height and 8.8 m width, is located above the caisson units except 1–3 and 48–50. The parapet structure increases the crest height of breakwater and gives higher calmness of harbor. All of the caissons were submerged in seawater and only their cap concretes were exposed in air. Three target structures, which have the same geometry with the parapet, were selected to compare the relative vibration responses by wireless vibration sensing system. Vibration tests were mainly performed on target caissons denoted by 18, 19, and 20 as shown in Figure 5. The size of each caisson is 20 m (width) × 20 m (length) × 16.78 m (depth).



(a) Grinding concrete surface

(b) Installed sensors for three measuring points

Figure 7: Sensor installation on the caisson.



(a) Sensor 2-y

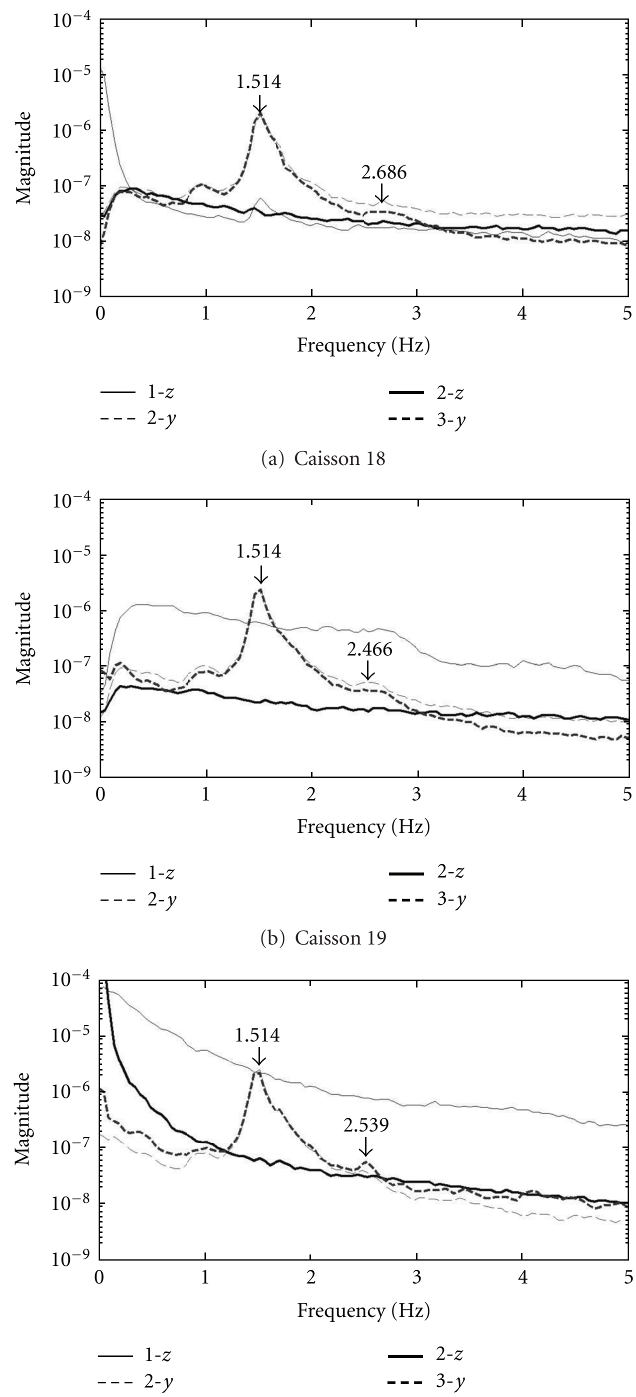
(b) Sensor 2-z

Figure 8: Acceleration signals obtained from sensor 2-y and 2-z of caisson 18.

3.2. Wave-Induced Ambient Vibration Test. In general, it is not easy to acquire forced vibration responses from heavy structures like Oh-Ryuk-do breakwater. To get the response, we may need a tugboat, which was not a possible option in the test. Instead, we measured ambient vibration signals without using any artificial impact load by utilizing the fact that the caisson structures were under incident waves and wind loads.

The measurement was made by the wireless vibration sensing system as schematically shown in Figure 1. As explained earlier, wireless vibration sensing system consisted of accelerometers, wireless data loggers, a wireless receiver, and a laptop. A system of 12 acceleration channels was employed to get the vibration responses of three target caisson units at the same time. Four channels were assigned to each caisson unit (18, 19, and 20) along the direction of the wave incident (y-direction) and upward vertical direction (z-direction), as shown in Figure 6. The sensors are denoted by 2-y, 3-y, 1-z, and 2-z, respectively. Here the first notation (1, 2, or 3) indicates the location of the sensors and the second notation (y or z) denotes the direction of acceleration. The orientation of sensors on the three caisson units was set as same as each other. Before installing the sensors in the precast steel blocks, the surfaces of the top concrete caps were ground down as shown in Figure 7(a). Figure 7(b) shows the components of local node and installed local node for three measuring points. Representative received signals, obtained from 2-y and 2-z of 18, were shown in Figure 8. As shown, the acceleration of the sensor 2-y has a bigger acceleration level than that of sensor 2-z because the wave-induced, ambient vibration was of the same direction as the y-axis.

3.3. Vibration-Based Damage Monitoring. For the three target caissons, damage monitoring was performed by the proposed methods. In the first step, six sets of acceleration measurements were acquired from each caisson and PSDs corresponding to the sets were calculated. The PSDs corresponding to the first set of each caisson were shown in Figure 9, respectively. We can observe from Figure 9 that there are two peaks in the frequency range from 0 to 5 Hz

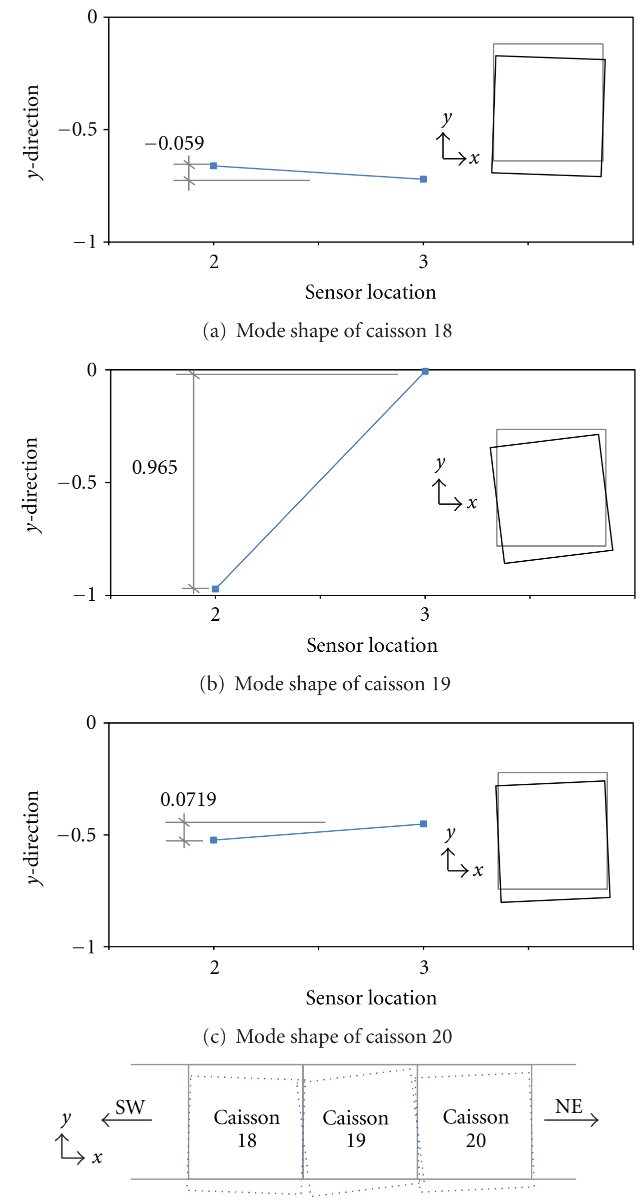


(a) Caisson 18

(b) Caisson 19

(c) Caisson 20

Figure 9: Power spectral densities of caissons 18–20.



(a) Mode shape of caisson 18

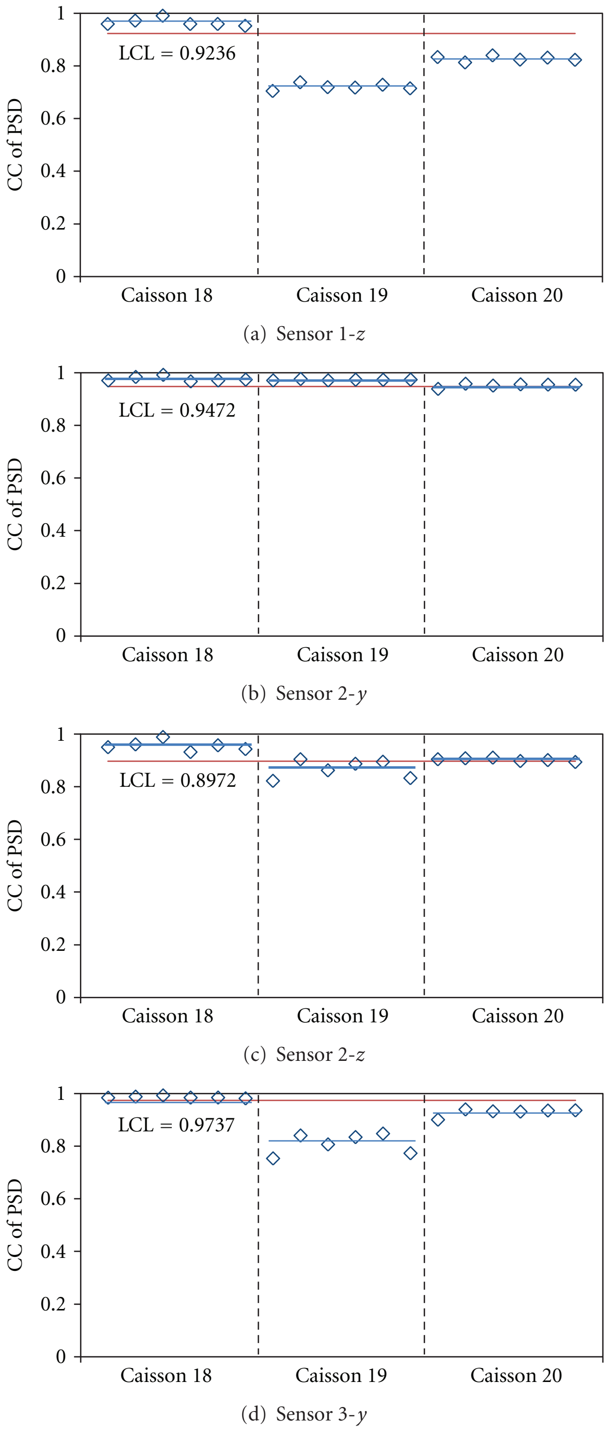
(b) Mode shape of caisson 19

(c) Mode shape of caisson 20

(d) Relative motion of three caissons

Figure 10: Planar mode shapes (mode 1) of caissons 18–20 and their relative motion.

and the y-direction responses are clearer than the z-direction responses. This result comes from the incident wave motion along with the y-axis on the caisson response. The first peak is located at the fixed value of 1.51 Hz for all of the caissons while the second peak is located approximately at 2.5 Hz with the variances such as 2.69 Hz in 18, 2.49 Hz in 19, and 2.54 Hz in 20. The maximum difference of the second peak values is about 8%, which means structural abnormality is sensitive to the second peak. In the second step, planar mode shapes (mode 1) were extracted to examine the relative motions between interfaces, as shown in Figure 10. Frequency domain decomposition (FDD) algorithm [43] was used to extract the mode shapes corresponding to the first frequency 1.51 Hz. As shown, the relative motion of 19 is much larger than those of 18 and 20. Between 18 and 20, the relative motion of 18 is slightly smaller than that of 20; thus, the caisson 18 was selected as the reference and then the states of 19 and 20 were compared with that of the reference caisson. In the final step, CC values were calculated and, accordingly, LCL values were determined as



(a) Sensor 1-z

(b) Sensor 2-y

(c) Sensor 2-z

(d) Sensor 3-y

Figure 11: Correlation coefficient of PSD for caissons 18–20.

shown in Figure 11. This figure illustrates the relative gaps in the healthy states among the caissons. The correlation between 18 and 19 is bigger than that between 18 and 20, which means the healthy state of 19 is worse than that of 20. This observation becomes clearer in the results from 1-z and 3-y because the gaps between the caissons are extinct.

4. Conclusion

In this study, a wireless sensing system for monitoring of the caisson structures of Oh-Ryuk-do breakwater was presented. The following approaches were implemented to achieve the objective. Firstly, a wave-induced vibration sensing system was designed for global structural health monitoring. Secondly, global SHM methods, utilizing correlation coefficient and modal parameters, were selected to alarm the occurrence of unwanted behaviors. Thirdly, autonomous SHM scheme, implementing correlation coefficient and modal parameter-based method, was designed for the target structure. Operation logics of the SHM methods were programmed based on the concept of the wireless sensor network. Finally, the performance of the proposed system was globally evaluated the caisson structures for which a series of tasks were experimentally performed by the wireless sensing system.

From the field test, we found that the proposed wireless sensing system can make an assessment of the healthy states of the target caissons by implementing the value of correlation coefficient with respect to the bound of the lower control limit. For the implementation, we need to establish the reference state, which can be possibly identified by comparing the relative motions of the target caissons. It should be also noted here that the direction of accelerometer is quite significant to get a strong signal. In this study, we found that the wave-induced, ambient vibration gave a strong signal when accelerometers were along with wave direction. Moreover, it is found that the clear peaks were established in the power spectral densities obtained from the sensors located in the y-direction. This fact supports the correlation coefficients extracted from the sensor 3-y, which distinguish the healthy states of the three caissons. However, the correlation coefficients from the sensor 1-z also gave a distinct assessment. It seems that the sensor location is also an important factor to get a promising test result, along with the sensor orientation. Thus, the distributed sensor system should be addressed with promising damage detection methods, schemes, and wireless networks.

This study shows a successful wireless monitoring procedure for the harbor caisson structures. Thus, we believe that the proposed wireless SHM method and process provide invaluable information for designers, construction crews, and field engineers when they design, construct, and inspect caissons of breakwaters and quays, which are widely used in connection with men and goods transportation from the mainland to an island, and from a nation to other nations.

Acknowledgment

This work was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2011-0004253). The authors also would like to acknowledge the financial support of the project "Development of inspection equipment technology for harbor facilities" funded by Korea Ministry of Land, Transportation, and Maritime Affairs.

References

[1] Intergovernmental Panel on Climate Change (IPCC), *Climate Change 2007: The Physical Science Basis*, Cambridge University Press, Cambridge, UK, 2007.

[2] T. R. Knuston and R. E. Tuleya, "Impact of CO_2-induced warming on simulated hurricane intensity and precipitation: sensitivity to the choice of climate model and convective parameterization," *Journal of Climate*, vol. 17, no. 11, pp. 3477–3495, 2004.

[3] K. Emanuel, "Increasing destructiveness of tropical cyclones over the past 30 years," *Nature*, vol. 436, no. 7051, pp. 686–688, 2005.

[4] J. B. Elsner, J. P. Kossin, and T. H. Jagger, "The increasing intensity of the strongest tropical cyclones," *Nature*, vol. 455, no. 7209, pp. 92–95, 2008.

[5] P. J. Webster, G. J. Holland, J. A. Curry, and H. R. Chang, "Atmospheric science: changes in tropical cyclone number, duration, and intensity in a warming environment," *Science*, vol. 309, no. 5742, pp. 1844–1846, 2005.

[6] Committee of Coastal and Ocean Engineering, "Current extent of damage due to typhoon Maemi and its countermeasure," *Civil Engineering, Korean Society of Civil Engineers*, vol. 21, no. 10, pp. 28–38, 2003.

[7] S. Y. Lee, J. T. Kim, J. H. Yi, and Y. K. Kang, "Structural health monitoring of harbor caisson-type structures using harmony search method," *Journal of Ocean Engineering and Technology*, vol. 23, no. 1, pp. 122–128, 2009.

[8] Y. Goda and H. Takagi, "Reliability design method of caisson breakwaters with optimal wave heights," *Coastal Engineering Journal*, vol. 42, no. 4, pp. 357–387, 2000.

[9] S. Takahashi, K. I. Shimosako, K. Kimura, and K. Suzuki, "Typical failures of composite breakwaters in Japan," in *Proceedings of the 27th International Conference on Coastal Engineering (ICCE'00)*, pp. 1899–1910, July 2000.

[10] R. D. Adams, P. Cawley, C. J. Pye, and B. J. Stone, "A vibration technique for non-destructively assessing the integrity of structures," *Journal of Mechanical Engineering Science*, vol. 20, no. 2, pp. 93–100, 1978.

[11] N. Stubbs and R. Osegueda, "Global non-destructive damage evaluation in solids," *International Journal of Analytical and Experimental Modal Analysis*, vol. 5, no. 2, pp. 67–79, 1990.

[12] S. W. Doebling, C. R. Farrar, and M. B. Prime, "A summary review of vibration-based damage identification methods," *Shock and Vibration Digest*, vol. 30, no. 2, pp. 91–105, 1998.

[13] J. M. W. Brownjohn, P. Q. Xia, H. Hao, and Y. Xia, "Civil structure condition assessment by FE model updating: methodology and case studies," *Finite Elements in Analysis and Design*, vol. 37, no. 10, pp. 761–775, 2001.

[14] F. N. Catbas, M. Gul, and J. L. Burkett, "Conceptual damage-sensitive features for structural health monitoring: laboratory and field demonstrations," *Mechanical Systems and Signal Processing*, vol. 22, no. 7, pp. 1650–1669, 2008.

[15] J. T. Kim and N. Stubbs, "Model-uncertainty impact and damage-detection accuracy in plate girder," *Journal of Structural Engineering*, vol. 121, no. 10, pp. 1409–1417, 1995.

[16] A. E. Aktan, D. N. Farhey, A. J. Helmicki et al., "Structural identification for condition assessment: experimental arts," *Journal of Structural Engineering*, vol. 123, no. 12, pp. 1674–1684, 1997.

[17] R. I. Levin and N. A. J. Lieven, "Dynamic finite element model updating using simulated annealing and genetic algorithms," *Mechanical Systems and Signal Processing*, vol. 12, no. 1, pp. 91–120, 1998.

[18] C. B. Yun and E. Y. Bahng, "Substructural identification using neural networks," *Computers and Structures*, vol. 77, no. 1, pp. 41–52, 2000.

[19] J. T. Kim, Y. S. Ryu, H. M. Cho, and N. Stubbs, "Damage identification in beam-type structures: frequency-based method versus mode-shape-based method," *Engineering Structures*, vol. 25, no. 1, pp. 57–67, 2003.

[20] G. J. Yun, K. A. Ogorzalek, S. J. Dyke, and W. Song, "A two-stage damage detection approach based on subset selection and genetic algorithms," *Smart Structures and Systems*, vol. 5, no. 1, pp. 1–21, 2009.

[21] T. H. Yi, H. N. Li, and M. Gu, "A new method for optimal selection of sensor location on a high-rise building using simplified finite element model," *Structural Engineering and Mechanics*, vol. 37, no. 6, pp. 671–684, 2011.

[22] T. H. Yi, H. N. Li, and M. Gu, "Sensor placement for structural health monitoring of Canton tower," *Smart Structures and Systems*, vol. 10, no. 4-5, pp. 313–329, 2012.

[23] Z. Yang, A. Elgamal, T. Abdoun, and C. J. Lee, "A numerical study of lateral spreading behind a caisson-type quay wall," in *Proceedings of the 4th International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics and Symposium*, pp. 1–6, 2001.

[24] D. K. Kim, H. R. Ryu, H. R. Seo, and S. K. Chang, "Earthquake response characteristics of port structure according to exciting frequency components of earthquakes," *Journal of Korean Society of Coastal and Ocean Engineers*, vol. 17, no. 1, pp. 41–46, 2005.

[25] Y. Chen and J. Zhou, "Monitoring strain study of cylinder caisson based on fiber grating sensing technology," *Applied Mechanics and Materials*, vol. 166–169, pp. 1308–1311, 2012.

[26] A. A. Shama, J. B. Mander, S. S. Chen, and A. J. Aref, "Ambient vibration and seismic evaluation of a cantilever truss bridge," *Engineering Structures*, vol. 23, no. 10, pp. 1281–1292, 2001.

[27] W. X. Ren and X. L. Peng, "Baseline finite element modeling of a large span cable-stayed bridge through field ambient vibration tests," *Computers and Structures*, vol. 83, no. 8-9, pp. 536–550, 2005.

[28] J. J. Lee and C. B. Yun, "Damage diagnosis of steel girder bridges using ambient vibration data," *Engineering Structures*, vol. 28, no. 6, pp. 912–925, 2006.

[29] C. Gentile and N. Gallino, "Ambient vibration testing and structural evaluation of an historic suspension footbridge," *Advances in Engineering Software*, vol. 39, no. 4, pp. 356–366, 2008.

[30] D. M. Siringoringo and Y. Fujino, "System identification of suspension bridge from ambient vibration response," *Engineering Structures*, vol. 30, no. 2, pp. 462–477, 2008.

[31] S. S. Ivanović, M. D. Trifunac, E. I. Novikova, A. A. Gladkov, and M. I. Todorovska, "Ambient vibration tests of a seven-story reinforced concrete building in Van Nuys, California, damaged by the 1994 Northridge earthquake," *Soil Dynamics and Earthquake Engineering*, vol. 19, no. 6, pp. 391–411, 2000.

[32] T. Yin, H. F. Lam, H. M. Chow, and H. P. Zhu, "Dynamic reduction-based structural damage detection of transmission tower utilizing ambient vibration data," *Engineering Structures*, vol. 31, no. 9, pp. 2009–2019, 2009.

[33] M. Amiri and S. R. Sabbagh-Yazdi, "Ambient vibration test and finite element modeling of tall liquid storage tanks," *Thin-Walled Structures*, vol. 49, no. 8, pp. 974–983, 2011.

[34] G. Osmancikli, Ş. Uçak, F. N. Turan, T. Türker, and A. Bayraktar, "Investigation of restoration effects on the dynamic characteristics of the Hagia Sophia bell-tower by ambient

vibration test," *Construction and Building Materials*, vol. 29, pp. 564–572, 2012.

[35] S. Jang, H. Jo, S. Cho et al., "Structural health monitoring of a cable-stayed bridge using smart sensor technology: deployment and evaluation," *Smart Structures and Systems*, vol. 6, no. 5-6, pp. 439–459, 2010.

[36] J. Min, S. Park, B. Song, and C. B. Yun, "Development of a low-cost multifunctional wireless impedance sensor node," *Smart Structures and Systems*, vol. 6, no. 5-6, pp. 689–709, 2010.

[37] J. H. Park, J. T. Kim, D. S. Hong, D. Mascarenas, and J. P. Lynch, "Autonomous smart sensor nodes for global and local damage detection of prestressed concrete bridges based on accelerations and impedance measurements," *Smart Structures and Systems*, vol. 6, no. 5-6, pp. 711–730, 2010.

[38] J. Wu, S. Yuan, S. Ji, G. Zhou, Y. Wang, and Z. Wang, "Multi-agent system design and evaluation for collaborative wireless sensor network in large structure health monitoring," *Expert Systems with Applications*, vol. 37, no. 3, pp. 2028–2036, 2010.

[39] G. J. Yun, S. G. Lee, J. Carletta, and T. Nagayama, "Decentralized damage identification using wavelet signal analysis embedded on wireless smart sensors," *Engineering Structures*, vol. 33, no. 7, pp. 2162–2172, 2011.

[40] D. D. Ho, P. Y. Lee, K. D. Nguyen et al., "Solar powered multi-scale sensor node on Imoete2 platform for hybrid SHM in cable-stayed bridge," *Smart Structures and Systems*, vol. 9, pp. 145–164, 2012.

[41] J. S. Bendat and A. G. Piersol, *Engineering Applications of Correlation and Spectral Analysis*, Wiley-Interscience, New York, NY, USA, 2003.

[42] D. Otte, P. van de Ponseele, and J. Leuridan, "Operational shapes estimation as a function of dynamic loads," in *Proceedings of the 8th International Modal Analysis Conference*, Orlando, Fla, USA, January 1990.

[43] J. H. Yi and C. B. Yun, "Comparative study on modal identification methods using output-only information," *Structural Engineering and Mechanics*, vol. 17, no. 3-4, pp. 445–456, 2004.