Long-Term Vibration Monitoring and Model Updating of Gageocho Ocean Research Station

Jin-Hak YI [1,2], Byungmo KIM [2], In-Ki MIN [1], Jae Seol SHIM [1]

[1] Korea Institute of Ocean Science and Technology, Busan, South Korea

[2] Ocean Science and Technology School, Korea Maritime and Ocean University, Busan, South Korea

Contact e-mail: yijh@kiost.ac.kr

ABSTRACT: In order to study ocean and meteorological issues related to the climate change, Korea has been operating several ocean research stations (ORS) in remote ocean area including Ieodo ORS since 2003, Gageocho ORS since 2009 and Sochengcho ORS since 2014. In 2011, the Gageocho ORS was directly attacked by Typhoon Muifa and its structural members and several observation devices were severely damaged. After this event, the Gageocho ORS was rehabilitated with 5 m heightening considering the 100-year extreme wave height, and the vibration measurement system was also instrumented to monitor the structural vibrational characteristics and to assess the structural integrity of the Gageocho ORS. In this study, the modal characteristics of the Gageocho ORS were identified and investigated using the long-term measurement data. As a result, natural frequencies of lower two bending modes and one torsional mode were reliably estimated as around 1.78, 1.82, and 2.65 Hz, respectively. It was also found that the damping ratios in the first mode could be more consistently obtained with lower level of uncertainty when the acceleration response was larger. The damping ratio was estimated as about 0.7%, 0.6%, and 0.5% for lower three modes, respectively. A preliminary finite element (FE) model was constructed using the design drawings and the several candidate baseline FE models were manually built considering different structural conditions such as corroded thickness. Among these candidate baseline FE models, the most reasonable baseline FE model was selected by comparing the differenes between identified and calculated natural frequencies, and this baseline FE model was updated using the identified modal properties and the pattern search method which is one of the direct search optimization methods. It was found that the calculated natural freqruncies from the updated FE model was very close to the indentified natural frequencies. Concludingly, it is expected that the present results obtained from long-term monitoring and the baseline FE model updating can be useful for establishing the essential database for jacket-type offshore structures and to assess the structural integrity of the Gageocho ORS.

1 INTRODUCTION

The ocean research stations (ORSs) play an important role for a comprehensive oceanography laboratory capable of supporting various researches through long-term observation of marine physics, marine climate, marine environment, and marine life. Currently three ORSs are in operation including Ieodo ORS since 2003, Gageocho ORS since 2009 and Socheongcho ORS since 2014, and these ORSs are located in the Yellow Sea waters between China and Korea (see Figure 1), and this area is very important to understand various ocean and meteorological phenomena occurring in the Yellow Sea, for example, many typhoons are passing through this area. In order to operate ORSs more stably for a design life time, it is very important to secure structural integrity of the ORS structures. In 2011, Gageocho ORS was severely damaged due to Typhoon Muifa and many facilities including data transmission cables and a diesel generator were also severely damaged and broken. It took a long time to repair and replace the damaged structural members and facilities and to enhance the structural integrity for operating the Gageocho ORS normally. Figure 2 shows a photograph of the Gageocho ORS before and after Typhoon Muifa attacked in 2011(Shim *et al*.(2015), Kim *et al*.(2017)). Major repair and replacement for the structural system includes 5 m heightening of the superstructure by inserting 4 vertical steel tubular members with 5 m long structural parts to increase the clearance for protecting the superstructure from unexpected high waves. Also the newly replaced structural parts have larger diameter and thickness to increase the structural strength. However, there is still a possibility that the structural performance is degraded and deteriorated due to continuously attacking typhoons and waves if the structure is not secured against such extreme loads.

For more practical and reliable integrity assessment, the measurement-based structural integrity assessment is being carried out by monitoring dynamic responses and analyzing the dynamic characteristics of the Gageocho ORS structure in this study. Long-term dynamic characteristics estimated by using measured dynamic response data can be useful not only for the evaluation of structural integrity but also as a useful basic data for structural design of ORS structures to be constructed in the future.

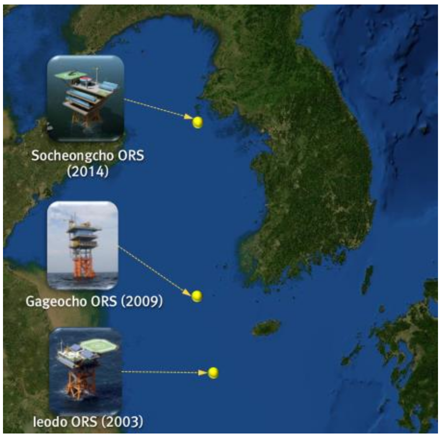


Figure 1. Operating ORSs in Korea

Figure 2. Gageocho ORS before and after recovery (Shim *et al*. 2015)

2 GAGEOCHO ORS AND MONITORING SYSTEM

2.1 *Gageocho ORS*

The Gageocho ORS was constructed using a 4-leg fixed-type jacket structure at 47 km west of Gageo Island (N33°56'30.96", E124°35'34.23"). The water depth of the Gageocho ORS site is 15 m, but the surrounding depth is 80 m and deeper (Shim *et al.* (2015)). Actually, this ORS is like a steel frame structure mounted on the submerged rock, i.e. Gageocho ("cho" means a submerged rock in Korean). The service life is redesigned to be 50 years, and the design fatigue life is also increased to be 100 years during the rehabilitation work. Currently observation facilities in operation include (1) meteorological observation devices to observe air pressure, temperature, humidity, wind direction and speed, and solar radiation and (2) ocean observation facilities to measure water temperature, salinity, tidal range, wave height and direction, and underwater noise.

2.2 Monitoring system

The dynamic response measurement system instrumented at the Gageocho ORS is shown in Figure 3, and it consists of 12 single-axis accelerometers and 2 double-axis inclinometers. Table 1 shows the specifications of the dynamic measurement sensors. As indicated, the measurement locations are set to four different levels including main deck, celler deck, access platform and intermediate deck. The responses at cellar deck and main deck are being continuously measured, while the responses at the access platform and the intermediate deck are irregularly measured because of the cable protection problem in the access platform and the intermediate deck. In addition, due to various observational and operational facilities such as computers, furniture, diesel tank and generator, only two single-axis accelerometers were installed at each level of the access platform and the main deck, while four single-axis accelerometers and one double-axis inclinometer were installed at each level of the cellular deck and the intermediate deck owing to the easy accessibility. The sampling frequency is set to 100 Hz considering the frequency range of fundamental natural frequencies under 10 Hz and Nyquist frequency, i.e. 50 Hz.

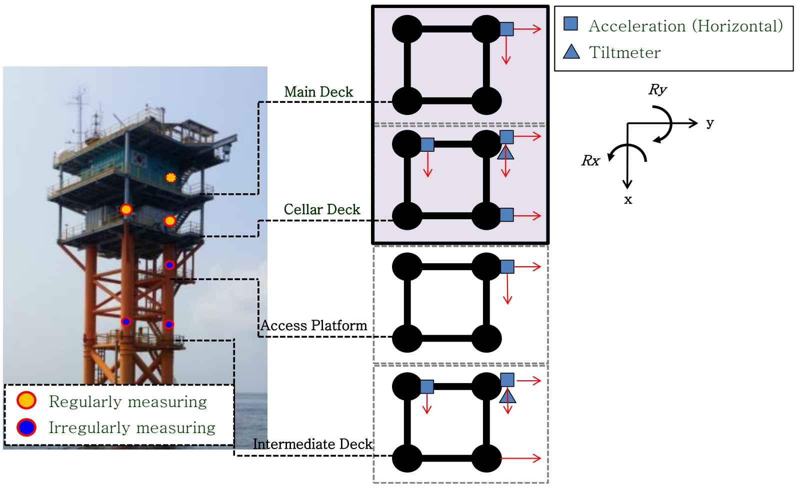


Figure 3. Dynamic response measuring system of Gageocho ORS (Kim *et al* 2017)

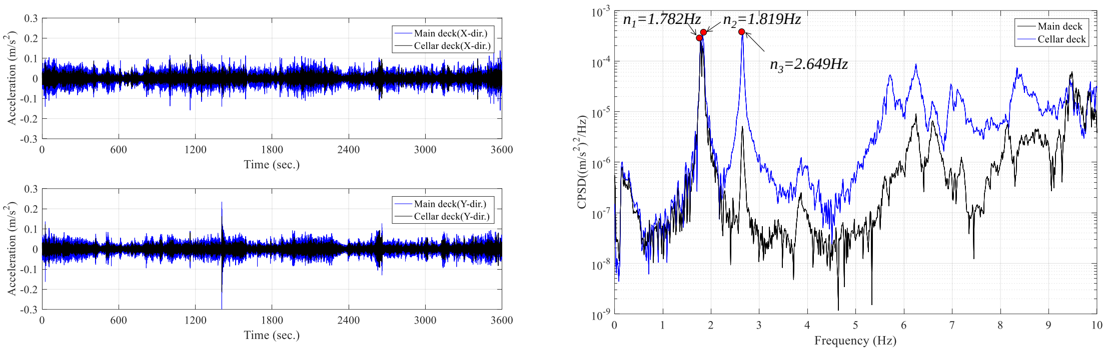
Table 1. Installed sensors on Gageocho ORS

Sensor	Model (Manufacturer)	Measuring range	Set	Location	Indicator
Accelerometer	2220-002 (Silicon Desings Inc.)	2g	2	Main deck	■
			4	Cellar deck	
			2	Access platform	
			4	Intermediate deck	
Tiltmeter	SCA121T-D07 (Murata Electronics)	±30°	1	Cellar deck	▲
			1	Intermediate deck	

3 DATA ANALYSIS

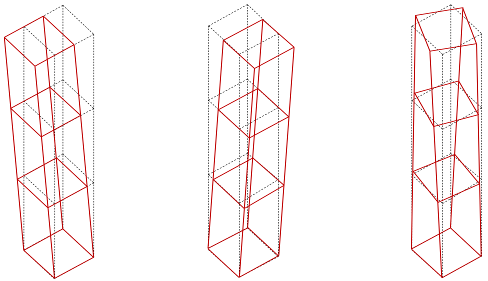
3.1 *Measured data*

Figure 4 shows the acceleration time history data and their cross spectral density when the high wind and wave were occurred, i.e. 15:00-16:00 on August 13, 2016. From Figure 4(b), it can be observed that the natural frequencies of the structure are identified as 1.782 Hz, 1.819 Hz, and 2.649 Hz for the first and second bending modes, and the first torsion mode, respectively by reading the peaks of the cross spectral density. The corresponding mode shapes are as shown in Figure 5.



(a) Acceleration time histories (b) Cross spectral density

Figure 4. Acceleration time histories and their cross spectral density (13 August, 2017)



(a) 1st mode (b) 2nd mode (c) 3rd mode

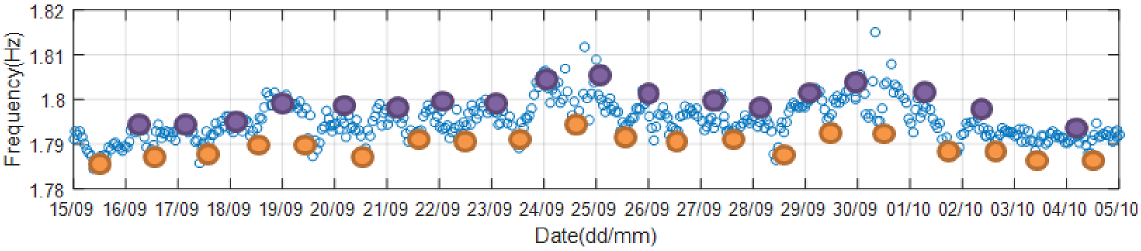
Figure 5. Estimated mode shapes

3.2 *Output-only modal identification with stochastic subspace identification*

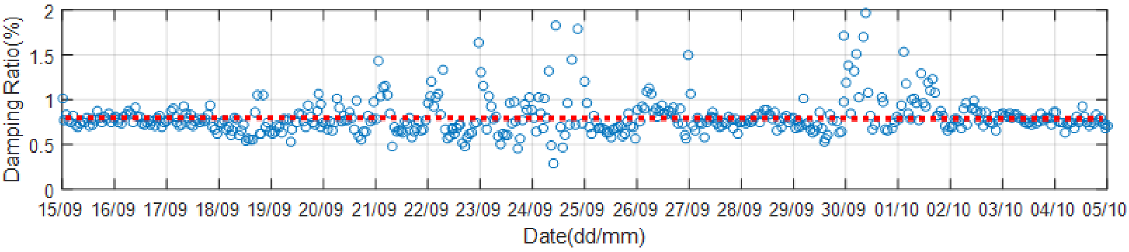
In this study, the stochastic subspace identification (SSI) is applied to estimate the dynamic characteristics of a structure. SSI is formulated based on a block Hankel matrix with a correlation matrix of response data and it can be classified as SSI-BR (Balanced Realization) and SSI-CVA (Canonical Variate Analysis) according to the method of constructing the Hankel matrix (Overschee *et al.* (1996), Peeters *et al.* (1999)). In this study, the SSI-CVA method is applied to obtain more stable results (Yi *et al.* (2004)). Since many literatures about SSI method are available, the fundamental ideas are briefly summarized as follows. First, the SSI-CVA method constructs a block-Hankel matrix by using the cross-correlation matrix from the stochastic discrete state equation considering the external load as a Gaussian random normal distribution load. A block-Hankel matrix with the cross-correlation matrix can be constructed and it can be decomposed into an observability matrix and an extended controllability matrix. Then, the system matrix can be calculated from the matrices from the observability matrix. Finally, the eigenvalue, the natural frequency, the modal damping ratio and the actual mode vector of the continuous state equation can be obtained using the system matrix.

3.3 *Long-term monitoring of modal parameters of Gageocho ORS*

The natural frequencies and modal damping ratios were identified using hourly data based on SSI-CVA and the frequencies and damping ratios for the first bending mode are shown in Figure 6. As shown in these figures, there is a daily fluctuation in natural frequencies which might be caused by daily temperature change. As indicated in the figure, the frequency goes up in midnight and goes down in the afternoon, and this means that the natural frequency is strongly associated with temperature. However, in the case of modal damping ratio, any daily fluctuation is not observed, but it can be obseved that high level of fluction in damping ratios exists in some cases. Therefore it is necessary to look into the causes of this high level of fluctuation in more detail by comparing the modal parameters with the changes of temperature, amplitude of responses, etc.



(a) First natural frequency



(b) First modal damping ratio

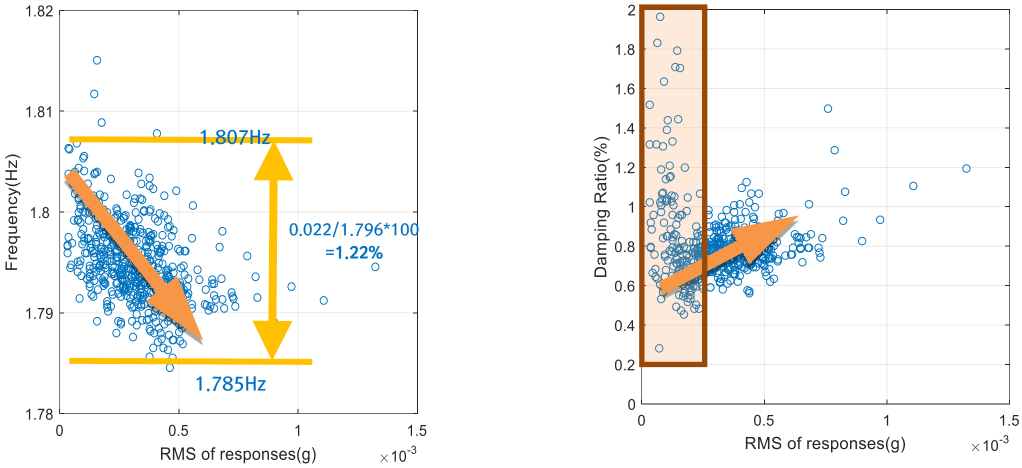
Figure 6. Fluctuation of modal parameters, i.e. the first natural frequency and modal damping ratio

When the modal parameters are compared with the amplitude of response (see Figure 7), it can be easily understood that the natural frequency is increased when the amplitude of response is increased, and it means that there is a certain level of nonlinearity in this structural system. But the difference is just limited within 1.2% and it can be considered as very low and acceptable in the viewpoint of engineering judgement. In the case of modal damping ratio, when the response is small, there is high level of fluctuation, and it means that it is very difficult to identify the modal damping ratio more accurately and precisely under weak excitation condition. And the damping ratio tends to be increased along with the increase of reponse level.

4 BASELINE FE MODEL UPDATING

4.1 *Baseline FE model*

The identified modal properties were compared with calculated results by preliminary FE model in Table 2, and it can be observed that the root mean squared (RMS) error between two values is around 1% which is not acceptable in most engineering purposes. Therefore, several candidate baseline FE models were constructed based on the preliminary FE model considering the following conditions such as member offset, added mass and anode mass. During the rehabilitation work, the inner side of jacket leg was filled with concrete and also strengthened by inserting inner steel frame to increase strength and safety. So it is also necessary to consider the concrere filling and inserted steel frame. The preliminary FE model doesn't have this kind of consideration because of the



(a) Frequency vs RMS of responses (b) Damping ratio vs RMS of responses
Figure 7. Comparison between modal parameters and RMS of responses

conservative design concept. Several candidate baseline FE models were constructed considering different structural conditions and the most reasonable baseline FE model was selected by looking at the RMS error between identified and calculated natural frequencies. From the Table 2, it can be observed that the frequencies from the baseline FE model is much closer to the identified frequencies than those of preliminary FE model, i.e. the RMS error between the identified and calculated using baseline FE model was reduced as 3.48% from that using preliminary FE model, i.e. 17.2%.

4.2 Updated FE model

In this study, the pattern search method (Wetter *et al.* (2003), Zhao *et al.* (2006), Mathworks (2011), Yi *et al.* (2012)) was utilized to minimize the error between calculated and identified modal parameters, i.e. FE model updating, and the updating parameters include material properties such as elastic modulus of concrete (Ec) and steel (Ec), and mass distribution ratio such as the mass ratio distributed in 12 nodes on 4 jacket legs for all additional mass (α), mass ratio of mass for access deck among all decks (β) as follows,

$$\boldsymbol{\alpha} = \frac{\boldsymbol{M_{L1}+M_{L2}+M_{L3}}}{\boldsymbol{M_T}},\ \boldsymbol{\beta} = \frac{\boldsymbol{M_{L1}}}{\boldsymbol{M_{L2}+M_{L3}}} \tag{1}$$

where M_{L1}, M_{L2} and M_{L3} are the lumped mass located in the access deck, main deck and roof deck, respectively. And the sum of the lumped massess is maintained as the same with the total lumped mass, M_T. The updated parameters are summarized in Table 3, and it can be found that the elastic modulus of steel is not changed a lot while that of concrete is significantly reduced as 9.4GPa from 27GPa.

The natural frequencies calculated using updated FE model were compared with identified values in Table 4, and it can be found that even the maxium difference is lower than 1% and the RMS error is also significantly reduced as about 0.72%. As explained, the RMS error was about 17.2% for the preliminary FE model, and it was significantly reduced as about 3.48% by revising the FE model manually considering different strcutral conditions. And this RMS error was again reduced as about 0.72% by estimating the structural parameters.

Table 2. Structural conditions in real, initial and baseline models

		Real Structure	Preliminary FE Model		Baseline FE Model	
Structural Conditions	Member Offset	Y	Y		Y	
	Joint Can	Y	Y		Y	
	Reduced Area	NA	Y		N	
	Added Mass	Y	Y		Y	
	Inserted Steel Pile	Y	N		Y	
	Concrete Filling	Y	N		Y	
	Anode Mass	Y	N		Y	
	Increased Density	N	Y		N	
	Additional Mass	Y	N		Y	
	Welding Stiffness	?	N		N	
		Freq*	Freq	Error**	Freq	Error
Modes	1st	1.78	2.21	23.6	**1.90**	**6.2**
	2nd	1.82	2.22	21.2	**1.91**	**4.5**
	3rd	2.65	3.10	16.8	**2.65**	**0.1**
	4th	5.60	6.13	9.5	**5.66**	**1.1**
	5th	5.69	6.26	9.9	**5.74**	**0.8**
	RMSE			**17.2**		**3.48**

*Frequency (Hz), ** Error (%)

Table 3. Initial and updated parameters

	α	β	M_{L1} (ton)	M_{L2} (ton)	M_{L3} (ton)	M_{P1} (ton)	M_{P2} (ton)	Ec (GPa)	Es (GPa)
Initial	0.800	1.200	9.87×10^{4}	7.29×10^{4}	0.94×10^{4}	8.94	9.16	27.0	200.0
Optimal	0.719	1.043	8.30×10^{4}	7.69×10^{4}	0.27×10^{4}	12.57	12.89	9.4	203.4

Table 4. Comparison of natural frequencies identified and calculated using updated FE model

		Real Structures	Baseline FE Model		Updated FE Model	
		Freq*	Freq	Error	Freq	Error
Modes	1st	1.78	1.90	6.2	1.81	0.96
	2nd	1.82	1.91	4.5	1.81	0.95
	3rd	2.65	2.65	0.1	2.65	0.02
	4th	5.60	5.66	1.1	5.62	0.38
	5th	5.69	5.74	0.8	5.65	0.81
	RMSE			**3.48**		**0.72**

5 CONCLUDING REMARKS

In this study, the long-term measurement data were analyzed using time-domain output only modal identification method, i.e. stochastic subspace identification method. The lowest three natural frequencies are compared with respect to the temperature and structural responses. The natural frequencies are highly associated with the temperature, i.e. as the temperature increases, the natural frequency decreases, and as the temperature decreases, the natural frequency increases. The natural frequencies tend to decrease as the amplitude of responses are increased while the modal damping ratio has little effect on temperature and RMS of response. The more reliable damping estimation cab be achieved during the responses are bigger.

Baseline FE model was constructed considering different structural conditions and it was updated by pattern search method. The difference between identified and calculated natural frequencies for the lowest 5 modes were coincided and below than 1%. It is expected that the present results obtained from long-term monitoring and the baseline FE model updating can be useful for establishing the essential database for jacket-type offshore structures and to assess the structural integrity of the Gageocho ORS. The updated baseline FE model can be useful for further performance analysis including reliability analysis, wave and seismic analysis, and also for structural health monitoring.

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