Structural Integrity Monitoring of Hybrid Offshore-Wind and Tidal-Current Turbines

Wonsul Kim[#1], Jin-Hak Yi[*2], Jin-Soon Park[*3]

[#]*Coastal Development Research Centre, Korea Institute Ocean Science & Technology*
Haeyang-ro, Yeongdo-gu, Busan, Korea

1w.kim@kiost.ac.kr

2yijh@kiost.ac.kr

3jspark@kiost.ac.kr

***Abstract*—As one of the efforts to harness energies from ocean, the hybrid offshore-wind and tidal-current turbines (HOTTs) have been studied for several years. In the HOTTs, the supporting structural parts including tower and foundation play an important role to secure the power generation facilities such as blades, hub and nacelle and to resist environmental loadings from wind, wave, and tidal current. The purpose of this study is to develop the structural integrity monitoring system and the damage detection method for the HOTT supporting structures through laboratory experiments. The laboratory experiments for the HOTT supporting structure have been performed using the scaled HOTT model in water flume. The dynamic characteristics of the HOTT model are estimated by least-squared frequency domain decomposition (LS-FDD) using the measured responses, and compared with those calculated by the commercial FEA software. The natural frequencies estimated by LS-FDD are very close to those of the FEA. To detect structural damages in the HOTT supporting structure, two different approaches are considered, (1) coherence-based method and (2) improved auto-regressive (AR) model based method. It is found that the improved AR model based method is superior to the coherence-based method and structural damage can be alarmed by the proposed improved AR model method.**

***Keywords*— Hybrid Offshore-Wind and Tidal-Current Turbine (HOTT), Structural Integrity Monitoring, Damage Detection, Dynamic Characteristics, Coherence-based, Improve auto-regressive model**

I. Introduction

After COP21, known as the 2015 Paris Climate Conference, global efforts to reduce greenhouse gas emissions have been strengthened. Renewable energies have been emerged from the perspectives of securing energy supply and addressing the challenges on climate change and greenhouse gas emission reduction. Recently, many countries including Korea have been started to accelerate deploying not only offshore wind turbines but also tidal current turbines. As a result, the contribution of wind power to the world electricity demand is expected to reach 8% by 2018 [1-3]. Further, a few studies have been focused on the integrated exploitations of offshore wind and ocean energy to efficiently utilize wind and ocean energy resources [4-5]. A study on the development for hybrid offshore-wind and tidal-current turbines (HOTT) has been carried out for several years. In the HOTT, the supporting structural parts including tower and foundation play an important role in securing the energy-generating facilities such as blades, hub and nacelle and resisting the environmental loadings from wind, wave, and tidal current. Hence, the structural integrity monitoring and damage detection are very important to guarantee the structural safety of the supporting structures in HOTTs. However, the relevant studies for the supporting structures in ocean energy systems are still not sufficient [6-8].

The purpose of this study is to develop the structural integrity monitoring and the damage detection method for the HOTT supporting structures through lab-scale experiments. The laboratory experiments for the HOTT supporting structures have been performed using the scaled HOTT model in water channel. The responses of the HOTT supporting structure are measured using accelerometers, strain gauges and tilt meters. The dynamic characteristics of the HOTT model are estimated by least-squared frequency domain decomposition (LS-FDD) using the measured responses, and compared with those of the FE model. The natural frequencies estimated by LS-FDD are very close to those of the FE model.

To detect structural damages in the HOTT supporting structure, the coherence-based and improved auto-regressive (AR) model-based damage detection techniques are applied. From the experimental studies, it is found that the improved AR model based method is superior to the coherence-based method and structural damage can be alarmed by the proposed improved AR model method.

II. Theoretical Backgrounds

A. *Experimental Modal Analysis*

In this study, LS-FDD method is applied to obtain the dynamic characteristics of the HOTT. The conventional FDD method starts with the fundamental assumption that the frequency response function can be approximately obtained by singular value decomposition of the power spectral density matrix of output responses when the frequency components are smoothly distributed; hence, it can be considered as a white noise spectrum near resonant or natural frequencies [9]. In such a case, the natural frequencies and mode shapes can be easily obtained by reading the peak frequency in singular value distribution and the corresponding unitary matrix at the peak frequency. In the LS-FDD method, a simple optimization algorithm is utilized to obtain the modal parameters by matching the theoretical frequency response function to the measured frequency response function near natural frequencies, and the optimal parameters consist of natural frequency and modal damping ratio. More details can be found in the Ref [10].

B. Damage Detection Methods

In this study, (1) Correlation criterion method and (2) Improved AR (auto regressive) model based method are applied to estimate structural damage.

1) Application of damage estimation method using correlation function: In order to estimate the structural damages in the HOTT structure, the coherence-based method is applied. The coherence-based method utilizes the modal assurance criteria in the measured frequency response as follows,

$$Coh_{ij}(f) = \frac{\left|G_{ij}(f)\right|^2}{G_i(f)G_j(f)} \tag{1}$$

where $G_i(f)$ and $G_j(f)$ are power spectral densities at *i* and *j* locations, respectively, and $G_{ij}(f)$ is the cross spectral density between the responses measured at *i* and *j* locations. $Coh_{ij}(f)$ can be expressed as a function of the real number of frequencies between 0 and 1.

The damage feature can be obtained by taking the averaged integration of coherence (AIC) values in the whole frequency range of the coherence using the following equation [8].

$$AIC_{ij} = \frac{1}{N}\sum_{k=1}^{N} Coh_{ij}(f_k) \tag{2}$$

In this study, AIC is obtained by using different response sensors (acceleration, tilt, and strain) installed on the HOTT supporting structure and the damage is estimated according to the damage scenarios. In this study, the upper limit and lower limit of the AIC are determined using the three-sigma rule and when distribution of AIC values is assumed as normal distribution, the confidence level of three-signal rule is about 99.7%.

2) Application of improved AR (auto regressive) model based damage estimation method: There are various physical quantities that can be used as damage sensitive features (DSF), such as changes in natural frequencies before and after damage, differences in mode shapes, and mode strain energy. In order to compensate the damage estimation method using the proposed correlation function, we proposed the damage estimation method using the AR model, which is widely applied to the structural health monitoring. The AR model can be expressed as a linear combination of the error with the finite past response as follows.

$$x_t = \phi_1 x_{t-1} + \phi_2 x_{t-2} + \cdots + \phi_p x_{t-p} + e_t \tag{3}$$

where x_t and x_{t-i} are the responses at time *t* and time $t - i\Delta t$, respectively, and ϕ_i is an AR coefficient representing the contribution of x_{t-i} to the reconstruction of x_t. e_t is an estimation error. The optimal order p for an AR model can be determined by various methods such as Akaike information criteria.

Since the coefficients of the AR model include the dynamic characteristics of the structure, monitoring the AR model coefficients is equivalent to monitoring the natural frequency and damping ratio. In this study, a band-pass filter is first applied to the obtain measured acceleration response in the range of major lower structural modes, and then the AR model is constructed using the cross-correlation function which is pseudo impulse response as follows,

$$r_j(\tau) = \frac{1}{T}\int_{t_0}^{t_0+T} x_j^{filtered}(t)\, x_{ref}^{filtered}(t+\tau)\,dt \tag{4}$$

$$r_j(\tau) = a_{j,1} r_j(t-\Delta t) + \cdots + a_{j,p} r_j(t - p\Delta t) + e_j(t) \tag{5}$$

where $x_{ref}^{filtered}$ is the filtered acceleration time series at the reference measurement point, and $a_{j,k}$ is the k -th AR coefficient for the cross-correlation function at the nodal point j . The cross-correlation function is more reasonable than using the original signal measured when applied to the AR model since the load has the same shape as the impulse response function when the load has no specific frequency component. In particular, for steady responses under a random load in a HOTT, a more stable signal can be obtained for the AR model by using the cross correlation function as described above.

In this study, the following damage sensitive feature (DSF) is used for detecting the structural damages in HOTT using the lower three AR coefficients,

$$DSF_j = \frac{a_{j,1}}{\sqrt{a_{j,1}^2 + a_{j,2}^2 + a_{j,3}^2}} \tag{6}$$

III. Experimental Study

A. Model Setup

Fig. 1 shows the specifications of the HOTT model structure and sensor layout. The wind turbine and the tidal current turbine are modelled using a fan and a thruster, respectively. The structural damages are simulated by loosening bolts on the transition piece and the foundation. The transition piece which is connecting the wind tower and tidal turbine, is known as the weakest part of the whole system. Hence, the simulated damage locations are sufficiently reasonable.

The types of structural damages caused by bolt loosening are classified into four stages as shown in Table 1 including (1) healthy state (HS), i.e. all the bolts are tightened with sufficient torque, (2) foundation damage state (FDS), i.e. the bolts of the foundation are partially loosened, (3) TP damage state (TPD), i.e. the bolts in transition piece are partially loosened and (4) multiple damages state (MDS) in which the bolts in TP and foundation are partially loosened. Four different loading tests are performed including (1) impact test, (2) ambient vibration tests with tidal turbine rotor rotation at

600 RPM, (3) ambient vibration tests with wind turbine rotor rotation at 300 RPM, and (4) ambient vibration tests with both rotors rotation at the same time. In the experiment, the responses of HOTT are measured at a sampling frequency of 300 Hz for 60 minutes. On the other hand, the rotor speeds of the tidal turbine and the wind turbine can be adjusted, but they are fixed at 600 RPM and 300 RPM for tidal and wind turbines, respectively. Fig. 2 shows an example of the measurement response of the HOTT model.

TABLE 1

DAMAGE SCENARIOS FOR HOTTMODEL

Damage Scenario	**Operation**	**Rotor speed(rpm)**	
		Tidal	**Wind**
Healthy State (HS)	Impact test (no operation)	0	0
	Tidal turbine operation	600	0
	Wind turbine operation	0	300
	Both turbines operation	600	300
Foundation Damage State (FDS)	Impact test (no operation)	0	0
	Tidal turbine operation	600	0
	Wind turbine operation	0	300
	Both turbines operation	600	300
TP Damage State (TDS)	Impact test (no operation)	0	0
	Tidal turbine operation	600	0
	Wind turbine operation	0	300
	Both turbines operation	600	300
Multiple Damage (Foundation & TP Damage) State (MDS)	Impact test (no operation)	0	0
	Tidal turbine operation	600	0
	Wind turbine operation	0	300
	Both turbines operation	600	300

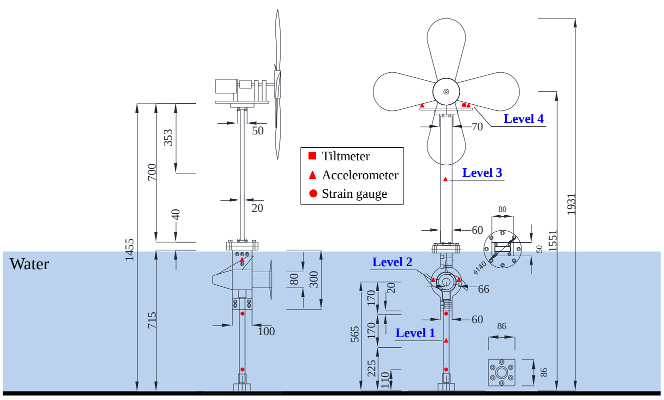


Fig. 1 HOTT Model Specification and Sensor Layout

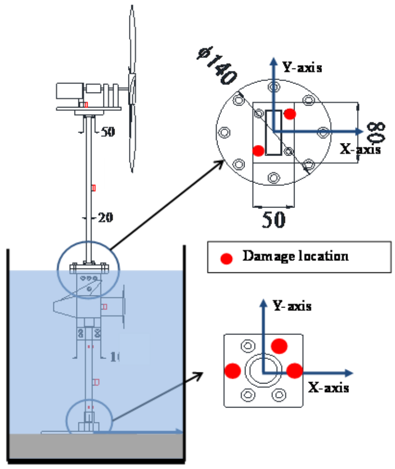
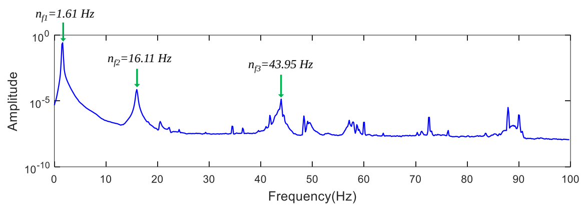


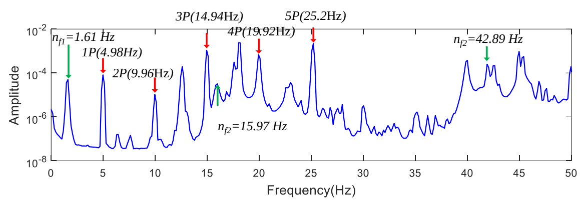
Fig. 2 Location of artificial damage and loosened bolots for HOTT model

B. *Estimated modal properties*

Fig. 3 shows distributions of the singular values of the response spectrum obtained from the impact tests and the ambient vibration tests with rotation of wind and tidal turbines from the LS-FDD method in the healthy state (HS). By looking at the peak frequency, it is possible to obtain the natural frequencies and the excitation frequencies. In Fig. 3 (a), the natural frequencies for the lower third modes can be obtained as 1.61, 16.11, and 43.95 Hz, respectively. From Fig. 3(b), the singular values have more peaks due to the rotation of turbines; i.e. tidal and wind turbines rotate at 600 RPM and 300 RPM, respectively. In this case, the harmonic excitations such as 1P, 2P, and 4P due to rotor rotation can be found as noted in the figure. Since the wind turbine with four blades rotates at 300RPM, the frequencies of 1P, 4P, and 8P components are found as 5Hz, 20Hz, and 40Hz, respectively. These are also 10Hz, 20Hz, and 40Hz components for 1P, 2P and 4P components from tidal turbine with two blades. Fig. 5 shows the bending mode shape of the lower three modes obtained by the impact test in the HS state, and a mode shape similar to the mode shape of a general cantilever beam can be obtained.



(a) Impact Test



(b) Operational Test under Two Rotors Rotation

Fig. 3 Singular values obtained from power spectra of response data

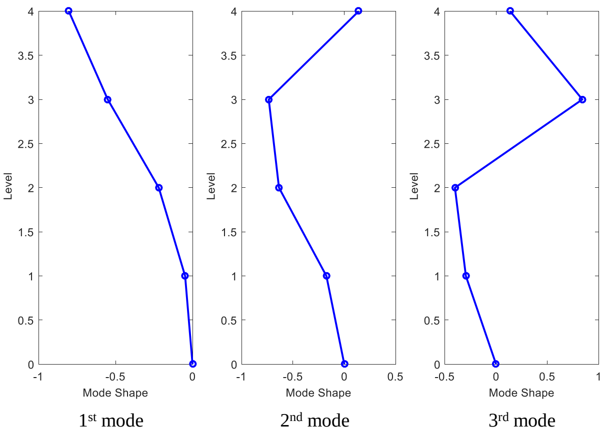


Fig. 4 Mode shapes for the lower three modes for healthy state by impact tests

The following Table 2 shows the comparison of the first and second modes natural frequencies according to the damage conditions of the HOTT structure. In case of damage states, it can be observed that the natural frequencies are reduced as much as about 0.3% ~ 0.9% to the natural frequencies in healthy state, and there is no significant correlation between the damage location and operation of the turbine.

TABLE 2
NATURAL FREQUENCIES CHANGES FOR FIRST TWO MODES DUE TO DAMAGES

(A) 1ST MODE

	Natural frequency(Hz)				Frequency ratio		
Cases	f_{HS}	f_{FDS}	f_{TDS}	f_{MDS}	f_{FDS}/f_{HS}	f_{TDS}/f_{HS}	f_{MDS}/f_{HS}
T	1.556	1.547	1.552	1.546	0.994	0.997	0.993
W	1.558	1.566	1.552	1.544	1.005	0.996	0.991
T+W	1.554	1.545	1.549	1.541	0.994	0.996	0.991

(B) 2ND MODE

	Natural frequency (Hz)				Frequency ratio		
Cases	f_{HS}	f_{FDS}	f_{TDS}	f_{MDS}	f_{FDS}/f_{HS}	f_{TDS}/f_{HS}	f_{MDS}/f_{HS}
T	15.918	15.852	15.745	15.626	0.996	0.989	0.982
W	16.022	15.852	15.746	15.671	0.996	0.989	0.984
T+W	15.861	15.852	15.706	15.625	0.996	0.987	0.982

The FE analysis is also carried out using the commercial software ANSYS and the FE model and the comparison are listed in the Fig. 5 and Table 3. As shown in Table 3, the 1st natural frequencies are very close to the experimental results, which means that the FE model can be applied to the extended analysis such as seismic analysis and so on, even though the 2nd and 3rd natural frequencies are not so similar to the experimental results. In the future, model updating will be carried out to make the FE model more close to the experimental HOTT model [11-12].

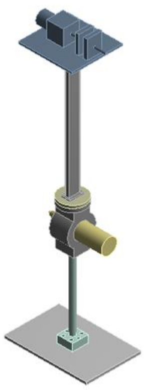


Fig. 5 FE model using ANSYS

TABLE 2
NATURAL FREQUENCIES CHANGES FOR FIRST TWO MODES DUE TO DAMAGES

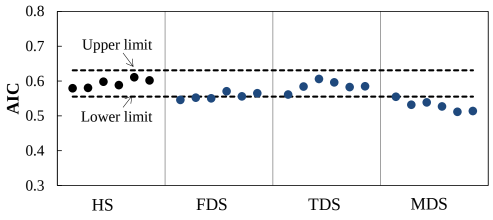
First three modes	Frequency (Hz) FEM	Measurement	Error (%)
1	1.55954	1.556	0.22
2	12.7084	16.11	11.11
3	48.0188	43.95	9.92

C. Damage Detection

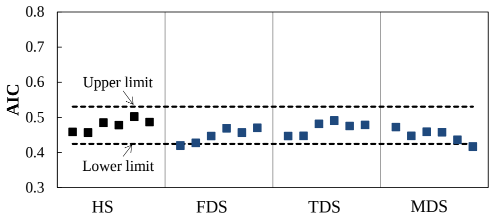
For the coherence-based damage detection, the acceleration response data are first divided into 6 segments with 10 minutes duration, and then, the coherence is calculated and compared. In calculating the coherence, the reference point is set to the 3rd level in Fig. 1 at which the maximum acceleration responses are measured.

Fig. 6 shows the damage estimation results for the HS, FDS, TDS and MDS cases using the acceleration responses under the tidal turbine rotates as a typical result. Obviously, it is very hard to conclude that the damage is successfully detected because the AIC values under damage states are not clearly distinguished from healthy state. Even though the previous research results indicate the coherence information can be useful for damage detection [13], it is not the same result in this study and it might be because the coherence usually utilize to estimate the measurement quality when the measurement noises exist and it is not so sensitive to the structural damages. Similar results are obtained from the different cases with different operational conditions, i.e. only wind turbine rotates, both wind and tidal turbines rotate, and also from different measures are used; i.e. acceleration, tilt, and strains.

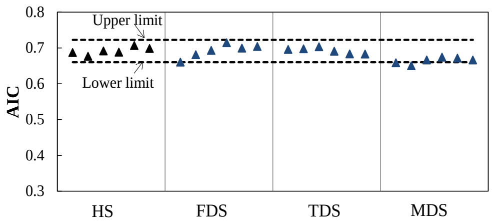
Even though the coherence information is not successfully utilized for damage detection, this information might be useful to investigate how much the measurement noises are corrupted in the raw measurement signals. More discussions will be made in the future.



(a) AIC 3&1



(b) AIC 3&2



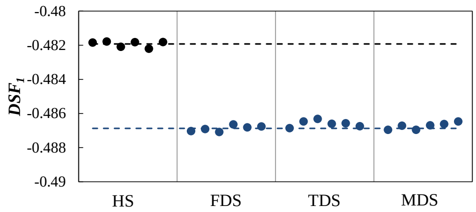
(c) AIC 3&4

Fig. 6 Damage detection by coherence-based method under tidal turbine operation

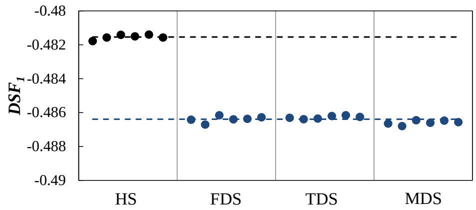
Fig. 7 shows the damage estimation results using the improved AR model based method for HOTT structure. Although the level of responses are relatively small and there is a slight level of low frequency trends, the structural damage states can be very successfully identified using this improved AR model based method. The damage sensitive feature (DSF) are clearly distinguished in the damage states from the healthy state. However the damage location is not clearly identified, and it means that this method can be effectively used for damage alarming not for damage locating and for damage quantification.

Similar discussion can be drawn in the other cases with different operational conditions, i.e. only wind turbine rotates, both wind and tidal turbines rotate, and also from different measures are used; i.e. acceleration, tilt, and strains.

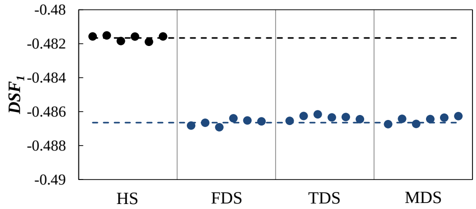
Therefore it is necessary to develop additional damage locating and quantifying method for locating and quantifying the structural damages such as modal information based techniques. For example, the neural networks technique can be efficiently utilized for damage locating and quantifying. It will be discussed in more detail in the future.



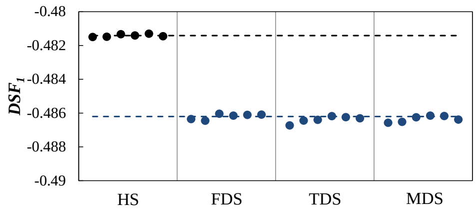
(a) level 4



(b) Level 3



(c) Level 2



(d) Level 1

Fig. 7 Damage detection by improved AR model under tidal turbine operation

IV. CONCLUSIONS

In this study, the damage detection methods for the HOTT supporting structures are applied using coherence-based and improved AR model-based methods, and the performances are compared through lab-scale experiments. The dynamic characteristics of the HOTT model are successfully estimated by least-squared frequency domain decomposition (LS-FDD) using the measured responses, and compared with those of the FE model. The 1st natural frequencies estimated by LS-FDD are very close to those of the FE model even though the 2nd and the 3rd natural frequencies are necessary to be tuned by adopting model updating techniques.

The coherence-based damage detection is not successfully carried out, but the improved AR model-based damage detection is investigated for the good damage alarming method. However, it still needs to develop more efficient methods to locate and quantify the structural damages.

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