

Experimental and operational modal analysis of a laboratory scale model of a tripod support structure.

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Abstract. The goal of the research is to develop a vibration-based procedure for the identification of structural failures in a laboratory scale model of a tripod supporting structure of an offshore wind turbine. In particular, this paper presents an experimental campaign on the scale model tested in two stages. Stage one encompassed the model tripod structure tested in air. The second stage was done in water. The tripod model structure allows to investigate the propagation of a circumferential representative crack of a cylindrical upper brace. The in-water test configuration included the tower with three bladed rotor. The response of the structure to the different waves loads were measured with accelerometers. Experimental and operational modal analysis was applied to identify the dynamic properties of the investigated scale model for intact and damaged state with different excitations and wave patterns. A comprehensive test matrix allows to assess the differences in estimated modal parameters due to damage or as potentially introduced by nonlinear structural response. The presented technique proves to be effective for detecting and assessing the presence of representative cracks.

1. Introduction

In the last few years, the use of renewable energy sources is strongly increased, with the aim of reducing the oil/carbon utilization and improving the life quality in terms of environmental and air pollution. One of the most important renewable energy sources regards the offshore wind technology. In many scenarios it is foreseen as *The Future* among all possible renewable energy sources. This continuous evolving technology requires constant improvements of knowledge in many fields of the research. The offshore wind industry is currently facing the challenge of reducing costs for fabrication (direct) and installation (indirect) of jacket and tripod like support structures. Very important are research activities oriented on the reduction of operational and maintenance costs [3-9]. This research activity can be placed in this scenario. The main goal of the presented research is the development of a vibration-based procedure for the identification of structural failures in a laboratory scale model of an offshore turbine. Further researches will be carried out to continue this activity in order to develop an autonomous system based on vibration experimental measurements as well as numerical models for the real time monitoring and diagnostics of the structural integrity of offshore wind turbines. In this context, the autonomous system can strongly reduce the maintenance costs (e.g. inspection costs) as well as reduction of the collapse risk.



In this paper, experimental vibration tests have been carried out in a laboratory scale model of a tripod supporting structure of an offshore wind turbine. A first experimental campaign has regarded an experimental modal analysis of the tripod tested in-air, while a second experimental campaign has addressed measurements in-water with the tripod model assembled in the towing tank. The in-water test configuration included the tower with three bladed rotor. The tripod was assembled on a turntable such that the orientation of the structure could be varied with respect to the incoming waves. In this paper only the dependency between natural frequency and modal damping values and the type of connection of the tripod brace was investigated. It has to be underlined that the natural frequencies of the observed object in marine environment might be affected by more factors like changes in the soil stiffness, scour, corrosion, marine growth. The presented approach can be considered a first attempt to tackle this fascinating field. Additional measures as well numerical models have to be used to identify the location of the damage and the corresponding reason.

2. Experimental modal analysis of the tripod model in air

2.1. Experimental tests and results

Hereafter, the experimental modal analysis carried out on the tripod for damage identification is presented. The object of investigation is a laboratory scale model of a tripod type supporting structure of an offshore wind turbine. It is made of aluminium cylindrical tubes. The model is about 2 m high and a mass of 30 kg (Figure 1, left). It comprises of three pile guides fixed to the central column with upper and lower braces. In one of the three upper braces, a flange is placed to interrupt the structural continuity (Figure 1, right). The screws in the flange can be closed with different tightening torques in order to simulate different types of circumferential representative crack in the cylindrical brace. In this study the flange was a practical measure to introduce the brace stiffness reduction. It has to be underlined that this paper does not address the investigation of a real system with a real circumferential crack behaviour with regard to the bolted flange connection, obtained for example after a fatigue test. The ability to reduce the stiffness of the flange and its influence on the member natural frequency was available through five screws present in the flange. A representative crack was introduced by means of pretention of Top Screw (TS), Right Screw (RS), Left Screw (LS), Right Bottom Screw (RBS), Left Bottom Screw (LBS). Moreover, five different extents of circumferential representative cracks have been considered, namely “All Screws Open” (ASO), “Full Open 1” (FO1), “Partial Open 2” (PO2), “Partial Open 3” (PO3), “Full Close” (FC). Table 1 lists the tightening torques for each screw in the different configurations being tested. As an example, “Partial Open 3” configuration means that TS has a tightening torque equal to 13.6 [Nm], RS and LS have a tightening torque equal to 27.1 [Nm] and RBS and LBS have a tightening torque equal to 54.2[Nm], which corresponds to the nominal value. Note that in the ASO configuration, the bolts were still present in the flange but they do not contribute to any bending moment in the flange.



Figure 1. Laboratory scale model of the tripod supporting structure (left) and detail of the flange (right) used in order to simulate the propagation of the circumferential representative crack in the cylindrical brace.

For the experimental modal analysis, the excitation was provided by two shakers that excite the tripod structure in the base of the central column, as shown in Figure 1, left. The two shakers excite the tripod structure along two orthogonal directions. The response of the tripod was measured by five piezoelectric tri-axial accelerometers. The set of transducers was placed on the particular measurement points and then moved to another until a full coverage of all 76 measurement points was reached. Measurement points were located in the vicinity of the flange and spread over the structure. Two sections of 4 measurement points each were defined on the circumference of the brace below the flange and the eight measurement points located above the flange. Each out of the three pile guides, upper and lower braces were measured in 5 locations. The tower was instrumented with 12 measurement points. For the in-water only the measurement points located on the tower were used due to the practical limitation of moving the sensors. Both excitations and responses have been measured simultaneously to obtain the Inertance, i.e. the Frequency Response Function (FRF) between acceleration and force. The signals were acquired by using sampling frequency and frequency resolution according with the type of model and with the kind of constrain condition. For each of the five different tightening torque configurations (Table 1), the experimental modal parameters have been estimated.

Once the experimental modal tests and analyses have been performed, natural frequencies, modal damping and mode shapes are available for all modes in the frequency band of analysis. The natural frequencies (f_n) and modal damping values (ζ) were obtained by averaging the corresponding solution from the Least Square Complex Exponential (LSCE) [1] method and PolyMAX method [1][2]. In particular, two different modal analysis algorithms have been used in order to increase the robustness of the solution: the LSCE method, which works in the time domain and the frequency domain algorithm PolyMAX.

Table 1: Screws and tightening torque configuration. NOM represents the nominal tightening torque value (54.2 Nm).

	All screws open (ASO) [Nm]	Full Open 1 (FO1) [Nm]	Partial Open 2 (PO2) [Nm]	Partial Open 3 (PO3) [Nm]	Full Close (FC) [Nm]
Top Screw (TS)	0	0	0	13.6	NOM
Right Screw (RS)	0	0	13.6	27.1	NOM
Left Screw (LS)	0	0	13.6	27.1	NOM
Right Bottom Screw (RBS)	0	NOM	NOM	NOM	NOM
Left Bottom Screw (LBS)	0	NOM	NOM	NOM	NOM

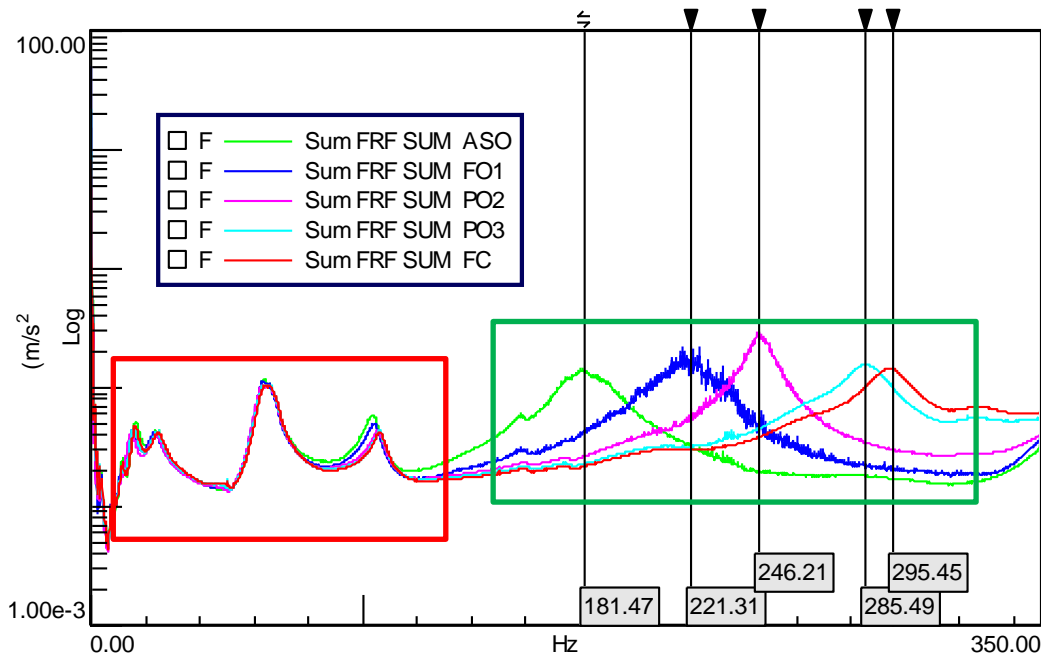


Figure 2. FRFs SUM.

The results for the EMA are presented in Figure 2 in terms of a FRF-sum, i.e. for each crack configuration the complex sum of the FRF's between the response measurements and the exceptional force is plotted. It can be noted that the modes in the frequency range between 0 and 150Hz (circled in red in Figure 2) remain the same for all the configurations (same natural frequency, same modal damping, same mode shape), while the peaks in the frequency range between 180 and 300Hz (green box in Fig. 2), referring to mode #6, show a clear variation of natural frequencies and modal damping values for the considered crack configurations. Such a mode shapes has different modal damping and natural frequency. This behaviour is due to the different extents of representative crack because of the different flange connection stiffness. Figure 3 and Figure 4 present the natural frequencies and modal damping ratio for the different configurations under tests, referring to mode #6. As mentioned, the natural frequency and modal damping values of mode #6 change significantly; In fact, the natural frequency increases from 181 Hz to 295 Hz, with screw configuration that changes from ASO to FC, respectively. This is particularly interesting, because it is expected that the frequency increases while the stiffness of the system increases due to higher tightening torque of screws. The observed change in the natural frequencies indicates that a certain change or damage to the structure did occur, which in this case is the tightening configuration of the flange simulating different crack states. Regarding the damping variation, Figure 4 shows a not monotonic behaviour probably due to a variation of the friction mechanisms in the bolt connection. It is interested to note that the frequency and modal damping variation involves only mode #6; this is due to the particular shape of this mode, which involves mainly the deformation of the brace connection and thus more related to stiffness connection.

The results show that the experimental modal analysis can be considered an effective tool for monitoring changes in the natural frequencies of a model scale tripod structure subjected to different artificial crack configurations.

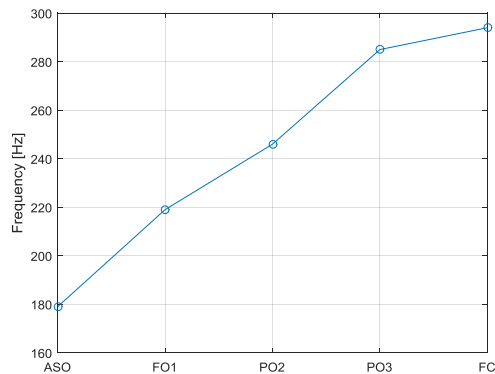


Figure 3. Sixth mode.

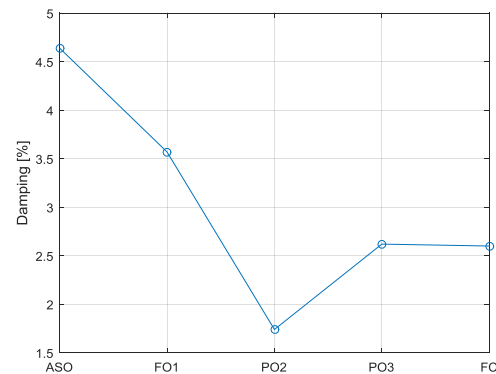


Figure 4. Sixth mode.

2.2. Non-linear effect verification

It should be recalled that one of the fundamental hypothesis, upon which the experimental modal analysis is based, is the linear dynamic behaviour of the structure [2]. Each modal analysis should start with a check of linearity of the structural dynamic behaviour. In order to identify and qualify non-linear dynamic behaviour different test procedures have been developed: the harmonic detection technique, the Hilbert transform, the damping plot and the direct time stepping method are typical examples of such techniques. Furthermore, comparing frequency response functions obtained using different excitation force levels can be used as a check for non-linearity. If the structure behaves linearly these frequency response functions are independent on the input of force level.

If the structure under test shows non-linear behaviour, the excitation becomes very important, since the measured frequency response functions will depend on the nature and the level of this excitation signal. So, the study of non-linear effects is a fundamental step in validating the results presented in the previous section. The tripod structure has a representative crack in the upper brace, as explained, since the flange with the screws interrupts the continuity of the structure. However, the structure could show linear behaviour in a certain frequency or force range while showing non-linear effects in other frequency or force ranges. Hereafter, the linear behaviour will be verified by exciting the structure with different excitation levels and by checking the variation in terms of natural frequency and modal damping ratio.

Figure 5 and Figure 6 presents the modal damping ratios for different levels of shaker excitation (0.5, 1, 1.5, 2 voltage excitation) for the configurations ASO and FO1, respectively. It can be noted that the damping values corresponding to mode #1 and 2 significantly change, while the damping values related to mode #3,4,5,6 remain approximately constant. A same trend is visible in Figure 7 and 8, which present the natural frequencies for the ASO and FO1 case, respectively. Therefore, the tripod structure exhibits nonlinear behaviour, but only in the low frequency range, where the dynamic behaviour is governed by mode #1 and #2. In the medium-high frequency range, nonlinear effects are not present. Therefore, the results presented in the previous subsection address a linear structural behaviour as the main hypothesis of modal analysis.

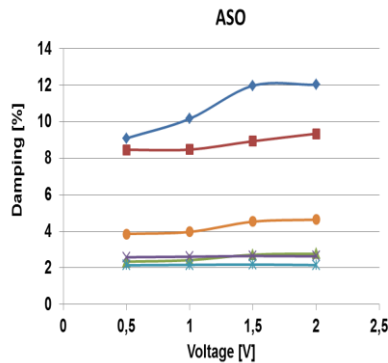


Figure 5. Damping variation – ASO.

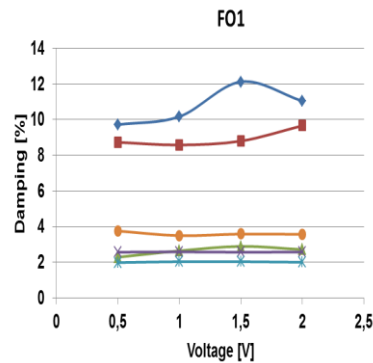


Figure 6. Damping variation – FO1.

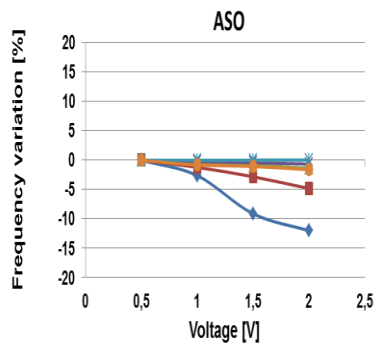


Figure 7. Frequency variation – ASO.

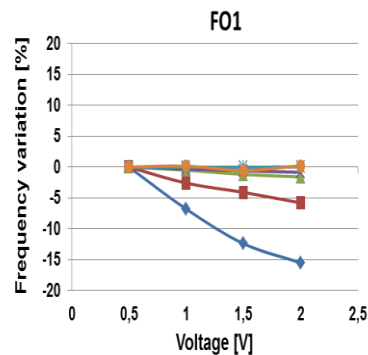


Figure 8. Frequency variation – FO1.

3. Operational modal analysis of the tripod model test rig in the water

The second part of the experimental campaign was performed in the auxiliary towing tank of the Ship Design and Research Centre in Gdansk (Poland). This tank has dimensions of 55.0 m x 7.0 m x 0.2-3.0 m and is equipped with an irregular wave generator, capable of generating irregular waves corresponding to sea state 8° of Douglas Sea Scale (scale 1:50) and regular waves of a height of up to 0,5 m at a length of up to 7,0 m or of a height of 0,18 m and length of up to 14 m.

The tripod was mounted on a thick polypropylene turntable such that the orientation of the structure could be varied with respect to the incoming waves. On the upper of the tripod a cylindrical tower section and a three bladed rotor were assembled, as presented on the Figure 9. The rotary plate allows to expose the representative cracked brace at different angle to the running waves. A full closed (FC) and full open (ASO) crack configuration was investigated to assess and verify the feasibility of the damage detection based on the mode shift method.



Figure 9. Assembled test setup in the towing tank mounted on the rotary plate table.

The irregular JONSWAP spectrum waves and regular waves (non-JONSWAP) were used for the excitation of the structure. Time data signals were acquired and processed for the estimation of the modal model parameters. To assess the influence of the wave angle with respect to the cracked brace on the validity of the analysis three different turntable settings are considered, as presented in Figure 10.

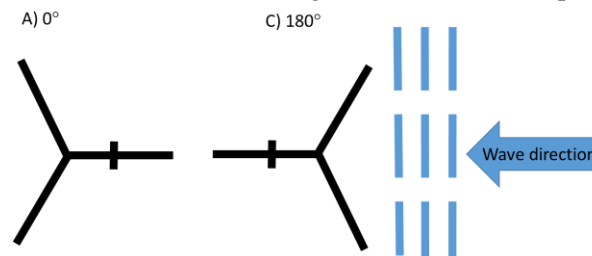


Figure 10. Top view of the three cases of exposure of the structure to the wave direction. A) 0 degrees is for the case the wave is impacting the representative cracked brace (opening the representative crack), and in C) 180 degrees the representative cracked brace is behind the structure with waves (closing the representative crack).

Two different waves were used for the excitation of the structure: (i) a regular wave (RW2) with a frequency of 1 [Hz] and an amplitude of the 0.1 [m], and (ii) an Irregular wave, representing a 1 year storm (IRW1) condition, generated in accordance with the JONSWAP spectrum. The time and frequency domain characteristics of the irregular 1-year storm wave are presented in Figure 11.

The parameters used to get a representative sea state of 1-year storm were: (a) spectrum type: JONSWAP, (b) significant wave height H_s , (c) peak period T_p , (d) peak enhancement factor " γ ". The sea state at model scale was achieved using Froude scaling, i.e.: $H_{s_model} = H_s / \Lambda$, $T_{p_model} = T_p / (\Lambda^{0.5})$.

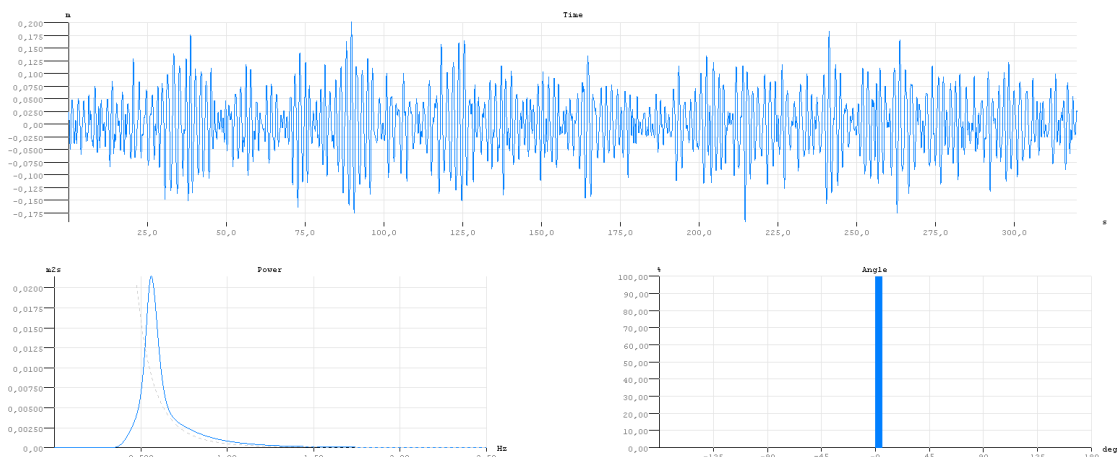


Figure 11. Characteristics of the model wave representing the 1 year storm.

Overall test matrix comprised of the combination of the tests done for the intact/damaged structure status, 0/180 degrees' orientation of the representative cracked brace, regular/irregular wave excitation. As a pre-test analysis, an impact modal analysis was performed in order to estimate the modal model parameters of the intact structure in the calm water. Unidirectional excitation by a modal hammer with force sensor was applied in the configuration A) from Figure 10. The 2nd column of Table 3 lists the frequency values, of four identified modes.

Next the structure was excited with the waves (Figure 12). The structure response was compared for the hammer and wave excitation by means of the percentage change of the frequency values as presented in Table 2 and

Table 3.

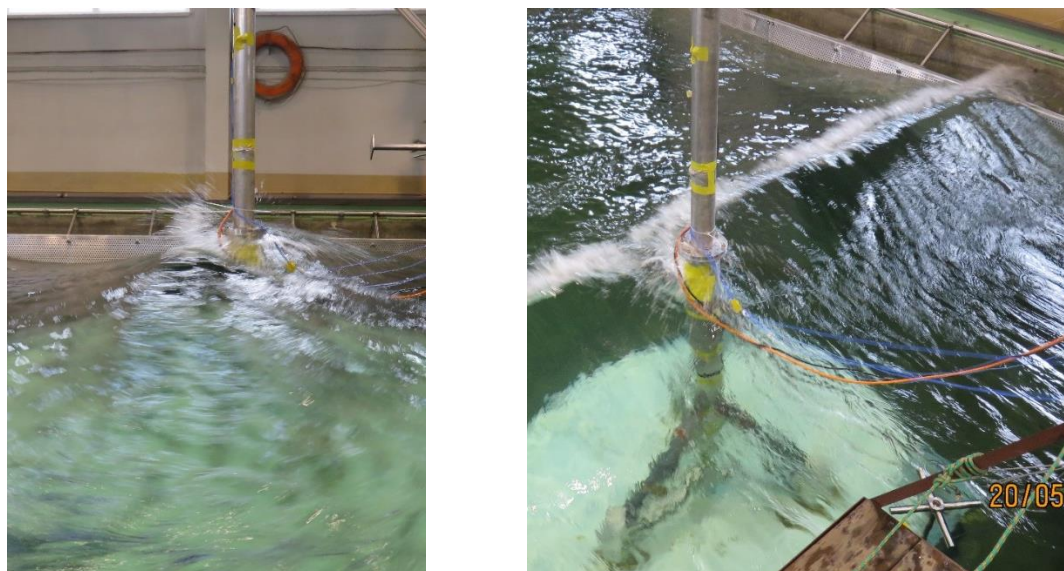


Figure 12. Output only measurement with the unknown force excitation from waves side view (left) and isometric view (right).

Table 2 Percentage change of frequency values for the modes between intact (FC) and damaged structure (ASO) for the A configuration.

Mode	0deg Impact FC	0deg IRW1 ASO	0deg Impact FC / 0deg IRW1 ASO	0deg RW2 ASO	0deg Impact FC / 0deg RW2 ASO
	Freq. [Hz]	Freq. [Hz]	Diff [%]	Freq. [Hz]	Diff [%]
1	2,9	2,7	-5,5	2,7	-5,5
2	4,1	3,7	-9,7	39	-6,1
3	8,4	8,2	-3,0	8,12	-3,0
4	10,2	9,2	-10,2	9,2	-10,2

Table 3 Percentage change of frequency values for the modes between intact (FC) and damaged structure (ASO) for the C configuration

Mode	180deg IRW1 ASO	0deg Impact FC / 180deg IRW1 ASO	180deg RW2 ASO	0deg Impact FC / 180deg RW2 ASO
	Freq. [Hz]	Diff [%]	Freq. [Hz]	Diff [%]
1	2,7	-5,2	2,7	-4,4
2	3,7	-4,4	4,5	9,5
3	8,2	-3,3	9,6	13,6
4	9,9	-3,6	10,6	3,6

In particular, Table 2 lists for the first four mode shapes of the structure with 0 deg of exposure of the structure to the wave direction, the natural frequencies regarding: the operational test with IRW1 wave excitation and ASO condition (3rd column); the operational test with RW2 wave excitation and ASO condition (5th column); the percentage difference between results FC and ASO condition with IRW1 wave excitation (4th column); the percentage difference between results FC and ASO condition with RW2 wave excitation (6th column). It can be noted that several modes (2nd, 4th) highlight a strong percentage difference (close to 10%) leading to conclude that the operational modal analysis by using as excitation the wave motion (IRW1 and RW2) can be considered a useful tool for the identification of modal parameters of intact and damage tripod structure of offshore wind turbines.

Table 3 collects for the first four mode shapes of the structure with 180 deg of exposure of the structure to the wave direction, the natural frequencies regarding the same operational tests presented in Table 2. For this exposure direction, the frequency difference between the damage and intact structure is reduced and it seems that the effectiveness of the modal analysis for the purpose of damage detection is reduced. This result is expected, considering the wave impact direction with respect to the cracked brace: the wave forces the two adjacent surfaces of the flange to be pressed and closed. On the contrary,

in the condition at 0deg, the wave forces the two adjacent surfaces of the flange to be opened, which increases the difference in terms of stiffness between the damaged and intact structure.

4. Concluding remark

Presented results show the potential of the damage detection based on natural frequency monitoring. Several experiments have been carried out on a laboratory scale model of a tripod type support structure of an offshore wind turbine. In one of the three upper braces of the tripod, a flange is placed to interrupt the structural continuity in order to simulate a crack. Several experiments address the tripod structure in dry and in-water conditions; for the in-water condition the entire offshore wind turbine model was assembled on the tripod.

The genuine experimental modal analysis and the operational modal analysis can be an effective investigative tool in the identification of the propagation of representative cracks in structures that require high maintenance costs as offshore wind turbines, due to environmental conditions and the necessary presence of skilled people. Attention should be paid in the operational modal test since the direction of the wave can reduce the effectiveness of the techniques. The presented approach can be considered a first attempt to tackle this fascinating field. Additional measures have to be taken to identify the location of the damage and the corresponding reason. The presented investigation was not observing the dynamics of the rotary table with the high damping of the thick polypropylene rotary plate. To transfer the obtained results to the full scale structure the more in-depth analysis of the sea bottom model and experimental characteristics of the used support should be accounted for.

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