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Damage Detection in Laboratory Scale Model of the Offshore Support Structure Using Two Different Measurement Techniques

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Abstract

The paper presents a comparison of two vibration-based methods for the damage detection in a laboratory scale model of a tripod. Tripods are a part of the support structures for offshore wind turbines. The damage being tested was a circumferential crack of the tripod upper cylindrical brace. The influence of the measurement uncertainty is accounted to prevent *"false alarm" due to the inherent scatter in the test results of the object under investigation.* The first damage detection method addresses the use of acceleration signals in a genuine experimental modal analysis (i.e. input-output modal analysis) and in an operational modal analysis (i.e. output only modal analysis). The progressive damage is monitored by the calculation of the modal parameters and following their deviations. The second method is based on the application of Fibre Bragg Grating (FBG) strain sensors. Both methods were performed on the undamaged and damaged structure for different support conditions and excitations (shaker, hammer, in water basin under wave excitation). The results suggest that the method based on modal analysis can be considered a useful tool for damage detection in dry and in-water conditions. Furthermore, the FBG and Frequency Domain Decomposition (FDD) based damage detection method shows its utility to detect damage (totally unfixed flange) for all analyzed cases, although its localization is possible for a wave excitation only.

1 INTRODUCTION

Offshore support structures installed in harsh sea environment have to withstand extreme and fatigue loads in form of vibrations from wind and waves, as well as from wind turbines operation [1]. Remote monitoring [2] can optimize the number of inspections and repairs and substantially reduce the related operation and maintenance costs and thus the cost of wind energy. Nowadays, operational and failure data availability allow for the predictive maintenance; thus, the development of condition monitoring systems is a high priority in the research agendas [3, 4] for the development of the future large size turbines.

Vibration based damage detection and condition monitoring methods [5] analyze the vibration spectra of the structure [6-8]. Component deterioration affects the stiffness properties and modifies the natural frequency of the structure [9]. Different types of sensors are used to monitor the support substructure: strain gauges, optical fiber sensors based strain measurement [14,15], vibration inclination and displacement sensors [10]. In this paper two methods for damage detection in a laboratory scale model of a tripod are investigated: a method based on modal analysis and a method based on Fibre Bragg Grating (FBG) and Frequency Domain Decomposition (FDD).

2 OBJECT OF THE INVESTIGATION

In the presented work the dynamic behavior of a laboratory scale model of a tripod offshore wind turbine support structure [11-13] is investigated (Figure 1, left). It is made of aluminium cylindrical beams. The model is 2 meter high and 30 kilos weights. This bottom fixed substructure comprises of the main tower supported by three upper and three lower braces, which are fixed to the three pile guides.

Figure 1 Instrumented tripod structure for the acceleration and strain measurements (left), with model of the circumferential crack in partial open (center) and total failure (right) configurations of screwed flanges.

In one of the upper braces (Figure 1, center) the model of the circumferential crack was implemented by means of the screwed flanges. In the fully tightened configuration the model represents the intact structure. Untightening five screws in the structured manner allow for considering the initiation and propagation of the crack up to the total failure. Five different degrees of circumferential cracks have been considered, namely “All Screws Open” (ASO), “Full Open 1” (FO1), “Partial Open 2” (PO2), “Partial Open 3” (PO3), “Full Close” (FC).

3 ACCELERATION BASED DAMAGE DETECTION

The first method presented in the paper utilizes the accelerometers for the monitoring of the vibration of the structure. Experimental study of the tripod encompassed two main test configurations. The first configuration addresses the genuine experimental modal analysis of the tripod model in dry conditions; the second test configuration regards the operational modal analysis of the tripod incorporated into the entire offshore wind turbine model in the in-water condition.

3.1 Experimental modal analysis in dry conditions

In the experimental modal analysis the excitation of the tripod was implemented by means of two electrodynamic shakers and modal hammer. Structure was supported by rubber blocks to ensure free-free boundary conditions. Vibration acceleration braces and piles was measured in five points in three directions. The tower was measured in eleven points. Each electrodynamic shaker stinger was instrumented with the force and acceleration sensors.

Frequency Response Functions were acquired and used in the estimation of modal model parameters. Linearity and reciprocity (Maxwell rule) were checked to observe the modal testing assumptions. Structure was measured in the intact and progressive damage cases for the comparison of the modal model parameter values. 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 frequency (fn) and modal damping (ζ) were obtained by averaging the values coming from the Least Square Complex Exponential (LSCE) method and PolyMAX method [17, 18]. 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.

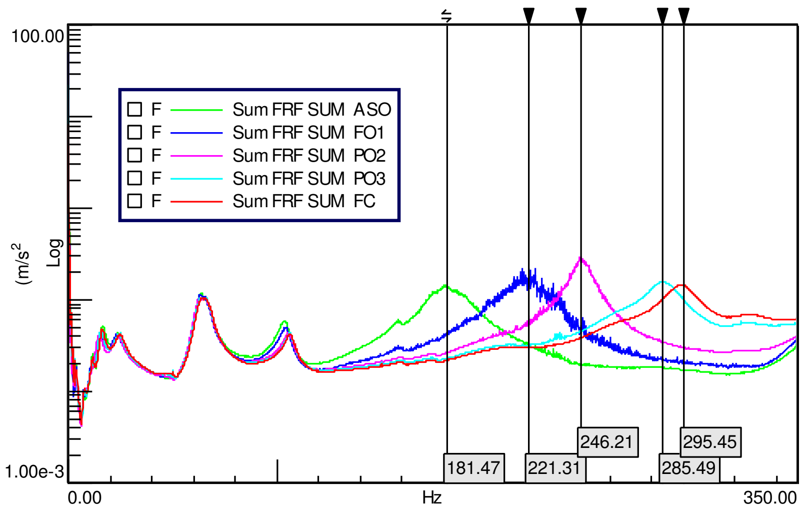

Figure 2 FRFs SUM.

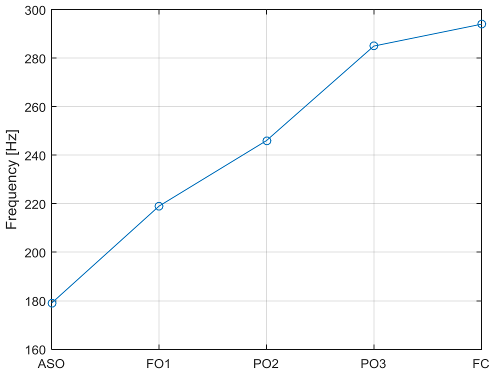

Figure 3 : Sixth mode.

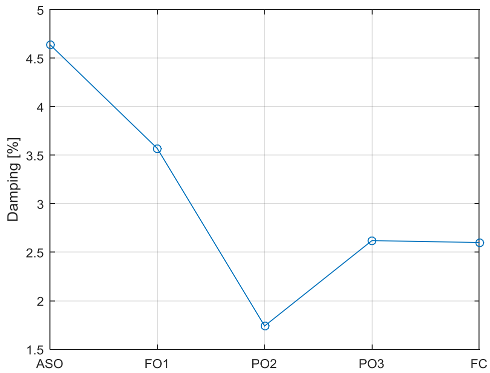

Figure 4: Sixth mode.

As an example of results, Figure 2 depicts the FRF-sum, i.e. the complex sum of FRFs for all the measured points in the five configurations being tested. It can be noted that the modes in the frequency range between 0 and 150Hz remain the same for all the configuration (same natural frequency, same modal damping, same mode shape), while the peaks in the frequency range between 150 and 350Hz refer to the same mode shape. Such a mode shapes has different modal damping and natural frequency, as depicted in Figure 3 and Figure 4. This behavior is due to the different degrees of crack propagation because of the different flange connection stiffness. Therefore, the genuine experimental modal analysis can be considered an efficient tool for the identification of crack in tripod supporting structures by monitoring the natural frequency and modal damping of an a priori selected mode shape.

3.2 Operational modal analysis in the wave tank

For the operational modal analysis in the water tank the tripod structure was screwed to a large rotary table (Figure 5, left). The rotary plate allows to expose the cracked brace at different angle to the running waves. Furthermore, the additional cylindrical section and three bladed rotor were assembled on the upper part of the tripod as presented in the Figure 5. In the submerged part of the tower, four biaxial underwater accelerometers (Wilcoxon Research model 757) were screwed to the structure. In this test, the crack configurations under investigation was the full close (FC) and full open (FO1).

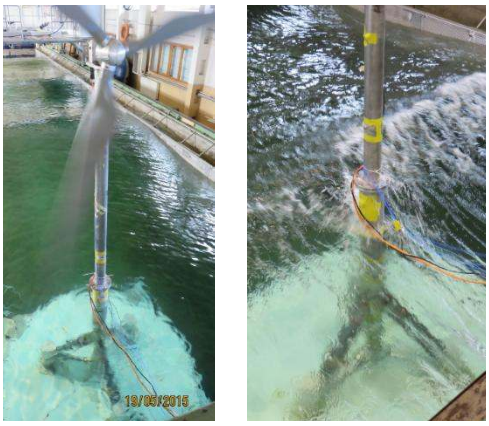

Figure 5 Water tank test setup mounted on the rotary plate table (left) and with wave excitation (right).

To model the different angle of the approaching waves against the cracked brace three different positions of the rotary table were implemented as presented on Figure 5 and Figure 6. Time data signals were acquired and processed for the estimation of the modal model parameters.

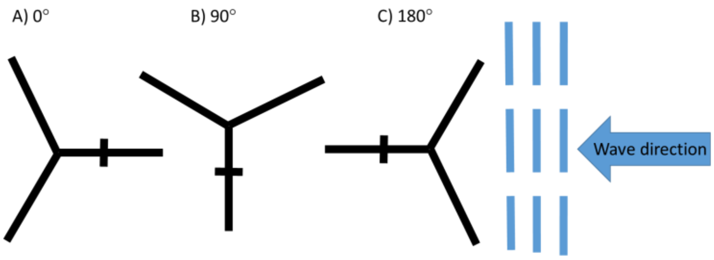

Figure 6 Top view of the three cases of exposure of the structure to the wave direction. A) 0 degrees is for the case the wave is impacting the cracked brace (opening the crack), B) the 90 degrees cracked brace is perpendicular to the waves and in C) 180 degrees the cracked brace is behind the structure with waves (closing the crack).

Different wave patterns were used for the excitation of the structure according to the JONSWAP spectrum. Regular wave has a frequency of 1 [Hz] and amplitude of 0.1 [m]. Irregular wave was a representative of 1 year storm (IRW1) and 50 year storm (IRW3), as depicted in Figure 7.

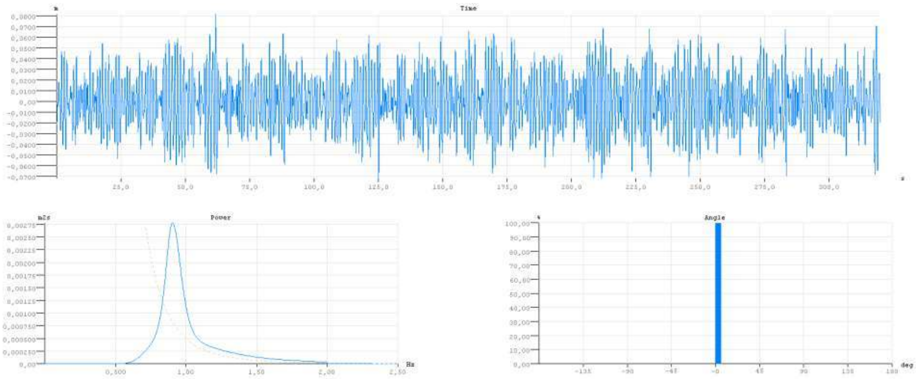

Figure 7 Characteristics of the model wave representing the 50 year storm

An impact modal analysis was performed as a pre-test in order to estimate the modal model parameters of the intact structure (FC) in the calm water. Unidirectional excitation by a modal hammer was applied in the configuration A) of Figure 6. Then, the intact structure was excited with the waves (Figure 5 right) and an operational modal analysis was carried out for the estimation of the modal parameters. The structure response was compared for the hammer and wave excitation by means of the percentage change of the natural frequency. In this test, the hammer test has to considered as a reference. In the majority of the cases the percentage difference was under 8%, leading to conclude that the operational modal analysis leads to reliable results with respect to the hammer test.

Mode	0deg IRW1wav FO1	IRW1 FC/FO1	0deg RW2wav FO1	RW2 FC/FO1
	Freq. [Hz]	Diff [%]	Freq. [Hz]	Diff [%]
1	2,697	-5,033	2,69812	-32,528
2	3,744	-4,365	3,89516	-12,098
3	8,187	2,064	8,1874	-9,235
4	9,193	-1,669	9,19301	-8,717
5				
6	20,029	0,277	20,0339	-1,033
7	25,282	-0,743	25,2783	0,110
8	32,784	10,556	33,7396	13,509
9	33,756	-3,423	37,7475	8,973
10	41,419	-0,539	41,419	-0,918
11	54,459	3,353	54,4587	-0,646

Table 1 Percentage change of frequency values for the modes between intact and damaged structure for the A configuration of the setup.

Table 1 lists for the first eleven 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 FO1 condition (2^{nd} column); the operational test with IRW2 wave excitation and FO1 condition (4^{th} column); the percentage difference between results FC and FO1 condition with IRW1 wave excitation (3^{rd} column); the percentage difference between results FC and FO1 condition with IRW2 wave excitation (5th column). It can be noted that several modes (8th for IRW1 and 1st, 2nd, 8th for IRW2) highlight a strong percentage difference (larger than 10%) leading to conclude that the operational modal analysis by using as excitation the wave motion can be considered a useful tool for the identification of modal parameters of intact and damage tripod structure of offshore wind turbines.

3.3 Measurement uncertainty assessment

A precise analysis regarding uncertainty has been accounted in the dry configuration by using shakers as exciters. Experimental campaign was realized by use of 5 triaxial accelerometers for the structure response measurement. The sensors were moved from one location to another to cover all measurement points. It resulted in the collection of numerous sets of signals corresponding to a particular measurement points. Such approach made possible to carry out an uncertainty analysis. In particular, the individual FRF functions were investigated for each measurement set of 5 sensors. Partial modal models were estimated based on each measurement sets.

The identification of the modes is considering the local maxima of a function obtained by a complex sum of all the acquired FRFs. These maxima are unambiguous and thus the only related uncertainty results from the resolution of the frequency measurement. We focused on the inevitable error that is due to represent the object by just one curve being a combination of all the FRFs. A representative series of such curves is presented in Figure 8, with each one of them being a sum of all individual FRFs for one measurement configuration.

To assess this uncertainty, we take into account all the FRFs. Once the modes are derived, the whole frequency range of interest is divided into intervals around each mode (maximum). The borders of the interval $B^i_{l,r}$ are calculated from equation (1).

$$B_{l,r}^{i} = f_i \pm inf\{f_i - f_{i-1}, f_{i+1} - f_i\}, \quad (1)$$

where $B_{l,r}^{i}$ is the left (right) border of the i-th interval and f_i is the frequency of the i-th mode.

Every interval spans over one mode and it does not overlap other intervals. For each interval, the position of the maximum for each individual FRF has been determined. An exemplary result for one interval is shown in Figure 8.

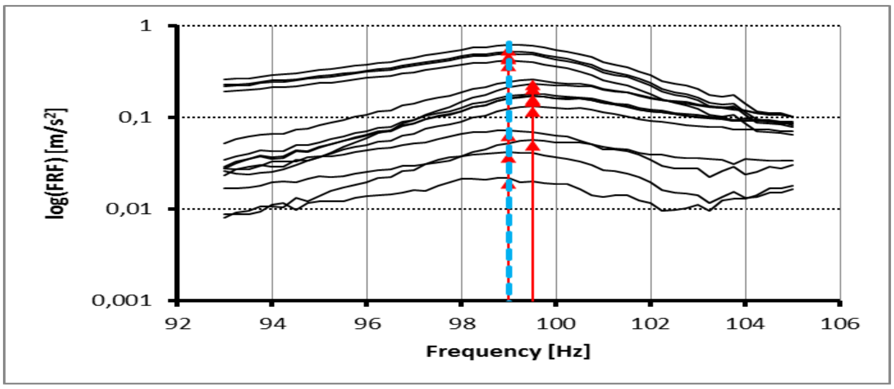

Figure 8 Maxima of individual FRFs; black lines are FRFs, red solid lines depict the maxima of FRFs and the dashed blue thick line presents the position of the mode.

The black lines are FRFs, the red solid lines depict the maxima of FRFs and the dashed blue thick line represents the position of the mode. In every interval, the standard deviation of the positions of the maxima is calculated and adopted as the uncertainty value for the corresponding modes. An example of obtained results is given in Table 2.

Mode	Frequency [Hz]	Uncertainty [Hz]	Relative Uncertainty
1	43	0.552	1.28%
2	62	0.190	0.31%
3	78.75	0.319	0.41%
4	99	0.259	0.26%
5	111	1.507	1.36%
6	120	2.243	1.87%
7	140	0.401	0.29%
8	158.75	1.125	0.71%

Table 2 Uncertainty of mode frequencies.

The final assessment of mode frequencies analysis is depicted in Figure 9. For better readability, the values of uncertainty have been multiplied by the factor of 25 only for plotting. The procedure has been done for every experimental modal analysis carried out in dry condition in order to establish reliable uncertainties.

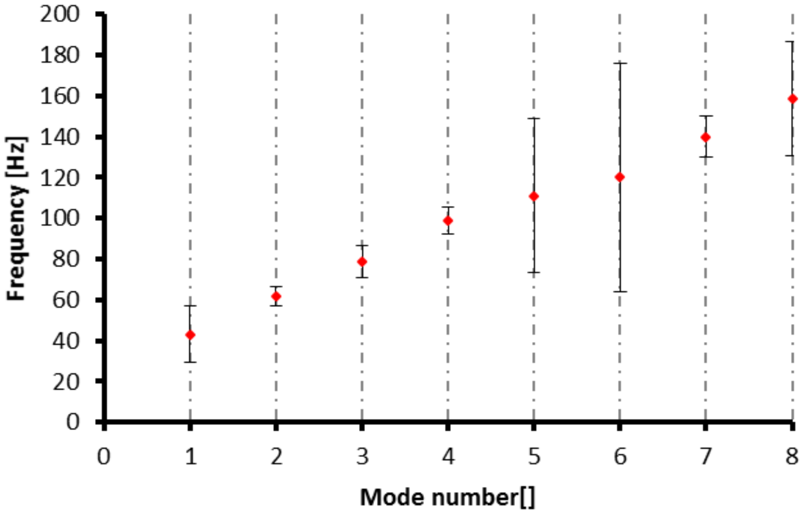

Figure 9 The uncertainties of the frequency of the modes (values of uncertainty multiplied by the factor of 25).

4 FDD STRAIN METHOD DAMAGE DETECTION

The analysed offshore support structure was equipped with 15 single os3120 Micron Optics FBG sensors together with os4100 Micron Optics temperature compensation sensor instrumented by si425-500 Micron Optics interrogator with sampling frequency of 250 Hz. The strain sensors were mounted equally on every leg side of the tripod: two on an upper brace, two on the tower (one under main joint and one over second joint) and one on a cylinder at the bottom of the structure [16]. The sensors were installed near the main node of the structure, because the neighbourhood of the main node of the tripod is the critical element due to the axial compression and bending moment above the node are converted mainly to axial forces in the upper braces. On the other hand, the symmetric location of sensors on the structure can be used to upper brace damage detection and localisation. Due to its geometry the analysed structure can be divided into three similar sections denoted as S1 (leg with the flange), S2, and S3. Every part contains upper and lower braces, cylinder, and part of the tower.

The utility of the proposed SHM method was analysed on the tripod structure for two experimental cases. In the first case, the structure was fixed to antivibration table in IFFM PASci laboratory, while during the second performed in the in the water basin in the Ship Design and Research Centre (CTO S.A.) laboratory the structure was fixed to the support base and partially submerged up to the water level about 150 cm from tripod's bottom flanges [17] in configuration denoted as c in Figure 6. In every case the measurements were performed both on healthy (fixed flange) and damaged (opened flange) structure.

For thermo-mechanical strain ε_{cs} calculated from FBG sensors the Frequency Domain Decomposition (FDD) method was applied. All signals before FDD decomposition were standardised to have zero mean and unit sample standard deviation. The sensors were divided into four different sets. The first one denoted as CC contains all FBG sensors, while the others (S1, S2, S3) contains only sensors located on a particular leg side [17]. The analysis was performed under two types of excitation: repeated hammer impacts in chosen points on the tripod structure and artificial waves. The utility of the FDD method for determination of natural frequencies of the same tripod model fixed to the antivibration table was earlier presented in [17]. The differences observed between curves contains first eigenvalues for intact and damaged structure can be used for detection of the damage. The proposed damage index DI is calculated using a relationship:

$$DI = \frac{A_h - A_d}{A_d}\ 100\ [\%], \tag{2}$$

where A_h and A_d are the area under the curves containing first eigenvalues for healthy and damaged structure for chosen frequency range, respectively.

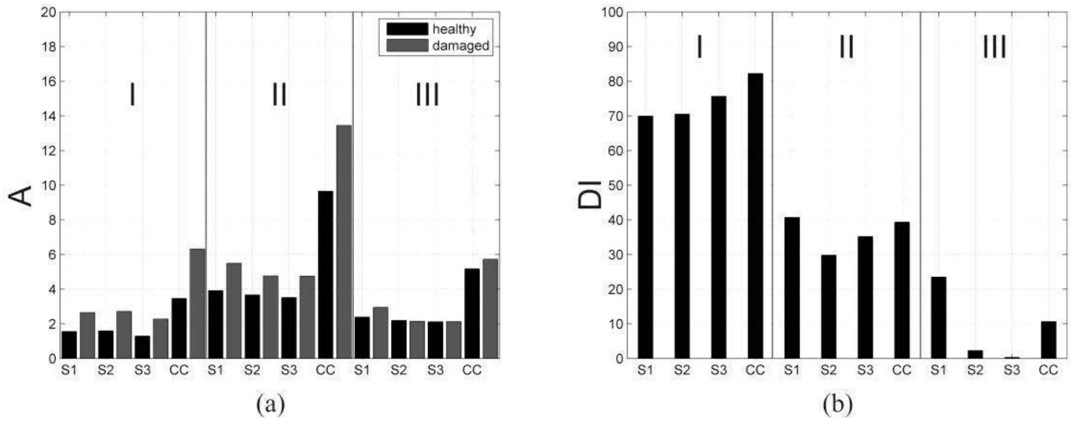

Figure 10. A comparison of (a) A and (b) DI values calculated for the tripod structure: (I) fixed to antivibrating table and excited by impacts, (II) submerged in the water basin and excited by impacts, (III) submerged in the water basin and excited by irregular wave.

A comparison of A and DI values determined for frequency range 0 Hz to 120 Hz for three cases are presented in Figure 10. For the first two cases, the structure was excited by several impacts in several points on the tripod structure, while in the last one – by irregular wave (0.22 H [m], 1.7 T [s], 4.36 γ [s]). For all impact excitation cases the A_h values are smaller than for A_d, although it is hard to determine which tripod side is damaged. For wave excitation the A_h and A_d values for intact and damaged cases for legs (S2 and S3) without flange are similar, while for the S1 leg slightly differ. The damage index DI also indicates a damage occurrence, but only for a wave excitation case the damaged can be localised with accuracy to the tripod side. The maximum damage index error calculating as a comparison for three repeated measurements for the same structural state and excitations parameters is equal to 20%.

5 CONCLUSIONS

In this work, the effectiveness of the experimental modal analysis, operational modal analysis and FBG sensors is studied with the aim of investigating the structural integrity of a tripod supporting structure of an offshore wind turbine. In particular, several experimental tests have been carried out on a laboratory scale model of the tripod type supporting structure of an offshore wind turbine. In one of the three upper braces of the tripod, a flange is placed to interrupt the structure continuity in order to simulate a crack. Experimental tests address the tripod structure in dry conditions and incorporated into the entire offshore wind turbine model in the in-water condition under wave excitation.

The genuine experimental modal analysis and the operational modal analysis can be an effective investigative tool in the identification of the propagation of cracks in structures that require high maintenance costs as offshore wind turbines, due to environmental conditions and the necessary presence of skilled people.

FBG sensors can be used for measuring strain for the tripod structure both in the air and submerged in the water basin and excited by impacts or waves. The proposed damage detection method shows its utility to detect damage (totally unfixed flange) for all presented cases, although its localisation with accuracy to the tripod leg side is possible for a wave excitation only.

The presented investigation was not observing the dynamics of the rotary table with high damping values 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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