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Ettore Funaioli

17 luglio 2015

A cura di
Umberto Meneghetti e Vincenzo Parenti Castelli

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INDICE

Prefazione

ON THE USE OF EXPERIMENTAL MODAL ANALYSIS FOR DAMAGE DETECTION OF A TRIPOD SUPPORTING STRUCTURE FOR AN OFFSHORE WIND TURBINE

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Abstract: *Since offshore wind turbine supporting structures are subjected to dynamic environments with time-varying loading conditions, it is important to model their dynamic behaviour and validate these models by means of vibrational experiments. In this paper, dynamical state assessment of the supporting structure is investigated by experimental modal analysis. In particular, it will be demonstrated that the experimental modal analysis can be an useful technique for the damage detection in the tripod supporting structure of an offshore wind turbine.*

Keywords: *offshore wind turbine, experimental modal analysis, damage detection*

1. INTRODUCTION

In the last few years, many European countries focused on alternative renewable energy sources, with the aim of reducing the oil utilization, which is not a renewable energy source and, in several cases, has to be imported from other countries. One of the renewable energy source is the offshore wind technology. The offshore wind technology is a rapidly developing area, especially in the North Europe. In many scenarios, it is foreseen as a future of European renewable energy source. This continuous evolving technology requires constant improvements of knowledge, in particular in the field of structural dynamic behaviour.

The following research work is part of the project *Development of selection method of the offshore wind turbine support structure for Polish maritime areas* with the acronym of AQUILO. Project AQUILO is supported by Polish National Research and Development Center. The aim of the project is to create a knowledge basis, from which the investors will be able to decide the best type of support structure for offshore wind farms in specific locations in Polish maritime areas. Focal point of the research is the support structure of the offshore wind turbine of the tripod type.

In particular, the aim of the following research addresses to consider the possibility of using experimental modal analysis for the damage detection in the tripod supporting structure of an offshore wind turbine. In fact, experimental modal analysis is generally a method used to verify any resonance presence, to verify numerical models (FE) and, finally, to verify structural integrity.

2. OFFSHORE WIND TURBINE SUPPORTING STRUCTURE

The object of investigation is a laboratory scale model of the tripod type supporting structure for the offshore wind turbine. It is made of aluminium cylindrical beams. The model is 2 meter high and 30 kilos weights (Figure 1). 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 structure continuity (Figure 2). This flange can be closed with different tightening torques of the screws that are present. The screws are distributed and named as: Top Screw (TS), Right Screw (RS), Left Screw (LS), Right Bottom Screw (RS), Left Bottom Screw (LBS).

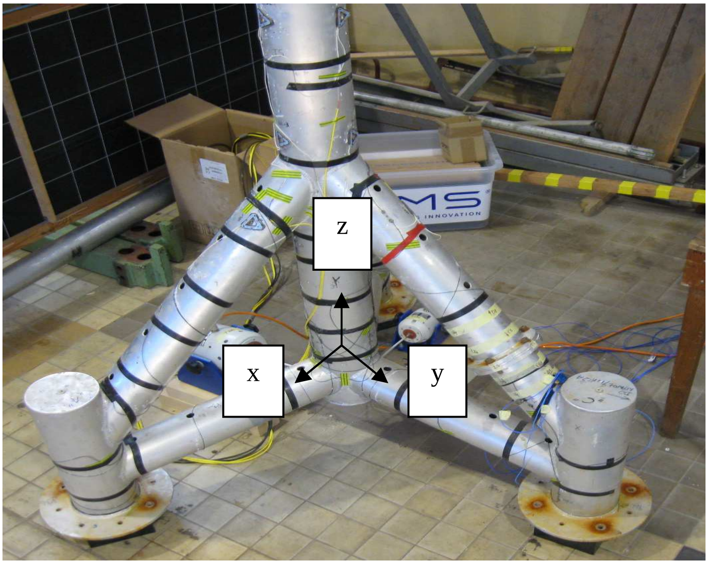

Figure 1. Laboratory scale model

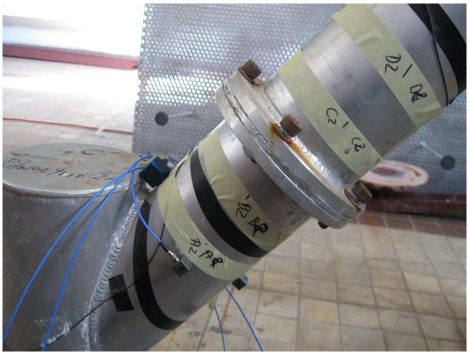

Figure 2. Flange, screws and accelerometers sections.

The set up used to perform the modal analysis is made of two shakers, that excite the tripod structure in the base of the central column, as shown in Fig. 1; in this case, the tripod aluminum model is supported by rubber supports (Fig. 3), to realize free-free boundary conditions. The two shakers excite the tripod structure along the x and y directions; the response of the tripod in x, y and z direction is measured by 16 piezoelectric tri-axial accelerometers, 8 placed before the flange and 8 placed after the flange. There are four sections: A, B, C and D (Fig. 2). In each section four accelerometers are placed. The flange can be closed with different tightening torques to simulate crack propagation in the tripod structure. In particular, five types of screw configurations have been accounted: All Screws Open (ASO), Full Open 1 (FO1), Partial Open 2 (PO2), Partial Open 3 (PO3), Full Close (FC).

ASO configuration means that all the screws are open and the tightening torque is equal to 0 [Nm]. FO1 configuration means that three screws are open (top screw, right screw and left screw) and the remaining screws have a tightening torque equal to the maximum (i.e. 54.2 [Nm]). PO2 configuration means that the top screw is completely open, right and left screws are closed with a tightening torque equal to 13.6 [Nm] and, finally, right and left bottom screws are closed with a tightening torque equal to 54.2 [Nm]. PO3 configuration means that the top screw is closed with a tightening torque equal to 13.6 [Nm], right and left screws are closed with a tightening torque equal to 27.1 [Nm] and right and left bottom screws are closed with a tightening torque equal to 54.2 [Nm]. At last, FC configuration means that all screws are closed with a tightening torque equal to 54.2 [Nm].

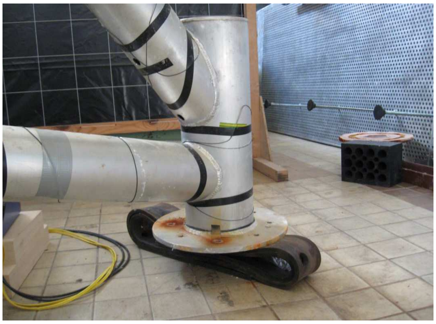

Figure 3. Rubber supports.

Table 1. Screws configuration

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

3. POST-PROCESSING METHOD

Several modal analyses have been done in different conditions: that means different tightening torques of flange screws and variable excitations realized by shakers, as explained in the previous section. Each post-processing analysis is done by using LMS Test.Lab [1], with two methods that allow to find the values of natural frequencies, damping and mode shapes: PolyMAX and LSCE. Figure 4 depicts the wireframe model used for the experimental modal analysis; the points in the figure represent the measurement response locations. As an example, Figure 5 collects several frequency response functions (FRFs, i.e. the ratio between response and excitation force) for the different measurement points.

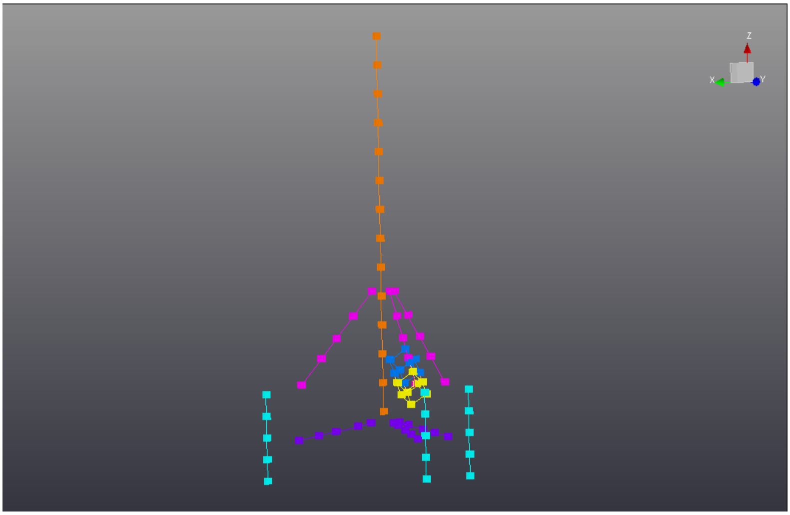

Figure 4. Wireframe model.

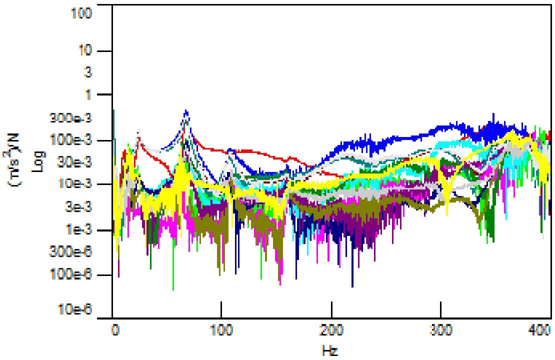

Figure 5. FRFs measured in x direction.

4. RESULTS AND COMPARISONS

Figure 7 depicts the FRF SUM, i.e. the complex sum of all the measured FRFs, for the different configurations being tested. The figure clearly shows several peaks that are due to the natural frequencies of the tripod. It is interested to note that several peaks remain at the same frequency for the different configurations, while the peak at about 200 Hz changes its frequency from about 180 to about 300 Hz. Figures 7 to 18 present the natural frequencies and modal damping ratio for the different configurations under tests. As argued by the FRF SUM, the natural frequencies and modal damping ratio of mode #1,2,3,4,5 do not change. On the other hand, mode # 6 significantly changes its frequency and damping.

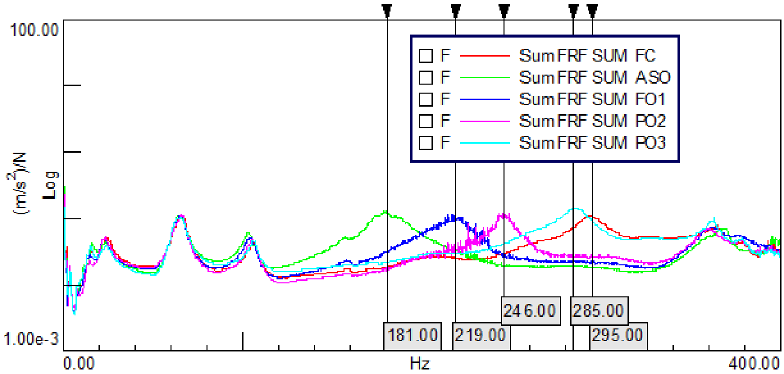

Figure 6. FRFs SUM

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. This rise of frequency indicates that something in the structure is changing, due to the different screw configurations that simulate a crack propagation on the tripod supporting structure.

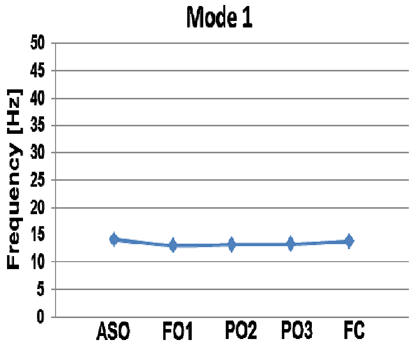

Figure 7. First mode, 15 Hz.

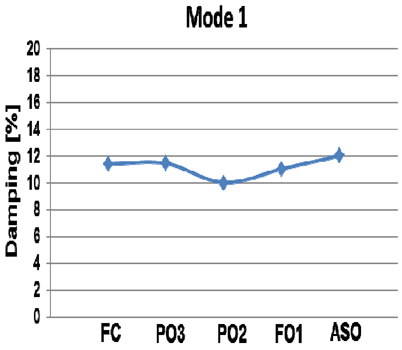

Figure 8. First mode, damping = 11%.

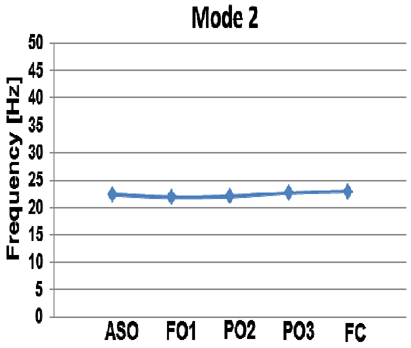

Figure 9. Second mode, 22 Hz.

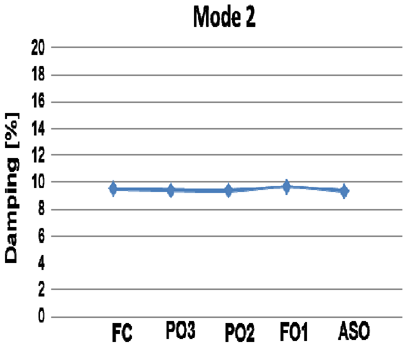

Figure 10. Second mode, damping = 9.5%.

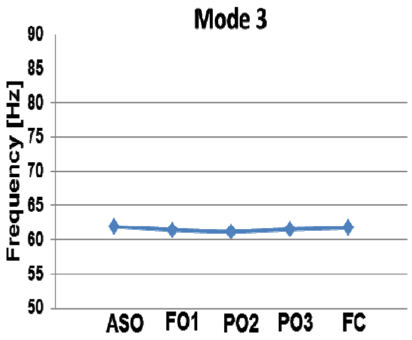

Figure 11. Third mode, 62 Hz.

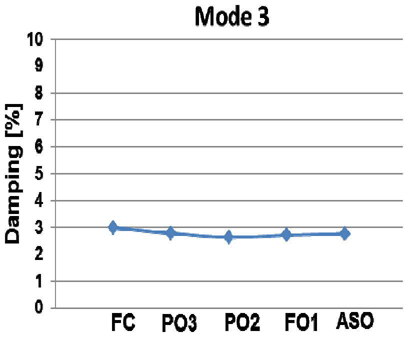

Figure 12. Third mode, damping = 2.7%.

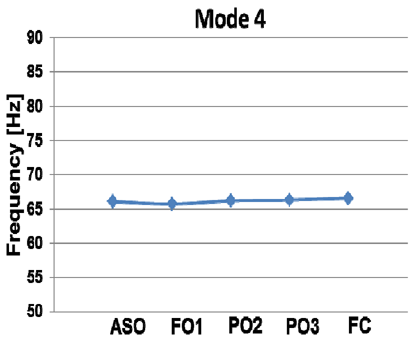

Figure 13. Fourth mode, 66 Hz.

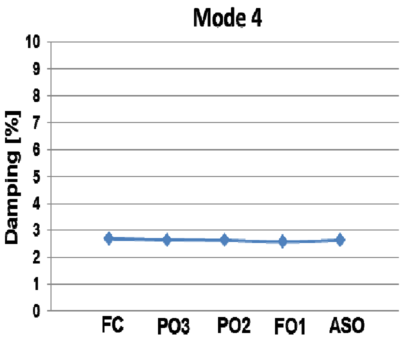

Figure 14. Fourth mode, damping = 2,5%.

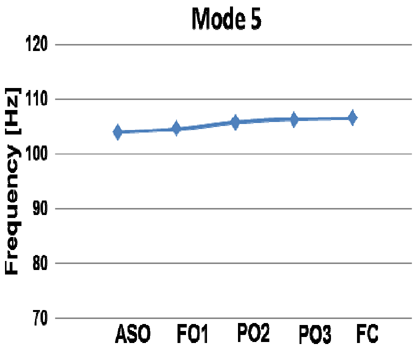

Figure 15. Fifth mode, 106 Hz.

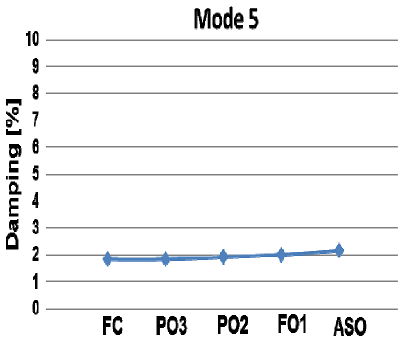

Figure 16. Fifth mode, damping = 2%.

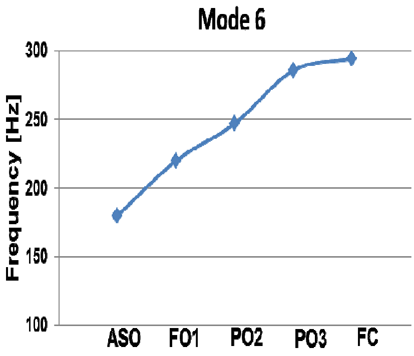

Figure 17. Sixth mode.

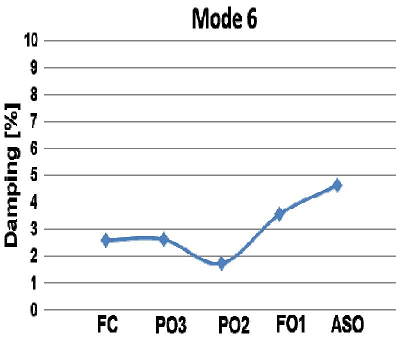

Figure 18. Sixth mode.

5. NON-LINEAR EFFECTS

It should be recalled that one of the fundamental hypothesis, upon which the experimental modal analysis is based, is the linearity of the structure dynamic behaviour [2]. Each modal analysis should start with a check of the linearity of the structure dynamic behaviour. In order to investigate the non-linear dynamic behaviour in terms of identification and quantification, several indicator functions and 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, measuring frequency response function at different force levels can partly check non linearity. If the structure is linear these frequency response functions are independent of the input of force level.

If the structure under test has a non-linear dynamic 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 fundamental to validate the results discussed in the previous section.

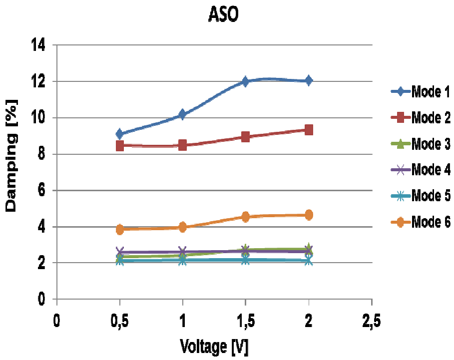

Figure 19. Damping variation – ASO.

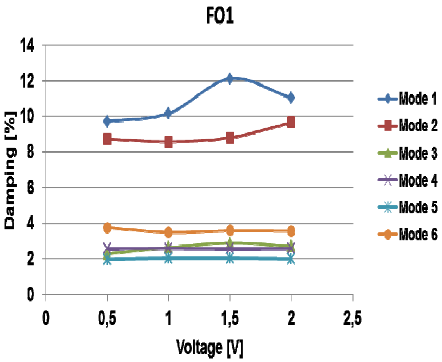

Figure 20. Damping variation - FO1.

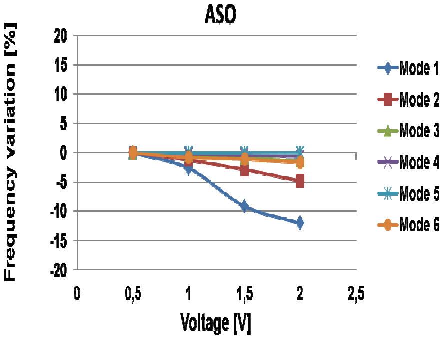

Figure 21. Frequency variation – ASO.

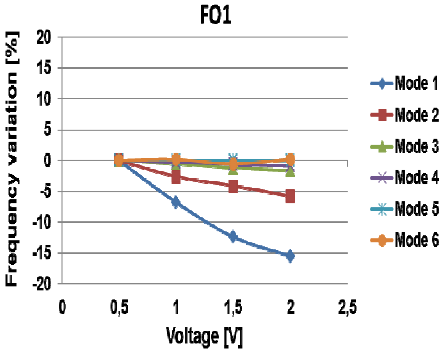

Figure 22. Frequency variation – FO1.

The tripod supporting structure has a discontinuity in a 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 range of frequency and non-linear effects in another range of frequency. 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.

Figures 19 and 20 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. It can be noted that the damping values referred to Mode #1 and 2 significantly changes, while the damping values related to Mode #3,4,5,6 do not change. A same trend is presented in Figures 21 and 22 in terms of natural frequencies. Therefore, the tripod structure exhibits a non linear 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, non linear effects are not present. This validates the results presented in the previous section.

6. CONCLUSIONS

In this work, the effectiveness of the experimental modal analysis is studied with the aim of investigating the structural integrity of a tripod supporting structure of an offshore wind turbine.

In particular, several experimental modal analyses 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. The variation in terms of modal damping ratio and natural frequencies has been used as a detection method for the evaluation of the crack presence. Thus, the experimental 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.

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[2] Heylen, Lammens, Sas, 2003. “*Modal Analysis Theory and Testing”*, Katholieke Universiteit Leuven.

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