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Structural Health Monitoring results as an input for asset management of offshore wind turbine support structures

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ABSTRACT: For an accelerated shift from fossil-based energy sources to renewable energy sources, being environmentally friendly only is not enough. The renewable energy sources need to be competitive with the other energy sources in cost and reliability. For the case of offshore wind energy industry, multiple studies showed that significant cost reduction can be achieved from minimizing the operation and maintenance (O&M) costs.

Optimized O&M strategies depend on reliable and continuous information on the structure condition and performance. Most of the already operating or planned offshore wind farm projects worldwide are or will be equipped with Structural Health Monitoring (SHM) systems to ensure structure safety. In Germany, the equipment of SHM system on 10% of the structures in an offshore wind farm even used to be a government requirement. The available SHM data represent an enormous and as of yet largely unexploited potential for optimization of asset management and wind farm operation.

In this paper, SHM data analysis results from operating offshore wind farm projects are used for evaluation and quantification of unfavourable operation conditions or scenarios.

1 INTRODUCTION

Wind industry is significantly contributing in the transition from non-renewable to renewable energy sources. According to Wind Europe (2016), in EU wind energy was covering an electricity demand of only 1% in 2000, but increased to about 16.50% in 15 years' time. Still EU is targeting for 32% renewables by 2030 with a possible upward revision in 2023 (Wind Europe, 2019). With such plans and being one of the main contributors, offshore wind industry needs to accelerate its pace. To fulfill these plans, wind turbines are being built bigger, taller, more efficient and in more challenging sea environments for higher power production.

Several studies showed that for wind energy industry to compete with the other energy sources and secure its future, a cost reduction of about 40% is required. A study carried out under the research program FLOW (Far and Large Offshore Wind) concluded in its report (De Vos, 2016), that 40% cost reduction can be achieved until 2023. A similar conclusion was also reached by DNVGL (2014), that the 40% cost reduction is achievable. The report further broke down the contributions as; 12% from innovative way of doing things in a better way, 6% from improving the efficiency of existing systems, 7% from reducing risks and 15% from other activities.

Structural Health Monitoring (SHM) is mainly used as a support for asset management decision making of operation and maintenance. It is also used as justification for possible safe service lifetime extension of the wind turbines. However, in this paper, SHM data analysis results in combination with environmental and operational data from the turbine are used to investigate unfavourable operation conditions or scenarios, which can affect the overall service lifetime of the structure. These operation conditions can result from human or machine errors.

For easier comparison and visualization of the different scenarios, the effects are quantified as measured stress diagrams (“to-from” plots) and accumulated fatigue damages. For easier comparison with the available 10-minute mean environmental and operational data of the turbine, the fatigue analysis is made for every 10-minute strain time history raw data.

2 STRUCTURAL HEALTH MONITORING

2.1 Monitoring concept

In the past, detection of defects or damages was done by basic inspection methods, such as visual, dye penetrant, acoustics etc. all these methods involve inspection of all structural components in detail, before the structure can be declared damage free. Such methods are obsolete for inspection of damages in large civil engineering structures, especially offshore structures considering the inaccessible components below water. This led to the development of global damage detection methods, where damage in any part of the structure is reflected in the global characteristics of the structure, which are sensitive to damage.

Almost all offshore wind farms all over the world are equipped with some monitoring system. This is necessary for the relatively young offshore wind industry, which is continuously dealing with uncharted waters. Every country has specific requirements. For example, in Germany until 2015 it was required by the government body BSH (German Federal Maritime and Hydrographic Agency) to install foundation monitoring system on 10% of the wind turbines in an offshore wind farm (BSH, 2007). But in the revised document BSH (2015), the 10% recommendation was replaced with “*representative offshore wind turbine sites*”. This gives the operators more flexibility but also more responsibility to proof to the authorities that appropriate safety measures are being taken. The lack of a clear guideline made almost all wind farm operators to still adopt the outdated 10% recommendation.

In the offshore wind industry, vibration based structural health monitoring (VB-SHM) is usually used. VB-SHM has been in use for several decades in monitoring of bridge structures. In this paper, SHM data from two offshore wind farms in the North Sea is used. For confidential reasons, the names of the wind farms are kept pseudonyms as Wind Farm A and B. All turbines in both wind farms are supported on Monopile foundations. In each of the wind farms, a monitoring system is installed on 10% of the turbines. The monitoring system consists of an array of sensors, such as accelerometers, inclinometers, displacement transducers and strain gauges. For an offshore environment, usually highly sensitive and robust sensors are used to continuously record the response of the structures.

2.2 Data management

The data collected from all the sensors in the monitored turbines is stored in the offshore server located at the offshore substation (OSS). The data is fetched to the onshore server or office through the internet. Usually, the 10-minute statistical data (maximum, minimum, standard deviation and mean) for all channels are immediately transferred to the office for display on web interface, while the raw data is analyzed on site and the analysis results also transferred for display with some time lag. The SHManager (2016) web interface being referred to in this paper was developed by airwerk GmbH and VCE Vienna. The web interface is not only for displaying monitoring data and analysis results, but also used as a decision making support tool for asset management. Figure 1 shows screen shot of SHManager.

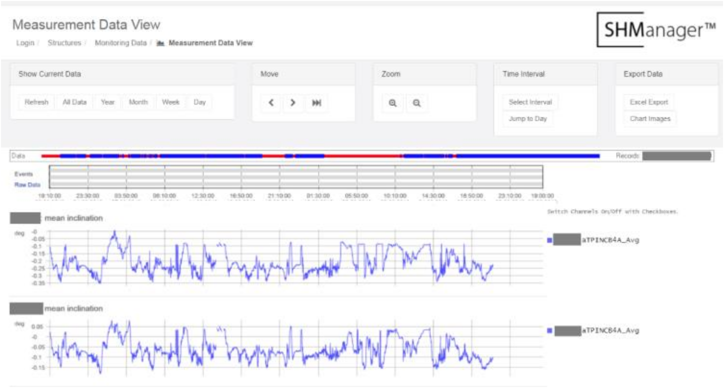


Figure 1. Screen shot of SHManager web interface

2.3 *Data analysis approach*

For the huge amount of data collected from offshore wind farms, a semi-automatic data analysis approach is used. More information can be obtained from Tewolde et al. (2018). Automatic routines have been developed to execute modal analysis, load cycles counting and fatigue analysis and save the result files as soon as the raw data files are available. Then, the result files are transferred for display on the web interface. In this section, a very brief over view of the fatigue analysis and modal analysis approaches used in this paper is given.

2.3.1 Fatigue analysis

For computation of the fatigue damages, the strain data is first pre-processed and temperature compensated before computing the stress time history. Then rain flow counting (RFC) is applied according to ASTM E1049-85 (2017) to calculate the rain flow matrix (RFM), which contains the stress ranges and mean stresses along with their corresponding counted number of cycles. The mean stresses from RFC provide information about the background of the stress ranges, whether they originate from tension or compression stresses. Stress ranges originating from tensile stresses have more damaging effect than those from compressive stresses of equal magnitude. Therefore, a reduction factor can be computed from the mean stresses, if the input stress is mainly compressive. However, in this paper, since welded connections are being considered, reduction factors are not applied. This is in compliance with the recommendation of DNV-RP-C203 (2016) not to apply reduction factors when dealing with welded connections.

Strain gauges cannot directly be installed on welded connections, but are fixed to smooth surfaces in the vicinity of the welded connections (hot spots), where the adhesive can hold firmly. Therefore, for the measured nominal stresses appropriate stress concentration factors (SCF) are applied to extrapolate the stresses to the nearest welded hotspots. For example, in offshore wind turbines, transitions piece (or sometimes, upper part of the Monopile) is usually designed with conical geometry for a gradual transition from the narrower diameter at the tower base to the bigger diameter of the monopile. However, this geometric change results in amplification of stresses. For such cases, the recommendations of the standard for 'Fatigue Design of Offshore Steel Structures', DNV-RP-C203 (2016) are used to compute the appropriate SCFs. The dimensions of the substructures considered in this paper are as follows. The Transition piece (TP) has an outer diameter of 5.0m at its upper most part, while it has an outer diameter of 5.50m at its bottom. The transition in diameter from 5.00m to 5.50m is achieved with a conical section over a height of 3.0m. The Monopiles have an average outer diameter of 6.0m with narrower diameter of 5.20m at the top, where it is connected to the TP by a grout connection containing shear keys.

To calculate fatigue damages an appropriate S-N curve needs to be used. DNV-RP-C203 (2016) standard contains S-N curves, not only for different connection types but also for different environments the structure is exposed to; such as air, seawater with corrosion protection or sea water without corrosion protection. The support structures of offshore wind turbines are usually protected by cathodic protection. Therefore, the application of an appropriate S-N curve depends on the location of the strain gauge in the wind turbine. For sensors located above the splash zone region, an S-N curve for air is used and for all other locations an S-N curve for seawater with cathodic protection is used.

The calculation of accumulated fatigue damage is made for every 10-minute strain data using Palmgren-Miner rule. 10-minute time window is selected for direct comparison with the 10-minute mean environmental and operational data.

Also the “to-from” plots are prepared from the RFM for visualization of the highest stress ranges, which are the main contributors for fatigue damages. The vertical and horizontal axes of the plots show from which stress magnitude a cycle started and at which magnitude it ended respectively (Figure 5, upper).

2.3.2 Modal analysis

Identification of the 1st Eigen frequency (EF) is made by operational modal analysis (OMA) of acceleration response data at two measurement levels. OMA is standard for large civil engineering structures, as only the responses of the structure are used for estimating the modal parameters. In this paper, for identification of the EFs stochastic subspace identification (SSI) is used after Van Overschee (1996) and Reynders (2012). Algorithms developed by Otto (2018) and Cheynet (2019) are customized and used. For identification of stable poles, the tolerances recommended by Kraemer and Fritzen (2010) are adopted as 0.1% for frequency, 5% for damping ratio and 0.99 for MAC.

3 INVESTIGATED CASES

3.1 As-built Eigen-Frequencies

Wind turbines, with their slender profile and heavy rotating mass at the top are dynamically sensitive structures. As a result, their EF is optimized during design stage, in order to avoid resonance of the excitation frequencies from operation with the structure’s 1st EF. For every turbine type the operation RPM range is known beforehand, therefore the optimization is made using the 1P (rotor frequency) and 3P (blade pass frequency). The blade pass frequency is caused by the shadowing effect of the blade as it passes the tower. This loss of wind load on the tower three times per one revolution of the rotor is dynamic in nature (Arany et al., 2014). These 1P and 3P frequencies are not distinct (fixed) frequency values. They are frequency ranges depending on the operation RPM range of the particular wind turbine under consideration.

Generally, there are three types of designs for wind turbines, soft-soft (very flexible structure with 1st EF less than 1P), soft-stiff (commonly used for fixed bottom offshore structures and the 1st EF is between 1P and 3P) and stiff-stiff (very stiff with 1st EF greater than 3P). All the turbines considered in this paper from Wind farm A and B are designed as soft-stiff. For such designs, if the 1st EF crosses the 3P curve, then the wind turbine controller is programmed to avoid or skip quickly the operation RPM causing resonance.

Experience from many monitored offshore wind farms showed that, the ‘as-built’ EFs are usually higher than the design EFs. Figure 2 (left-side) shows a stability diagram for identification of EFs from 10 minute acceleration data and the right-side figure shows comparison of the identified ‘as-built’ Fore-after (F-A) and Side-Side (S-S) first EFs with the design F-A and S-S first EFs. The maximum obtained difference is for turbine number 02 (between the design and as-built S-S EFs), which is 9.43%.

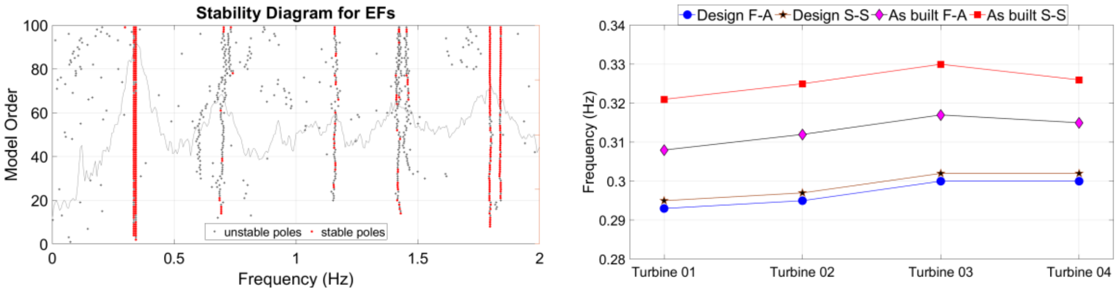


Figure 2. Stability diagram of EFs for Turbine 03 (left). Comparison of the ‘as-built’ and design EFs in wind farm A (right)

This means the turbines are built stiffer than designed. The main reason for the stiffer structures is usually underestimation of the soil stiffness during design. Since the turbines are built stronger, there is more chance of service lifetime extension beyond design lifetime. However, to achieve this, the negative consequences of a stiffer structure needs to be taken care of.

Figure 3 (left) shows a Campbell diagram overlaid with the design and as-built 1st EFs from wind farm A. The higher as-built EF resulted in shifting of the resonance region. Figure 3 (right) shows a plot of the RPM versus measured bending strain. It can be seen from the plot that the resonance region is being skipped. The resonance range is wider than shown in figure 3 left, as ±10% allowances are added to the 1P and 2P (not shown on the plot to avoid congestion).

The controllers of wind turbines should be updated using the as-built EFs as soon as possible after commissioning. For the unmonitored turbines, a measurement campaign using a mobile device could be arranged or if available, the acceleration sensor in the nacelle could be used.

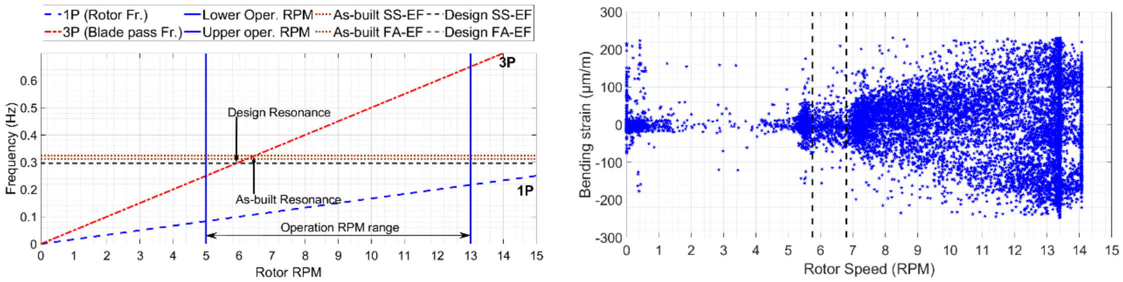


Figure 3. Campbell diagram (left). Skipping of operation RPM causing resonance (right)

3.2 *Turbine shut down for maintenance visit*

Wind turbines are idled during maintenance visits, when wind speed is above cut-out or below cut-in and in other emergency cases. This is achieved by pitching (increasing the blades’ pitch angles). During maintenance visit for the whole duration of working time in the wind turbine mechanical brake is also applied. As shown in figure 4, pitching of the blades very significantly reduces the magnitude of maximum stresses the structure experiences. Nevertheless, during pitching the fluctuation of stresses also results in higher fatigue damages.

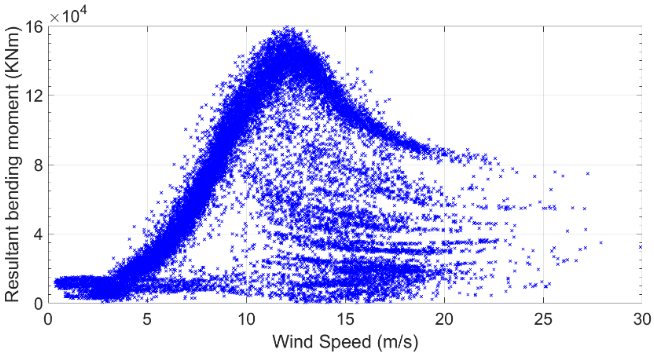
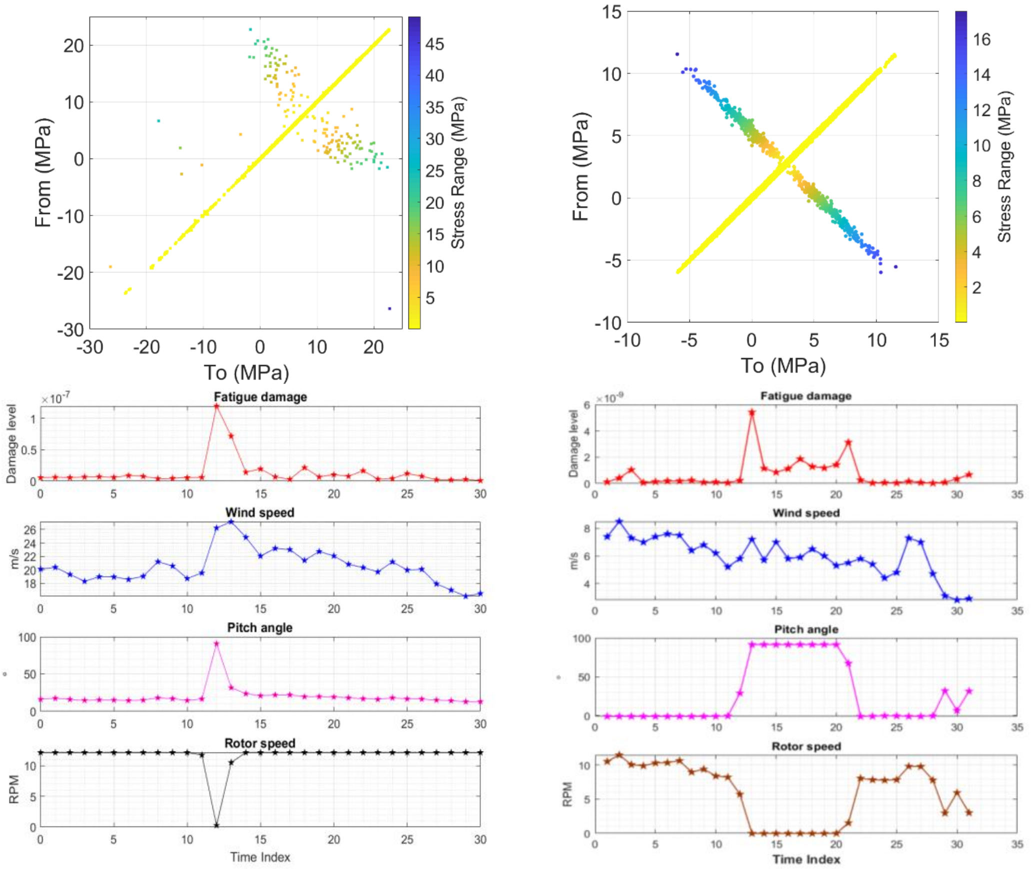


Figure 4. Measured near seabed bending moment versus wind speed

In this section, two cases of turbine shut down in wind farm B are investigated. The first is emergency shutdown due to very sudden change of wind direction during high wind speed (gust) of above 26m/s and the second is maintenance visit during lower wind speed of less than 8.5m/s. The cut-out wind speed for the turbines of this wind farm is 30 m/s. Figure 5 shows comparison of the records by the same strain gauge sensor for both cases.



(a) Turbine shutdown during high wind speed (b) Turbine shutdown during low wind speed

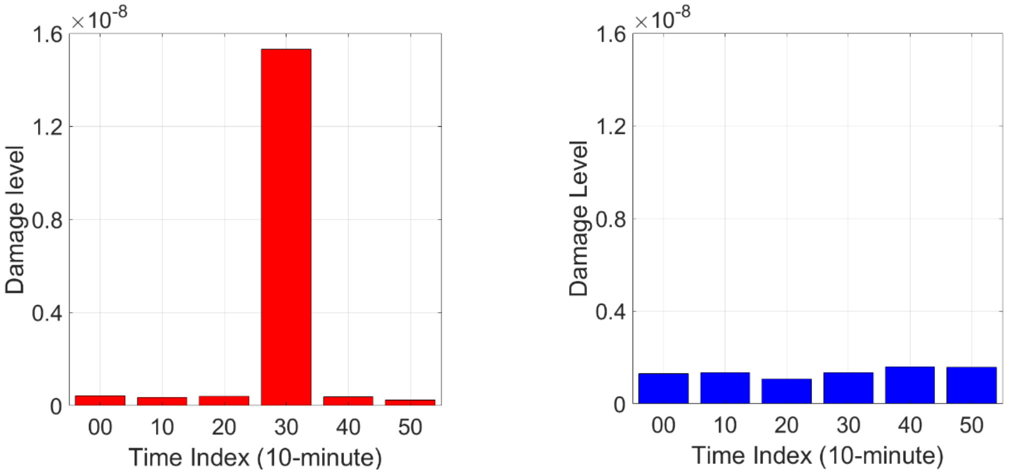
Figure 5. Comparison of turbine shut down events during low and high speed

The maximum-recorded stress range for the emergency shut down during high wind speed is 49.14MPa and 17.00MPa for the low wind speed case. Further quantification of both cases is made by calculation of the 10-minute accumulated fatigue damage and the results showed that the maximum 10-minute fatigue damage for the higher wind case is 22 times higher than of the low wind case. This emergency shutdown example is chosen to illustrate the damaging effect of shutdowns at high wind speed below cut-off. If it is not an emergency, as much as possible the wind farm operators should try to minimize maintenance visits during high wind speeds.

For fatigue damage, the fluctuation of the stresses is very determinant. Usually the 10-minute standard deviation of the wind speed is more meaningful than the 10-minute mean wind speed when comparing the cause and effect for fatigue damages.

3.3 Boat collision accident

Offshore wind turbines are designed for accidental limit state (ALS), including collision with vessels or boats. The collision scenario considered in this sub-section happened due to a personal error at wind farm A during a maintenance visit. The impact was not very high due to the size of the boat, its slow approach speed and fortunately low wind speed of about 4.43m/s. In addition, the wind turbine was idling for the planned maintenance visit. Nevertheless, as shown in figure 6, the impact resulted in a fatigue damage of around 8 times that recorded during full capacity operation of the turbine by the same sensor.


During collision (Mean wind speed = 4.43m/s)

Full capacity operation (Mean Wind speed = 11.14 m/s)

Figure 6. Comparison of collision event at low wind speed (idling) with full capacity operation

Collision accidents occur very seldom, but if they occur specially at high wind speeds and high wave heights they can be very dangerous.

4 CONCLUSIONS

In this paper, SHM data analysis results from two offshore wind farms in the North Sea are used to investigate selected scenarios that can be useful for enhancing the safe operation and optimization of offshore wind turbines. In a long term, it can also be useful for service lifetime extension of the structures beyond the design lifetime. For example, for the turbines considered in this paper, the highest accumulated fatigue damage from monitoring data was found out to be only 5% of the design fatigue damage for the same time window.

The first example illustrated with four wind turbines, the common experience from other wind farms that wind turbines are usually built stiffer (higher EFs) than designed. In the example considered, the highest difference between the design and as-built EF is 9.43%. This shows a good chance of service lifetime extension. However, in order to achieve this, the negative consequences of a stiffer structure need to be taken care of. An example using a Campbell diagram and measured as-built EF is shown to locate the new resonance region, according to which the controller setting is updated.

Furthermore, the damaging effect of two dangerous-scenarios is quantified. The first example deals with the damaging effect comparison of turbine emergency shut down during high wind speed and a shut down for maintenance visit during low wind speed. The comparison showed that, for the scenarios considered, the damaging effect of the shutdown during high wind speed was about 22 times higher than that of the lower wind speed visit. The second example deals with a boat collision accident. The damaging effect of the boat collision impact was 8 times higher than the damage caused during full capacity operation. The damaging effect of collisions can be much more higher as the example used was during low wind speed, idling turbine and slow approach speed of the boat.

The examples also illustrate that when appropriate SHM system is available, in addition to the main aim of damage detection, it is also possible to quantify the damaging effect of natural extreme events or accidents almost in real time.

REFERENCES

Arany, L., Bhattacharya, S., Macdonald, J. and Hogan S. J. (2014). Simplified critical mudline bending moment spectra of offshore wind turbine support structures. Wind Energy. (2014)

ASTM E1049-85 (2017). Standard Practices for Cycle Counting in Fatigue Analysis. West Conshohocken, PA: *ASTM International*

BSH (2007). Federal Maritime and Hydrographic Agency. Design of Offshore Wind Turbines. 2007

BSH (2015). Federal Maritime and Hydrographic Agency. Minimum requirements concerning the constructive design of offshore structures within the Exclusive Economic Zone (EEZ)”

Cheynet, E. (2019). Operational modal analysis with automated SSI-COV algorithm. MATLAB Central File Exchange.

DNV GL (2014). Offshore wind: a manifesto for cost reduction.

DNV-RP-C203 (2016). Fatigue Design of Offshore Steel Structures. *DET NORSKE VERITAS AS*.

Germanischer Lloyd (2012). Guideline for the Certification of Offshore Wind Turbines (Part 2). Edition 2012. IV Rules and Guidelines, Industrial Service

Kraemer, P. and Fritzen, CP. 2010. Aspects of Operational Modal Analysis for Structures of Offshore Wind Energy Plants. Proceedings of the IMAC-XXVIII 2010, Jacksonville, Florida USA

Otto, A. (2018). Output Only Modal Analysis toolbox. MATLAB Central File Exchange.

Reynders, E. 2012. System identification methods for (operational) modal analysis: review and comparison. Archives of Computational Methods in Engineering, 19(1):51-124, 2012

Rolf de Vos. 2016. FLOW: competitive through cooperation.

Tewolde, S., Höffer R., Haardt, H., Krieger, J.: 2018. Lessons learned from practical structural health monitoring of offshore wind turbine support structures in the North Sea. *The International Conference on wind energy harvesting 2018 (WINERCOST`18)*. Italy, 2018.

Van Overschee, P. and De Moor, B. 1996. Subspace Identification for Linear Systems: Theory, Implementation, Applications. Kluwer Academic Publishers.

Wind Stats (2006). Operation and Maintenance costs compared and revealed, *Wind Stats Vol.19, No.3*

Wind Europe (2017). *Wind energy in Europe*: Outlook to 2020.

Wind Europe (2019). *Wind Europe Bulletin January 2019 Foreword*.