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INVERSE WIND LOAD RECONSTRUCTION WITH APPLICATION TO WIND TURBINE STRUCTURES

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Abstract. *With growing demands for clean energy, wind turbines play a significant role as a renewable energy source. In order to reduce the cost of financing for constructing the wind turbine structures, it is very useful to get a better knowledge on wind load time histories acting on the structure in order to reduce design uncertainties. This knowledge can also be used to utilize fatigue assessment procedures, damage diagnosis and life-time forecast. Since the wind load in most cases cannot be measured directly, a possible alternative is to inversely identify the wind load using structural response measurements gained through structural health monitoring. In the past, many authors dealt with inverse load reconstruction using different approaches, but not much research has been done in the field of wind load identification for wind turbine structures. This paper gives an overview of methodologies that can be used to reconstruct the wind load, as well as their applicability for a more precise design of land-based wind turbines.*

1 INTRODUCTION

Renewable energy technologies play an increasing role in today's world. With improvements in technology and its growing presence in everyday life, it becomes possible and needed that energy is produced and consumed in a secure, affordable, efficient and sustainable manner. However, global carbon emission trends nowadays still show growth in CO_2 emission from human sources (91% in 2013) , which originate mainly from fossil fuels such as coal (42%), oil (33%), gas (19%), cement (6%) and gas flaring (1%) [1]. The development in use of renewable resources, such as wind power, geothermal energy, hydroelectric power, solar energy, ocean energy, biomass and hydrogen, is therefore a particularly important aspect. Relaying on these sources will reduce the carbon dioxide emissions into the atmosphere during the generation of electricity.

When it comes to wind energy, it is known that the wind power potential may be enough to satisfy the entire human population needs. In many locations in Western Europe, wind power usage is technically more meaningful than the direct use of solar energy. Research shows that, in 2016, around 4.7 % of the world's electricity demand was supplied by wind turbines [2]. Globally, wind turbines are still underutilized as renewable energy source, but with growing trend due to the modernization and new technical solutions for the wind turbine structures. Having in mind all the advantages of wind power use, such as the great energy potential, renewability, space efficiency of wind turbines and increasing annual installed capacity and investments, there are still disadvantages regarding the investment price and social acceptance of such structures. The costs of financing for building wind energy converters and for the maintenance may be influenced and improved through the research in the field of wind load. Not much research has been dedicated to estimate the precise wind load acting on the structure, which affects the design phase. Wind load is currently modeled based on the wind field statistical data and by using safety factors to cover the uncertainties. Following this approach may lead to increasing the cost of financing for the structure itself and contribute to maintenance difficulties during the operational phase.

For this reason, better knowledge on the wind load time histories acting on the structure is desirable, for both design and operational phase. Since the direct measurements of the load during the operational phase of the structure are often not possible and tend to be too expensive, alternative approach is to reconstruct the loads inversely from the response of the structure. This approach, where the output of the problem is known and the input is to be determined is known as the inverse problem. Many authors have dealt with inverse problems in structural engineering in order to determine the loads, but not enough research has been done in the field of wind energy converters.

For this purpose, the current paper presents state-of-art-report for inverse load identification to be considered for land-based wind turbines. The approach combines the fields of inverse load identification, structural health monitoring and operational modal analysis, which will be briefly explained in the paper.

2 INVERSE WIND LOAD IDENTIFICATION

2.1 Structural health monitoring

After the installation of wind turbines it is necessary to ensure the operational functionality and safety of wind turbine structures during their life-time. Besides the planned maintenance of the structure, condition based maintenance is also possible and more desirable. This can be done by installing the structural health monitoring systems that provide information about potential damages and anomalies which require intervention. The objectives of SHM include the early identification of structural damages, accurate life time prediction and planning of maintenance measures, as well as reducing the risk by reducing the uncertainties.

There are more types of SHM systems, but in general they consist of system state definition, data acquisition, data filtration, feature extraction, data reduction, pattern recognition and decision making [3]. The SHM uses sensors (strain gauges, optical-fiber sensors for strain measurements, vibration and temperature sensors, inclination sensors, displacement sensors, photometry and laser interferometry [4]) to obtain dynamic response measurements of the structure. These measurements are statistically being analyzed in order to get conclusions regarding the possible deterioration and state of the construction in general. Figure 1 shows the scheme of a SHM system of 500kW wind turbine structure in Dortmund, Germany, equipped with sensors in frames of a research project founded by DFG at Ruhr-Universität in Bochum [6].

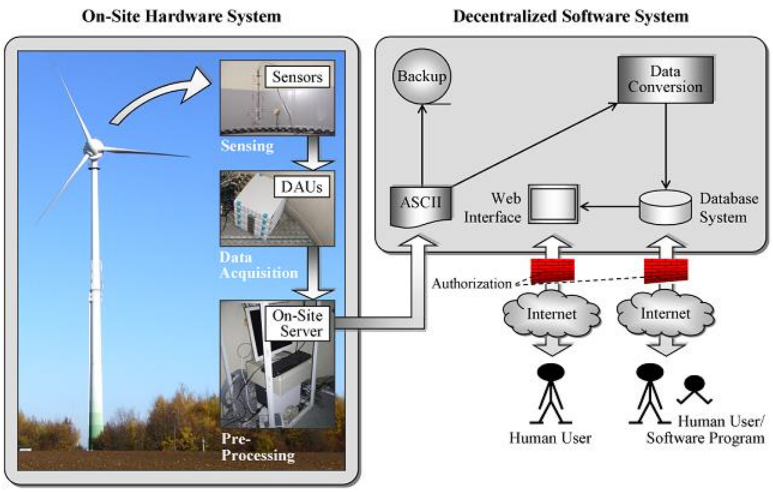

Figure1. Scheme of a SHM system [5]

The wind load acting on the structure cannot be measured and monitored directly using the sensors due to several limitations, which include unapproachable locations on the structure, influence of the sensor on the load signal and most off all high expense and infeasibility of such measurements. For this reason the dynamic response measurements gained through the SHM supposedly can be used to determine the wind load on sensor positions or to determine the rotor thrust force. Long-term research including the measurements gathered since 2010 on the wind turbine in Dortmund, will be used for wind load investigation through the inverse analysis.

The Figure 2 shows the positioning of the sensors on the wind turbine tower and the foundation [7, 8]. The turbine is equipped with 6 deformation sensors along the towers height.

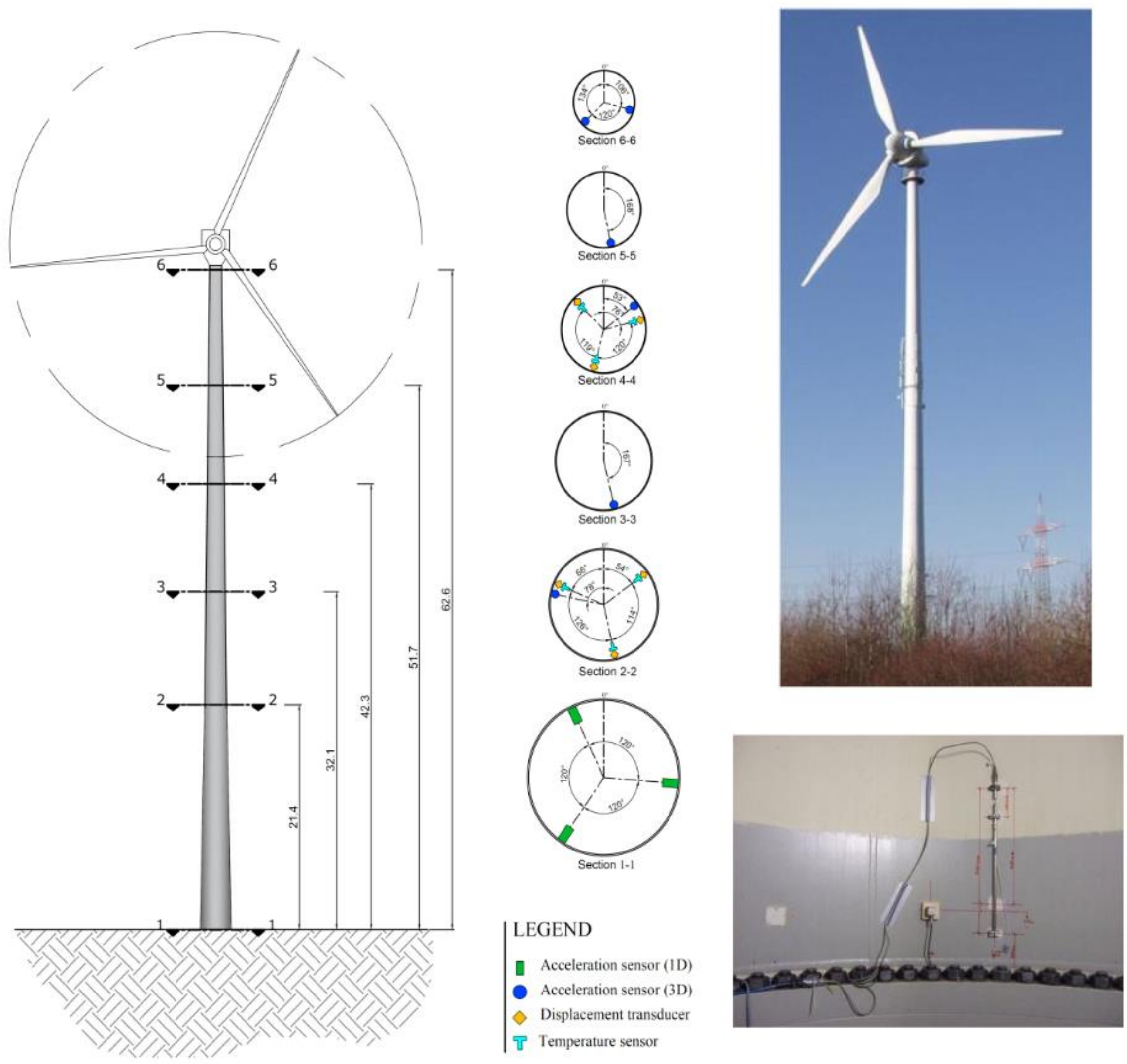

Figure 2. Positioning of the sensors on an on-shore wind turbine in Dortmund and displacement transducer (down)

More information on this SHM system can be found in [7], along with the information about the wind climate, mean wind velocities, and terrain surface at the wind turbine site.

2.2 Operational modal analysis

For large and complex structures as wind turbines, determination of modal parameters of the system is a challenging task, especially for the operating structure. The standard or straightforward modal analysis is not applicable for this case, since the input parameters, the wind load and excitation are unknown. Possible approach is artificial, controlled excitation of the construction, usually by using an impact hammer or one or more modal exciters. However, in the case of large structures this approach becomes very expensive. The most common and suitable strategy used for estimation of the dynamics characteristics of the wind turbines is Operational Modal Analysis, known also as output-only or ambient modal analysis. Identification of modal properties of a structural system here presents the process of establishing a correlation between the dynamic characteristics of a mathematical model and the physical properties of the system derived from experimental measurements [9].

OMA is a vibration-based SHM technique that uses vibration sensors such as accelerometers, but also temperature sensors for environmental effect compensation. The basic concept is to determine the modal parameters of the healthy structure, if possible, such as resonant frequencies, mode-shapes and damping factors, and to track their changes in time. The concept is that changes in modal parameters and vibration responses are indicators of changes in the structural system that can be caused by the damage and deterioration in the structure. Higher damping or lower natural frequency could be the indicators of the damage.

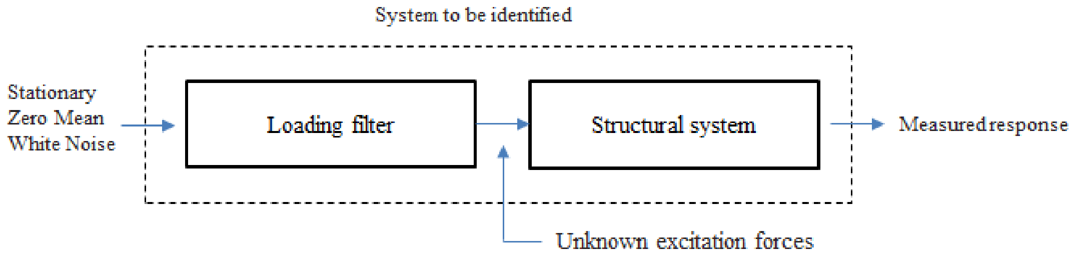

Figure 3. Scheme of the OMA concept

There are number of limitations of OMA for its application in wind turbine structures that are mainly related to the operating conditions. The basic assumptions of OMA require that the structure is time invariant, which is not met when it comes to wind energy converters. They consist of number of substructures that move in time, such as rotor, or yaw and pitch angles. Other difficulties include the aeroelasticity and complex stochastic nature of the wind load, when OMA assumes only the zero mean white noise load. This can be overcome by using the loading filters that do not change the physical modes of the system [10].

In general, the main recognized problems when using OMA for modal identifications are the mode-shapes mass scaling and uncertainties in mode-shape and natural frequency cause determination [9]. Numerous random errors, including environmental and operation factors, can occur and influence the results. Also, since the excitation is not controlled, it is possible that not all the modes of interest are excited by the ambient loading. These concerns have to be taken in consideration when applying ambient vibration based methods and analyzing the data. Nowadays, a lot of attention has been drawn for solving these drawbacks caused by the turbine operation and uncertainty presence [11, 12].

Knowing the structural response obtained by SHM techniques and modal characteristic of the structure gained by means of OMA is possible to inversely obtain the loading of the whole wind turbine structure or its substructures. Also, this knowledge can later help to filter out the uncertainties in application of these methods. Like mentioned before the SHM system has already been applied on the 500kW AIRWIN wind turbine in Dortmund, Germany. Considerable research has also been done in the field of OMA on the same structure. Investigations had been done by Bogoevska [11], where the bi-component SHM framework on an operating WT structure has been implemented. The method uses SP-TARMA method and PCE probabilistic model for the purpose of tracking the uncertainty evolution in structural response due to the randomness of environmental and operational parameters. Accordingly, more reliable modal parameters of the structure can be obtained and later used for the more precise wind load reconstruction technique application on a wind turbine structure. More on this topic can be read in [11].

2.3 State-of-the-art report on wind load identification

Better knowledge on wind load in engineering problems is important part of design and maintenance phase of the structure, especially when it comes to high, slender and flexible structures with low natural frequencies such as tall buildings, bridges or wind turbines. The investment and maintenance costs are one of the decisive factors when it comes to further construction and development in the field of harvesting the wind power using wind turbines. The direct load measurements for high and complex structures in general are not feasible. For this reason methods such as OMA as an addition to SHM have been developed in order to be able to determine and predict the condition of the structure. However, knowledge on the load can contribute to improvement of these methods and additionally improve the design phase by applying the more precise load. Building codes and standards are only applicable for typical structures. For not common structures, the wind tunnel tests are usually conducted and have shown good reliability and effectiveness. However, the situation on site may be different from the one simulated in the laboratory. Therefore, having in mind the development and higher application of monitoring systems, it makes sense to deepen the knowledge on the actual wind load acting on wind turbine structures.

When direct measurements are not possible, the alternative approach is to use response measurements and reconstruct the loads inversely. This approach is well known in the engineering world for different types of static and dynamic problems. The main difficulty here is that the inverse problem is usually ill-posed, which has been proven by Hadamard [13] in 1923. This leads to inaccurate and unstable solutions that are sensitive to noise presence.

Besides of ill-posedness, one should keep in mind following difficulties when dealing with inverse problems for the monitored structures:

- Only limited number of sensors is available, so that response of the structure is not fully known. Optimum sensor positioning should also be considered
- Noise presence in the response signal causes inaccuracy in the identified load on different levels depending on the identification method used
- Possible errors in modal parameters, mode-shapes, natural frequencies and damping factors
- Type of the response chosen for the load identification varies with the method chosen for the analysis

A lot of research has been done in the past years in the field of inverse load identification for various engineering problems. Reviews of possible methods have been suggested by more authors. In 1987, Stevens [14] did a review of force reconstruction techniques for linear vibration systems. Later on, in 2006 there is a report done by Uhl [15] regarding the inverse identification problem with an application for indirect measurements of contact forces in railway equipment testing. Sanchez and Benaroya [16] did a review of force reconstruction techniques in 2014, in which they have grouped and compared the methodologies and have discussed their advantages and disadvantages for general engineering application, with a focus on mechanical engineering. Jankowski [17] has reviewed the load identification strategies and highlighted the importance of load identification for SHM.

However, not so much research has been done for the case of the wind load (e.g. [18-23 and 25]), especially in the field of wind turbines, where only limited number of investigations has been done [23, 25]. For this reason, further research and better understanding of the wind load acting on the wind turbine structures is necessary. In this paper, previous investigations and conclusions in different types of problems will be presented and considered for the application for on-shore wind turbines, where wind is main loading factor. The general idea is to combine an appropriate strategy for wind load identification with the information gained through SHM and OMA. Figure 4 presents a schematic illustration of the approach for general wind load investigation method considered for the application on wind turbine structure in Dortmund, Germany.

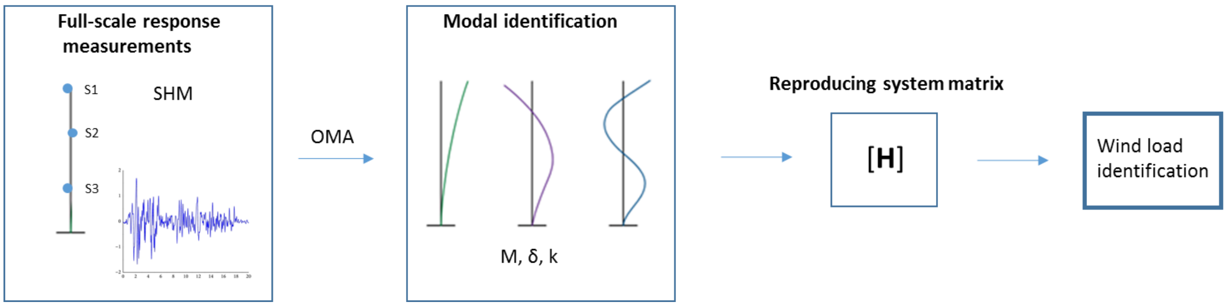

Figure 4. Example of a wind load investigation strategy

According to [17], load identification methods can be separated in two main categories:

- Model-based methods
- Computational intelligence techniques

First category includes the methods that use the analytical or numerical model of the structure in order to solve the inverse problem. These methods can be deterministic or statistical (stochastic). Time-histories of the structural response are being used for offline and online load reconstruction, where the model of the structure is inversed, which leads to the so called ill-posed problem. The analysis can be done in time, frequency or wavelet domain. Most of these methods are the offline techniques that require the records of the structural response and afterwards apply the deconvolution process. Convolution integral (2) is typically used in time domain methods, where impulse response functions for different response types, such as displacement, velocity acceleration, or strain are used to solve the differential equation of motion (1), where $m, c, k,$ and p stand for mass, damping, stiffness and external load of the structure. Structural response quantities are represented as $u, \dot{u}, \ddot{u}$ and t and τ represent the time; $h(t)$ stands for the impulse response function IRF of the system. Frequency domain methods use similar approach with frequency response functions that define dynamic characteristics of the structure.

$$m\ddot{u} + c\dot{u} + ku = p(t) \tag{1}$$

$$u(t) = \int_0^T h(t-\tau)p(\tau)dt \tag{2}$$

The ill-posedness of the deconvolution procedure can be dealt with by using different regularization methods. Sanchez and Benaroya [16] reported a list of possible regularization techniques categorized as Tikhonov regularization method, frequency range truncation methods, optimization methods and weighted basis functions. In their work, they have compared these approaches and discussed their advantages and flaws. The most commonly used regularization method is the one developed by Tikhonov in 1977 [26]. It defines a norm for smoothing the condition on the least squares problem. The method has a following form:

$$min\{\|-Hp\|^2 + \alpha^2\|p\|^2\} \tag{3}$$

where H represents the impulse response matrix of the system, and u_{poll} is response of the structure polluted with noise and α^2 stands for the regularization parameter. According to [16] and [17] Tikhonov regularization method provides satisfactory results despite the noise presence, but it tends to distribute the identified excitation among all degrees of freedom and time instances.

Various methods have been developed for online load reconstruction such as Kalman filter based methods [18, 19], unknown input observer [23] and inversed system filter techniques [27].

The second category, computational intelligence techniques, includes the methods that do not use full model of the structure, but only the relationship between chosen parameters of the excitation, such as amplitude or location and the system output. These methods are based on artificial neural-network algorithms, fuzzy algorithms and evolutionary algorithms [15]. The learning process is needed in order to find a relation between input and output parameters. In general, the approach uses neural networks to establish an artificial intelligence basic system by means of a non-linear mapping function between input and output data through the training process. Some application of these methods can be found in [17] where authors have developed a load identification technique using the virtual distortion method. In the next section of the paper few research projects that have been done in the past regarding the wind load identification will be described.

2.4 Kalman filter based methods

In their work in 2010 Hwang et al. [18] presented the method for modal wind load identification from limited response measurements by using the Kalman filtering scheme, see Figure 5. The method was verified through the wind tunnel test using a model of a 210m tall rectangular chimney. The model was built at a scale 1:200 as a single degree of freedom structure, having in mind that the first mode is the governing mode. It was subjected to the influence of the across-wind load and the displacements at the top of the model were measured using an optical displacement sensor. The relation between the response and the load was established by using the closed-form Kalman filter gained by solving the Riccati equation. Displacements and accelerations were used as the structural response, and influence of modal parameter errors and noise presence was considered. The results have shown that acceleration gives more accurate results than the displacement and that the noise presence (30%) affects the solution, therefore the usage of additional low-filters is suggested and the knowledge on noise properties is needed. The 5% error in natural frequency influenced the results in frequency domain near the natural frequency of the structure in the wind load spectrum. The time domain remained accurate enough, as well as for the case when damping was set to be 2% instead of 1%.

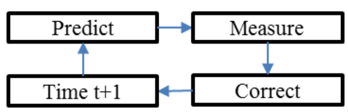

Figure 5. Kalman filter scheme

In 2016, Zhi et al. [19] have extended the work done by Hwang et al. [18]. Zhi et al. [19] have combined continuous-time Kalman filter and proper orthogonal decomposition (POD) technique for estimation of the wind load acting on tall buildings. The method was applied on a slender, 256.9m tall building with the rectangular shape. The building has been experimentally tested at scale of 1:300 for different wind directions with wind directions (0° to 360°). The pressure measurements on the model were conducted. The results were similar to those obtained in the previous study, meaning that the acceleration gives more accurate results than the displacement. Also, it was noticed that results were not strongly influenced by the noise presence and error in modal parameters (10% modal parameters error combined with 10% noise). However, larger sensitivity was shown in the along-wind direction. Azam et al. [20] suggest using the dual Kalman filter for dealing with the noise pollution influence.

2.5 Methods using the Tikhonov regularization

One of the possible ways to deal with the ill-posed problems is to transform them into well-posed ones. This can be done by applying the regularization procedures, among which the Tikhonov regularization method is most commonly used and suggested (3). In 2005, Law et al. [21] developed a method for wind load identification and applied it on 50m tall guyed mast. The method used Tikhonov regularization scheme and L-curve method for defining of the regularization parameter α^2. Numerical simulation was used for the verification of the proposed procedure. The modal wind loads were modelled as a multivariate stochastic process along the height of the mast. Different number of sensors was considered and the goal was to achieve accurate wind loads by using sparse response measurements, which the authors achieved by applying the iteration scheme based on wind field site characteristic, correcting the wind load in every step due to numerically gained response errors. The research showed that by applying the iteration scheme it is possible to achieve satisfactory results with low noise influence for the wind load, even with sparse response measurements, as in the case of only one sensor. The main flaw of this approach is that it requires pre-knowledge of wind field on the site.

Kazemi et al. [22], in 2016, also applied the Tikhonov regularization technique and developed a method for wind load reconstruction method that was applied on 9.1 m tall guyed mast. In addition to work done by Law et al. [21], author compared the L-curve and GCV method for choosing of the regularization parameter, where L-curve turned out to be more reliable. The iteration scheme was not used, but instead the modal decomposition of the response. The time domain method developed here uses the augmented impulse response matrix as an addition to previous methods using impulse response functions of the structural response. This contributes to more precise results verified through the numerical simulation. Comparison of the type of the response showed that the displacement gives better results than the acceleration, which is different compared to the methods using Kalman filter. The sensitivity to noise presence was also studied.

2.5 Wind turbine application

In the past only few projects concerning the load estimation for the wind turbines have been conducted. Klinkov and Fritzen [23] developed a load observer for online force reconstruction of 5MW wind energy plant. The method is based on previously developed load and state input observer approach [24]. Observer matrices are created based on the information obtained from the FE model of the structure. The observer (see Figure 6) is continuously updated through the measurement information and is capable to determine the forces acting on the top of the wind turbine tower verified through the comparison to rotor thrust force calculated by means of Betz theory. As expected the comparison shows disagreements caused by the influence of changing yaw and pitch angles, thus the load spectrum contains the frequencies caused by operational effects. Nevertheless, good agreement for stationary conditions has been shown. The load identification has been installed as a part of the SHM system on the wind energy plant. The modal model of the structure is used in the procedure. Disadvantage here is also the fact that number of sensor needs to be higher or equal to number of input forces plus the nonlinear members. Identified load is also overestimated.

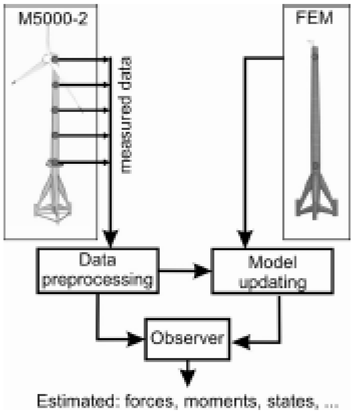

Figure 6. Online wind load observer, courtesy of Klinkov et al. [23]

In the study done in 2012 by Phan et al. [25] in cooperation with NREL, the numerical model of 5MW onshore wind turbine with 3 blades and tubular mast was developed in Code FAST. The model takes into account aerodynamic influences and turbine controls. Also, the method for inverse rotor thrust forces identification from the response is developed. In this study, the frequency response matrix is used and the procedure is done in a similar way as in the previous study [23], that is the number of sensors needs to be higher or same as the number of identified forces, so the problem is overestimated and solved by means of least squares method. For the inverse calculation, analytical model is reduced to first two tower modes and maximum 2 responses can be used. The inverse load is presented as superposition of static/quasi-static component (below cut-off frequency) and dynamic component (above cut-off frequency). Operational effects are taken into account through three load cases with different wind speeds. The results show that for quasi-static component accurate results can be gained, but for dynamic case the load is overestimated.

3 CONCLUSIONS

Load identification has been widely investigated in the past. However, many methods have been developed to reconstruct the load based on the structural response, a few studies have dealt with the recovering of the wind load, which is especially challenging due to its stochastic nature. For the on-shore wind turbines, as tall slender structures with low natural frequencies, wind is the dominant load and dictates their design, behavior and maintenance. As seen in the paper, modern technology and development provides a lot of possibilities to control and utilize the wind harvesting by means of SHM and OMA systems. SHM and OMA systems can also be used to obtain the broader knowledge and information on the wind load, which can in multiple ways contribute to the field of wind engineering.

Based on the research done in the field of wind load identification of wind turbines, it can be concluded that more methods should be developed in order to get the better insight into the problem from different perspectives and improve the possibilities to determine the load in reliable and accurate way. The methods presented in the state of the art report show similar conclusions that the wind load can be recovered from the dynamic responses, but many difficulties are still in the way. Sparse response measurements, caused by the reasonable sensor number, their positioning and type of the response measured play the important role. Many limitations of the methods are caused by the complexity of wind turbine structures and operational conditions. More improvements can be done when dealing with the signal noise pollution, where progress has been made by means of filter usage. Applicability of the methods also plays significant role, especially when considering the load reconstruction as a part of structural health monitoring system. Having this in mind, the future plan is to continue the research in this field, with a goal of developing a new approach for wind load reconstruction of an off-shore wind turbine.

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