

Comparative study of performance of neutral axis tracking based damage detection

R Soman¹, P Malinowski¹, W Ostachowicz^{1,2}

¹ Institute of Fluid Flow Machinery, Polish Academy of Science
14 Fiszerza St., 80-231 Gdansk, Poland

² Faculty of Automotive and Construction Machinery, Warsaw University of Technology
84 Narbutta St., 02-524 Warsaw, Poland

e-mail: rsoman@imp.gda.pl

Abstract. This paper presents a comparative study of a novel SHM technique for damage isolation. The performance of the Neutral Axis (NA) tracking based damage detection strategy is compared to other popularly used vibration based damage detection methods viz. ECOMAC, Mode Shape Curvature Method and Strain Flexibility Index Method. The sensitivity of the novel method is compared under changing ambient temperature conditions and in the presence of measurement noise. Finite Element Analysis (FEA) of the DTU 10MW Wind Turbine was conducted to compare the local damage identification capability of each method and the results are presented. Under the conditions examined, the proposed method was found to be robust to ambient condition changes and measurement noise. The damage identification in some is either at par with the methods mentioned in the literature or better under the investigated damage scenarios.

1. Introduction

Over the last few years, there has been an increasing awareness about the environmental hazards posed by the extensive use of fossil fuels. As a result a search for clean source of energy has intensified. Wind Energy appears to be one of the leading sources of clean energy. The main hindrance for more widespread deployment of the wind turbines is the high initial costs for setting up of wind farms and its subsequent maintenance. These high initial costs make the energy more expensive than the conventional energy sources. The cost of generation being the biggest drawback of wind energy, there is a concerted effort to reduce it. This can be achieved by increasing the life-time of the wind turbines; reducing maintenance costs and ensuring high availability. The lifetime may be increased by ensuring a more robust design while the maintenance cost may be lowered and the high availability ensured through the use of condition monitoring (CM) and structural health monitoring (SHM), [1].

Traditionally, the evaluation of the condition of civil infrastructure has been carried out through visual inspection mainly due to its low cost and simplicity. However, visual inspection is prone to human errors, as it depends on the perception and the experience of the inspector. Furthermore, visual inspection can be carried out periodically and therefore cannot provide information of the condition of the system in between two inspections. The realization of these shortcomings along with the increasing dependence of the society on the civil engineering infrastructure has made the Structural



Health Monitoring (SHM) systems an imperative. The process of damage can be broadly classified into 4 levels, namely detection of the presence of damage (level 1), identification of damage location (level 2), determining the extent of damage (level 3), and estimating the remaining life of the structure (level 4), [2].

The SHM systems should be able to perform continuous monitoring, be low cost for setting up and maintenance and able to raise an alarm in case the system performance undergoes a sudden change. The common SHM strategy thus is the study of vibration characteristics like the natural frequencies and mode shapes is an inexpensive way for continuous monitoring. These techniques are based on the concept that, the change in mechanical properties of the structure will be captured by a change in its dynamic characteristics [3]. The SHM process involves the observation of a system over time using periodically sampled dynamic response measurements from an array of sensors, followed by the extraction of damage-sensitive features from these measurements, and the statistical analysis of these features to determine the current state of the system's health. The SHM process requires use of sensors for data collection, filters for data cleansing, and central data processing units for feature extraction and post processing. Doebling et al. [4] give an extensive overview of the vibration based detection methods. Many different parameters for the damage detection have been suggested in literature [5-8]. These parameters yield promising results under controlled conditions, but the damage detection is not accurate in in-service conditions. Thus there is a need for a robust methodology, which can detect damage in the presence of measurement noise and ambient temperature changes.

The present paper proposes a comparative study of a new methodology, making use of strain sensors for tracking the Neutral Axis (NA) through the use of Kalman Filter (KF). The position of the neutral axis can be assessed by measuring the strains on opposite surfaces of the tower in bending. The NA is the property of the cross section of the tower independent of the bulk temperature effects, and the ambient wind loading. The methodology is applied to a finite element (FE) model of the DTU 10MW RWT and its performance is compared with some widely used methods namely the Enhanced Co-ordinate Modal Assurance Criterion (ECOMAC) [8], the Mode Shape Curvature Method [5], and the Strain Flexibility Index Method [9]. The performance of these established methods is compared in simulated operating conditions, like, error in yaw angle measurement, measurement noise and ambient condition changes.

2. Proposed Methodology

2.1. Neutral axis

The primary function of the tower structure is to support the hub, and the nacelle of the wind turbine. The nacelle and the hub are axial loads which are eccentrically loaded on the tower. This eccentric loading gives rise to axial compressive loads as well as bending loads as shown in Figure 1. The axial compression is uniform over the entire cross section while the bending loads will be tensile at one end and compressive at the other. Furthermore, the tower experiences wind loads which result in bending strains in the tower. The wind turbine tower is a tall slender structure and hence, Euler-Bernoulli beam theory may be used with limited approximation errors [10]. The bending strains are given by (1)

$$\epsilon = \frac{M_b y}{EI} \quad (1)$$

where, ϵ is the longitudinal strain in bending, M_b is the net bending moment at the cross section due to wind loading and eccentricity, E is the Young's modulus and I is the area moment of Inertia, y is the distance from the NA [11]. The Figure 1, explains the abbreviations used and the concept. The NA can thus be estimated based on the strain measurements.

Thus, one surface of the tower experiences, a combination of two axial compressions, (right side in Figure 1) while the other end experiences a combination of compressive load due to the weight and tensile load due to the bending, (left side in Figure 1). If the line connecting the two strain levels is extended, there will be a point where the strain experienced will be zero, which is identified as the Neutral Axis point. The neutral axis of the section is a function of the flexural rigidity of the structure,

and does not depend on the applied bending loads, thus by, measuring the strains at the opposite edges of the beam, the neutral axis can be located, which in turn may be an indicator of the damage. The figure 1 shows a solid beam-type structure for ease of visualization of the NA. For wind turbine applications, the tower is generally hollow but the response of the structure is more or less similar. A more in depth discussion and sensitivity studies about the methodology may be found in [12-15]. The method is able to detect damage even when the damage is not in the vicinity of the sensor. Although for accurate damage isolation, (along the longitudinal direction as well as along the circumference) bi-axial neutral axis tracking is necessary.

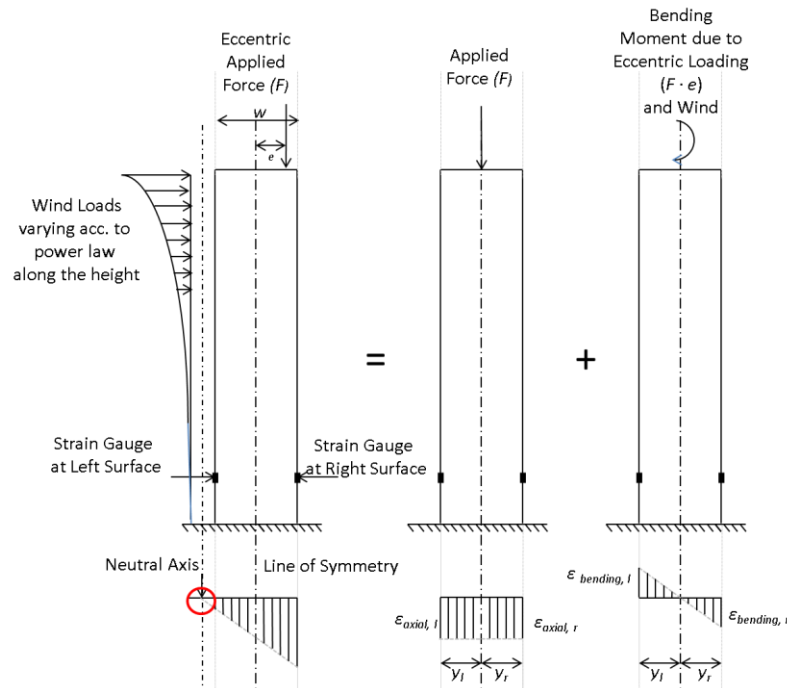


Figure 1: Flexural Strain Distribution over the tower cross-section subject to loading

2.2. Kalman Filter

The KF is a set of mathematical equations that provides an efficient computational (recursive) solution of the least-squares method. Theoretically, KF combines a system's dynamic model (physical laws of motion) and measurements (sensor readings) to form an estimate of the systems varying quantities (system state) that is better than the estimate of the system obtained by measurement alone, [16]. Figure 2 concisely explains the implementation of the KF.

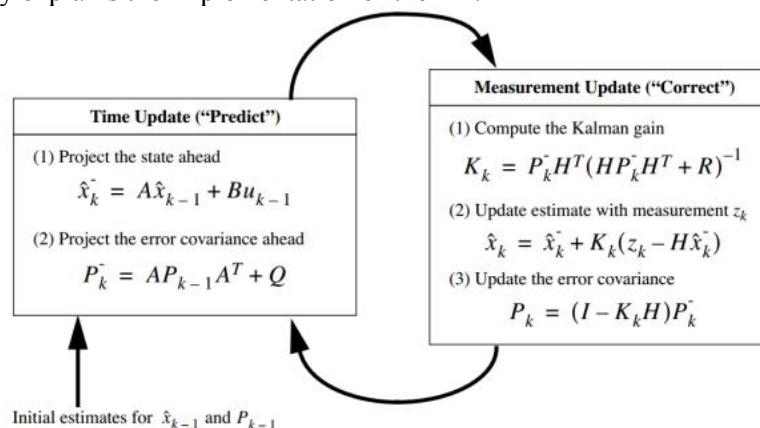


Figure 2: Flow Chart for the implementation of the KF [16]

where, x is the estimate of the state, A is the state transition matrix, B is the control matrix, u is the control variable, P is the state variance matrix, Q is the process variance matrix, K is the Kalman gain, H is the measurement matrix, z is the measurement variable, the ‘super minus’ indicates a priori estimate while the subscripted k indicates the time step.

In the present application, the state estimate variable is a 3×1 vector consisting of the ratio, $\frac{2x}{w}$ (referred to as Neutral Axis Estimate - NAE) which in undamaged condition should remain constant independent of the applied loads. x is the location of the neutral axis, the second variable tracks constant 1. This constant for tracking 1 is incorporated to ensure, accurate system depiction, and formation of square measurement matrix which allows faster computations. The third variable is θ for the yaw angle. It is a linear estimate of the measurement from the sensor. The measurement update matrix takes into consideration the observability of the neutral axis based on the locations of the sensors.

3. Numerical Modelling

The proposed methodology was verified on a simulated FE model of the DTU 10 MW Reference Wind Turbine. The model was simulated in commercial FE modelling software ABAQUS [17] based on the design data in the reference [18].

The tower is a 115.63 m tall hollow steel structure. The outer diameter varies linearly from 8.3 m at the base to 5.5 m at the top of the tower. The tower is divided in 10 sections where the wall thickness is constant in each section, but gradually decreasing from the bottom to the top. The tower is encastred at the bottom (Figure 3). The tower is made from steel S355 with a Young's modulus of 210 GPa, Poisson's ratio 0.3 and the density 8500 kg/m³ (8% increase of the density to account for the secondary structural components).

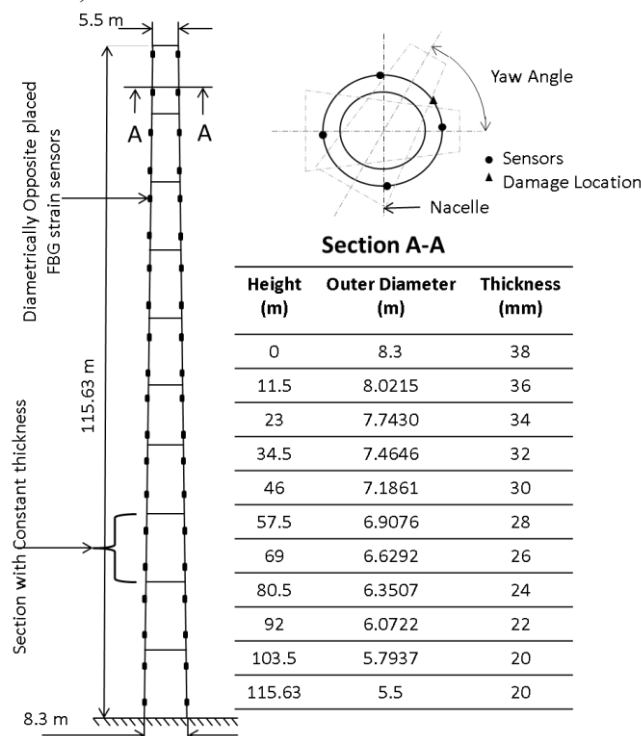


Figure 3: FE modelling details of the Tower.

The nacelle and hub loads were applied as point loads, at specified eccentricity and height indicated from the design specifications. The wind loads were simulated as random loads using Euro-codes, [19]. A peak wind pressure was selected and applied on the surface area facing the wind, in order to

compute the force. The force increases according to the power law along the height of the tower. The blades, however, were assumed to be pitched into a full aerodynamic brake position to ensure minimal rotor motion and consequent change in mass distribution, which may affect the NA [20].

3.1. Modelling the effect of temperature

For a steel structure like the tower, the ambient temperature changes affect the performance in two primary ways [21], the bulk effects due to the change in the temperature of the entire structure and the gradient effects, caused due to the direction of the sun. Tower being made of steel is a good conductor of heat, and as such the resultant gradient of the temperature will be quite small. Thus, only the bulk effects have been modelled. The bulk effect of the change in temperature manifests in many different ways, but two of these effects are considered to be most significant namely, changes in the geometry of the structure, and the change in the material properties.

3.1.1. Change in geometry of the structure due to temperature. Changes in the dimensions of the components of a structure are directly proportional to the change in temperature. The rate of change in dimension depends on the co-efficient of expansion α , of the material. For the S355 steel, the expansion coefficient is assumed to be 1.7×10^{-5} m/C° [22]. In studies carried out on civil structures, the effect of these changes alone is significant. A temperature difference of 40°C causes a 1.3% variation in the natural frequencies [23].

3.1.2. Change in the material properties. The material properties have a linear relationship with the change in temperature. The Modulus of Elasticity (E) varies with temperature, the modulus thermal coefficients for steel is -3.6×10^{-4} Pa/C° [21]. The constants are higher by an order of magnitude than the coefficient of expansion but there contribution to the change in natural frequencies is of the order 1.72% for a variation of 40°C [23].

4. Vibration based damage identification (VBDI)

4.1. Vibration parameters

The vibration based damage identification methods use vibration characteristics to monitor the performance of the structure. It is an effective strategy for low-cost continuous monitoring. The methods are distinguished based on the basis of the structure property used for monitoring. The commonly used parameters are: change in natural frequencies, change in mode shapes, change in mode shape derivatives, change in modal strains etc. The properties monitored are acceleration data and strain data for the structure subject to unknown ambient excitation.

The modal properties are a function of the condition of the structure. Hence any change in the structure will be reflected by a change in these parameters. These parameters have a varying sensitivity to the physical changes and have their own merits and limitations. Some of the commonly used VBDI methods are mentioned below.

4.2. Enhanced coordinate modal assurance criterion method (ECOMAC)

The first systematic use of mode shapes for damage detection was carried out by West (1984) [24]. In the future, several other methods were proposed in order to overcome the insensitivity of mode shapes. In 1992, Hunt [25] proposed the ECOMAC method which correlates the two mode shapes. The ECOMAC [8] metric can be computed by

$$ECOMAC(j) = \frac{1}{2N} \sum_{i=1}^N |\psi_i^*(j) - \psi_i(j)| \quad (2)$$

where, ψ_i^* , and ψ_i , denote the i^{th} damaged and undamaged mode shape respectively, N , is the number of mode shapes and j , is the joint number. The highest peak in the ECOMAC plot indicates damage. The derivation of ECOMAC is given in detail in [8].

4.3. Mode shape curvature method (MSC)

The sensitivity of the mode shape changes to damage was low. Thus the mode shape curvature was proposed by Pandey et al. [5] as a damage indicator. The modal curvature is the second derivative of the mode shape and is highly sensitive to damage. This metric is, hence ideal for the detection and isolation of damage. The central difference operator may be used to get the mode shape curvature (MSC) from the measured mode shapes [5]. It is given by:

$$\phi_i'' = \frac{\phi_{i+1} - 2\phi_i + \phi_{i-1}}{l^2} \quad (3)$$

where, ϕ is the mode shape curvature at i^{th} location, ϕ is the mode shape at particular location, and l is the distance between the sensor nodes.

4.4. Strain modal flexibility index method (MFI)

There is a recent trend to use strain mode shapes for damage detection [9]. The strain mode shapes are more sensitive to damage, and the numerical error in the computation of MSC as a result of the central difference operator can be overcome. Strain Energy metrics are commonly used for damage detection [3]. An improvement to these methods is the use of strain based flexibility matrix. The flexibility matrix of the structure is an inverse of the stiffness matrix and hence can be calculated precisely even with a few lower modes of vibration [8]. The flexibility can be computed by:

$$F = \sum_{i=1}^N \frac{1}{\omega^2} \psi_i \psi_i^T \quad (4)$$

where, ψ_i denotes the i^{th} mode shape, N , is the number of mode shapes, and ω , is the diagonal matrix with natural frequencies of vibration.

The change in flexibility matrix computed from the first few modes of vibration for the damaged and undamaged structure can be used for damage detection and isolation as shown in equation 5.

$$MFI(j) = \frac{|\Delta F_{jj}|}{F_{jj}} \quad (5)$$

where, $MFI(j)$ is the flexibility index, j denotes the j^{th} degree of freedom, and ΔF is the change in flexibility, F is the flexibility of the undamaged structure.

5. Analysis results and discussion

The performance of the four methods introduced in the earlier sections can be assessed in terms of their ability to isolate damage successfully. The isolation method is considered to be successful, if the value of the corresponding parameter is highest at the damage location. The damage was introduced at various locations and the ability of the methods was validated. Figure 4 indicates one such analysis carried out. It is noted that in these analyses 42 sensor nodes (21 each for acceleration measurement along x and y axis) assumed without taking into account measurement noise and temperature variation. For this case the damage was introduced by reducing the Flexural Rigidity of an element (size-0.38m $\times$ 0.25m) by 25%. Reduction of flexural rigidity is a valid damage simulation strategy as indicated by [26]. It may be treated equivalent to loss of material thickness due to corrosion or cracking and is a commonly used strategy for global level damage simulation in bridge structures, [12]. Analyses have demonstrated that the NA based method is able to detect low damage extents (10% reduction) [13-15]. However, a higher degree of damage is assumed, to facilitate the comparison of the four methods under varying conditions of measurement noise or temperature, for which the performance of the above methods has already been, validated [8]. As can be seen in Figure 4, all the four methods were able to isolate the damage successfully.

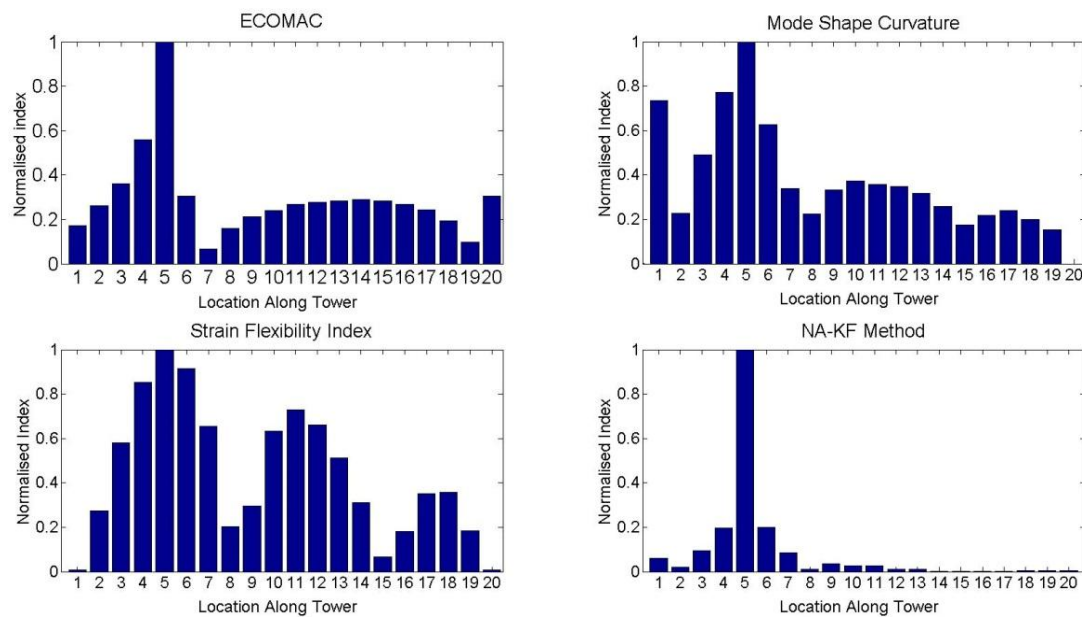


Figure 4: Comparative performance of damage isolation methods

The relative difference in the peak corresponding to the damage location and the other locations is highest for the NA tracking based method, while it is the least for the MFI method. Similar results were obtained for different damage locations along the circumference of the tower. The damage was not detected in the NA based method only when the damage was at a location perpendicular to the plane of the sensors, and as a result bi-axial neutral tracking is necessary. But for other locations, the NA method is able to detect damage even when the sensors are not in the vicinity of the damage.

5.1. Noise

The experimental readings are usually altered by measurement noise thus making the selected parameters less sensitive to damage isolation. The effectiveness of the proposed method was therefore checked through analyses under various levels of measurement noise. The noise component was generated randomly and added to the base measurement [3]. The damage isolation algorithm was run 1000 times to determine the probability of damage isolation and is given in Table 3. Strain and modal curvature based methods like MFI and MSC are more sensitive to damage, than the mode shape based methods, and hence, are expected to perform better in the presence of noise. But, due to the numerical differentiation and round-off errors associated with the computation of MSC, its performance is affected significantly at higher noise levels. On the other hand, the MFI method does not need any post-processing, and hence demonstrates a better performance. The use of KF as indicated in [13] yields robustness to the NA tracking methodology and the performance of the NA-KF method is better than the other methods. It must be noted that the noise was added to the measurement of strain and displacement mode shapes only, the yaw angle measurement is assumed to be accurate. The discussion on the effect of noise on yaw angle measurement is included in a later section.

Table 1: % Probability of Damage Isolation with varying Noise.

Methods	Noise Level				
	0%	1%	2%	5%	10%
ECOMAC	100	100	78	58	19
MSC	100	100	58	46	15
MFI	100	100	95	90	76
KF-NA	100	100	99	91	82

5.2. Temperature

The effect of ambient condition changes has been discussed in Section 3.1. The performance of the proposed method was compared with that of the other methods in varying ambient temperature conditions. The ECOMAC and MFI methods have a comparable performance in changing temperature conditions. The MSC being more sensitive to damage performs better than the methods based on mode shapes, while KF-NA method performs better than MSC for the reasons explained in Section 5.1. Only the effects of temperature change mentioned in section 3.1 on the structure were considered. The acquisition equipment was assumed to be unaffected by the temperature, as the sensors are almost always, temperature compensated, and the rest of the acquisition equipment is designed for the temperature range.

Table 2: Damage Isolation for changing temperature conditions

Methods	Temperature Variation				
	-30°C.	-15°C.	0°C.	15°C.	30°C.
ECOMAC	×	✓	✓	✓	×
MSC	×	✓	✓	✓	✓
MFI	×	✓	✓	✓	×
KF-NA	✓	✓	✓	✓	✓

5.3. Yaw

Yawing of the nacelle for alignment with the direction of the wind improves the efficiency and as a result the power output of the wind turbine. Unfortunately, due to the yawing of the nacelle, the load distribution around the tower changes and as a result the mode shapes of vibration of the tower change as well. So, a damage detection system which does not consider the yaw of the nacelle will not be able to successfully detect damage in the tower structure. Thus it is of utmost importance to track the yaw of the nacelle. Unfortunately the 3 methods namely ECOMAC, MSC and MFI have not been formulated specifically for such an application and do not fuse the information in the prediction. Thus, this information which is easily available has to be incorporated artificially, which may lead to systematic errors if the estimate of yaw angle is wrong. This estimation may be due to system faults or just measurement noise. A small change of 2° significantly affects the resultant mode shapes and the damage detection. On the other hand, the KF based method can easily incorporate the Yaw angle through data fusion as shown by Soman et al. [13]. Furthermore; the yaw angle tracking based method is robust to measurement noise and hence yields accurate damage detection in presence of noise in the yaw angle measurement

6. Conclusion

A novel damage detection method using KF for NA tracking is compared to other popular damage detection techniques. The performance of the methodology is examined in conditions which simulate the different temperature conditions and different levels of contamination of measurements because of noise. The study indicates that the KF based methodology performs better than the other methods. It combines the benefits of the use of a sensitive damage detection parameter, use of strain sensors in the dynamic domain and powerful numerical tool for post processing, and allows us to have reliable damage isolation and also damage diagnosis. However, an experimental validation is required for this method. Furthermore, more realistic damage scenarios need to be introduced like fatigue cracks, and the effectiveness of the methodology should be validated.

Acknowledgement

The authors would like to acknowledge the European Commission for their research grant under the project FP7-PEOPLE-20120ITN 309395 “MARE-WINT” (new Materials and RELiability in offshore WInd Turbines technology). The authors would also like to thank DTU Wind Energy, for providing

valuable information for the modeling of the 10 MW RWT tower for the purpose of this study. The authors are also grateful to TASK-CI for allowing the use of their computational resources. The opinions expressed in this paper do not necessarily reflect those of the sponsors.

References

- [1] Cho S, Park J, Jung H J, Yun C B, Jang S, Jo H, Spencer B F Jr, Nagayama T, Seo J W, Structural health monitoring of cable-stayed bridge using acceleration data via wireless smart sensor network, *Bridge Maintenance, Safety, Management and Life Cycle Optimization* (2010), pp. 158-164.
- [2] Rytter A, PhD Dissertation: Vibrational Based Inspection of Civil Engineering Structures, Aalborg, University of Aalborg (1993).
- [3] Abedwuyi A, Wu Z, Serker N H K M, Assessment of Vibration-based Damage Identification Methods using Displacement and Distributed Strain Measurement, *Structural Health Monitoring*, 8(6), 443-461 (2009)
- [4] Doebling S, Farrar C, Prime M, A Summary Review of Vibration based Damage Identification Techniques, *Shock and Vibration Digest*, 30(2) (1998) 91-105.
- [5] Pandey A K, Biswas M, Samman M M, Damage Detection From Changes In Curvature Mode Shapes, *Journal of Sound and Vibration*, Vol. **145**, No. 2, pp. 321-332, (1997)
- [6] Pandey A K, Biswas M, Damage Detection In Structures Using Changes In Flexibility, *Journal of Sound and Vibration*, (1994) Vol. **169**, No. 1, pp. 3-17.
- [7] Stubbs N, Kim J T, Farrar C R, Field verification of a non-destructive damage localization and severity estimation algorithm, *Proceedings of 13th International Modal Analysis Conference*, vol. I, (1995).
- [8] Talebinejad I, Fischer C, Ansari F, Numerical Evaluation of Vibration-Base Methods for Damage Assessment of Cable Stayed Bridges, *Computer-Aided Civil and Infrastructural Engineering* 26 (2011).
- [9] Zonta D, Bernal D, Strain-based approaches to damage localization in civil structures, *Proceedings of XXIV international modal analysis conference*, Saint Louis (2006).
- [10] Labuschagne, A., Janse van Rensburg, NF., and Van der Merwe, A., Comparison of linear beam theories. *Mathematical and Computer Modelling* 49, no. 1 (2009): pp. 20-30
- [11] Xia H W, Ni Y Q, Ye X W, Neutral-axis position based damage detection of bridge deck using strain measurement: formulation of a Kalman filter estimator, *Proceedings of the 6th European Workshop on Structural Health Monitoring*, Dresden, Germany. (2012).
- [12] Soman R, Malinowski P, Ostachowicz W, Neutral Axis Tracking for damage detection in wind turbine towers, *Proceedings of the EWEA 2014*, Barcelona, Spain. 10-14 March 2014.
- [13] Soman R, Malinowski P, Ostachowicz W, Kalman-Filter Based Data Fusion for Neutral Axis Tracking for Damage Detection in Wind-Turbine Towers, *Proceedings of 7th European Workshop of Structural Health Monitoring Vol.20 No.02 - The e-Journal of Nondestructive Testing* pp-245-252.
- [14] Soman, R, Malinowski, P and Ostachowicz, W. "Threshold determination for neutral axis tracking based damage detection in wind turbine towers", In: *Proceedings of the EWEA Offshore2015*, Copenhagen, Denmark. 10-12 March 2015.
- [15] Soman, R, Malinowski, P and Ostachowicz, W., Paulsen, U "Kalman filter based data fusion for neutral axis tracking in wind turbine towers", In: *Proceedings of the SPIE smart Structures.NDE*, San Diego,US. 8-12 March 2015.
- [16] Brown R G, Hwang P Y C, Introduction to Random Signals and Applied Kalman Filtering, 3rd Edition, *John Wiley & Sons, New York*, (1997).
- [17] ABAQUS, Analysis User's manual, version 6.12-3 ed., (2013).
- [18] DTU Wind Energy Report-I-0092. "Description of the DTU 10 MW Reference Wind Turbine",

July (2013)

- [19] Eurocode NS-EN 1991-1-4; "General actions - Wind actions". Standards Nor-way, 2005+NA: (2009).
- [20] Bas J, Carriveau R, Cheng S, Newson T, Strain Response of a Wind Turbine Tower as a Function of Nacelle Orientation, *In BIONATURE 2012, The Third International Conference on Bioenvironment, Biodiversity and Renewable Energies (pp. 12-18)*, (2012)
- [21] Soman, R, Onoufriou T, Kyriakides, M, Damage assessment of bridges using compound SHM-signal processing and communication challenges, (*EUSIPCO*), *2013 Proceedings of the 21st European Signal Processing Conference*, pp. 1-5. IEEE, 2013.
- [22] Xu Z D, Wu Z, Simulation of the Effect of Temperature Variation on Damage Detection in a Long Span Cable Stayed Bridge, *Journal of Structural Health Monitoring* (2007), 6: pp. 177-189.
- [23] Xia Y, Chen B, Wong S, Ni Q, Xu Y, Temperature effect on vibration properties of civil structures: A literature reviews and case studies, *Journal of Structural Health Monitoring*, 2012, 2 pp. 29-46.
- [24] West W M, Illustration of the Use of Modal Detection in Steel Framed Structures by Vibration, *Proceedings of the AirForce Conference on Aircraft Structural Integrity, Los Angeles* (1984).
- [25] Hunt D L, Application of an enhanced coordinate modal assurance criterion, *Proceedings of the 10th International Modal Analysis Conference*, San Diego, CA, 1, 66–71 (1992).
- [26] Jang, S, Jo, H, Cho, S, et al. Structural health monitoring of a cable-stayed bridge using smart sensor technology: deployment and evaluation. *Smart Structures and Systems*, 2010 6(5-6), 439-459.