BI-AXIAL NEUTRAL AXIS TRACKING FOR CRACK DETECTION IN WIND TURBINE TOWERS

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(received: 4 May 2015; revised: 6 June 2015;
accepted: 10 June 2015; published online: 1 July 2015)

Abstract: This work concentrates on Structural Health Monitoring (SHM) of a wind turbine tower. The paper investigates the use of a decision level data fusion based on bi-axial tracking of change in the neutral axis (NA) position for damage detection in wind turbine towers. A discrete Kalman Filter (KF) is employed for the estimation of the NA in the presence of measurement noise from the strain sensors. The KF allows data fusion from the strain sensors and the yaw mechanism for the accurate estimation of the NA. Any change in the NA position may be used for detecting and locating the damage. The tan inverse of the ratio of the change in the NA along two perpendicular axes is taken and used for the localization. The study was carried out on a simulated finite element (FE) model of a wind turbine tower with a surface crack. The sensitivity studies carried out on the structure in terms of different crack sizes, crack locations and crack orientations indicate that the methodology is robust enough to detect the crack under different operational loading conditions.

Keywords: Structural Health Monitoring (SHM), crack detection, wind turbine tower, Neutral Axis (NA), Kalman Filter (KF), Data Fusion, Strain

1. Introduction

Wind energy is seen as one of the most promising solutions to the man's ever increasing demand for a source of clean energy. The use of wind energy has received an impetus due to the advancements in the field of materials engineering. Newer, bigger wind turbines are now possible which are more robust and lighter in weight. The main drawback of the wind energy is the high initial cost for setting up and maintenance. These high costs make the wind energy more expensive than the conventional sources like fossil and nuclear fuels, and hence, wind energy has not been widely accepted. 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 through 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]. SHM allows early detection of damage and allows maintenance planning which reduces the cost [2]. Furthermore, it can allow us to avoid unnecessary downtime, hence, increasing the availability of the system.

The SHM needs to be low cost and suitable for continuous monitoring. These techniques are based on the concept that a change in the mechanical properties of the structure will be captured by a change in its dynamic characteristics [3]. The SHM process involves 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 the use of sensors for data collection, filters for data cleansing, and central data processing units for feature extraction and post processing.

Vibration based damage indicators have been traditionally used due to their low cost implementation. Many vibrational parameters like changes in natural frequency [4], mode shapes [5], mode shape derivatives [6], Modal Flexibility Indices [7], etc. have been suggested in the literature. These methods are global level damage detection techniques and are sensitive to large scale damage only and may not detect local level damage. Thus, there is an increasing trend to use strain sensors for local level damage detection. Strain sensors are local level sensors, and hence, they are more sensitive to smaller levels of damage [8]. Many strain based damage detection techniques have been proposed in literature and their performance has even been compared with displacement based methods [9–11].

The SHM methods are still not up to the desired standards, and as such there is still a need for a robust damage detection technique. The discrepancy between the expected and measured results of different SHM techniques is mainly attributed to the uncertainty in the measurement environment with respect to noise, temperature and the excitation mechanism of the structure. Thus, the search for an SHM system which will be able to detect small levels of damage but at the same time, be robust enough to overcome the ambient noise and temperature changes and detect damage under operational conditions is on-going.

In this paper, a method for damage detection of towers is studied. The research focuses on tower structures, as tower damage is the third most common damage in wind turbines [12]. Furthermore, the savings in maintenance costs and the reduction in downtime due to early detection of damage are most significant for the tower structure. As reported by Faulstich *et al.* [13], the downtime for minor damages in towers (support and housing) is far less significant (0.14 days) than in the case of major damage (28.01 days). Thus, SHM on tower structures can help achieve a significant increase in the availability and in turn reduce the cost of power generation.

The present research builds on the research work presented by the authors in [14–18]. It has been shown in [14] that the position of NA of the tower structure may be used as a robust damage indicator. This is possible as the NA is a property of the cross section of the tower independent of the bulk temperature effects, and ambient wind loading. The position of the NA can be assessed by measuring the strains on opposite surfaces of the tower in bending. The paper has also proposed the use of Kalman Filter (KF) [19] accurate tracking of the NA. In [15, 16] the authors have extended the methodology to include the effect of yaw of the nacelle on the observability of the NA and validated it using real strain data from NTK 500/41 wind turbine [20]. In [18], the decision level data fusion has been used in order to accurately establish the damage location both along the axial and radial directions. In the research work until now, the damage has been modeled as the reduction in flexural rigidity of one element of the tower. The reduction of flexural rigidity may be considered equivalent to the loss of material due to corrosion [21] but is not a realistic damage scenario for the tower structure. The tower structures are more susceptible to fatigue related surface cracks and as such the study of the methodology in such circumstances is required. Thus, this paper attempts to employ the bi-axial NA tracking and decision level data fusion for surface crack detection in wind turbine towers. The study is undertaken on an FE model of the 10 MW wind turbine tower which is seen as the future of off-shore wind turbine industry [22]. The study also includes some sensitivity studies in terms of the crack length, location and orientation in order to establish the robustness of NA tracking as an indicator of damage.

2. Theoretical Background

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 bending strains are given by

$$\epsilon = \pm \frac{M_b y}{EI} \tag{1}$$

where, ϵ is the longitudinal strain in bending, M_b is the bending moment at the cross section, E is the Young's modulus, I is the area moment of inertia, and y is the distance from the NA [23].

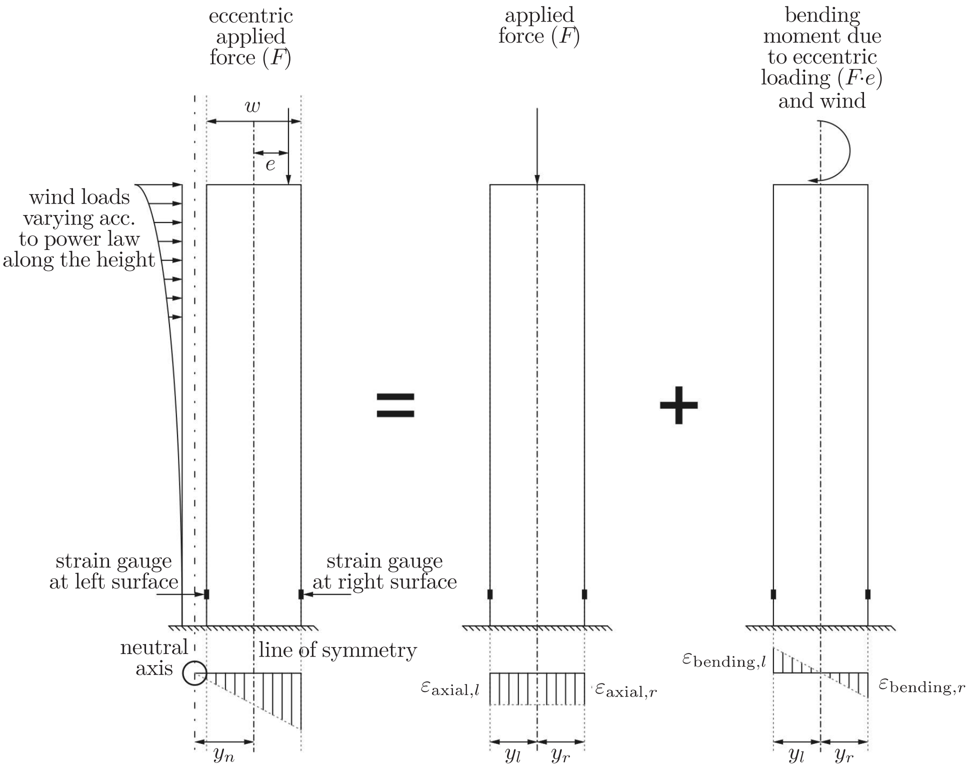


Figure 1. Flexural Strain Distribution over the beam cross-section [15]

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 NA point. The NA 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 NA can be located, which in turn may be an indicator of the damage. Figure 1 explains the abbreviations used and the concept. The NA can thus be estimated based on the strain measurements and is given by

$$\mathrm{NA} = \frac{\epsilon_l}{\epsilon_r + \epsilon_l} = \frac{y_n}{w} \tag{2}$$

2.2. Kalman Filter (KF)

The KF is a set of mathematical equations that provides an efficient computational (recursive) solution of the least-squares method. Theoretically, the 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

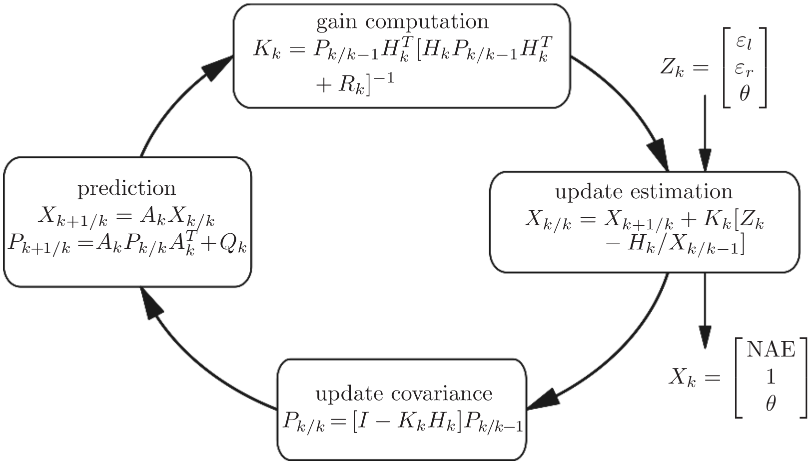


Figure 2. Flowchart for KF implementation [15].
Here x is the estimate of the state, A is the state transition matrix, P is the state variance matrix, Q is the process variance matrix, K is the Kalman gain, H is the measurement matrix, z is the measurement variable, the subscripted k indicates the time step

by measurement alone [24]. Figure 2 concisely explains the implementation of the Kalman Filter.

In the present application, the state estimate variable is $X_k = [NAE, 1, \theta]^T$, where NAE is the Neutral Axis Estimate which in undamaged condition should remain constant independent of the applied loads, x is the location of the NA, the other variable tracking the constant 1. This constant for tracking 1 is incorporated to ensure accurate system depiction and formation of a square measurement matrix which allows faster computations. The third component of the vector is the variable θ for the yaw angle. It is a linear estimate of the measurement from the sensor. The input for the KF algorithm is essentially the state transition matrix (A) which relates the state estimate variable in time. In this case, A is a unity matrix of dimension 3 as the state estimates are random and not co-related in time. The other input is the measurement matrix (H) which links the X_k, and the measurement variable (Z_k) at each time step (measurement from the sensors). The H matrix takes into consideration the observability of the NA based on the locations of the sensors and is designed for accurate system modeling while maintaining the linearity of the measurement step. In the present case, $Z_k = [\epsilon_l, \epsilon_r, \theta]^T$ vector consisting of the strain measurements from the left (ϵ_l) and the right side (ϵ_r) of the tower and the yaw angle measurement (θ) of the nacelle. The KF incorporates the noise information, namely in the system design and the sensor measurement seamlessly and yields an accurate estimate of the state.

2.3. Damage Sensitive Feature

As mentioned in an earlier section, the NA location is independent of the loading conditions, and depends only on the condition of the structure. Thus, the percent change in the NAE is taken as the damage sensitive feature and is given by [18]

$$\Delta NAE = \frac{NAE_{\text{healthy}} - NAE_{\text{monitored}}}{NAE_{\text{healthy}}} \times 100\% \tag{3}$$

The NAE_{healthy} is developed at the time of the installation of sensors when the structure is known to be in healthy condition. $NAE_{\text{monitored}}$ is the estimate at every time step. If the % change exceeds a certain threshold, an alarm is raised indicating damage. This threshold is based on sensitivity studies and the trade-off between the probability of false positive and false negative detections. For the present study of the DTU 10 MW tower it was selected as 1% [17].

2.4. Bi-Axial NA tracking

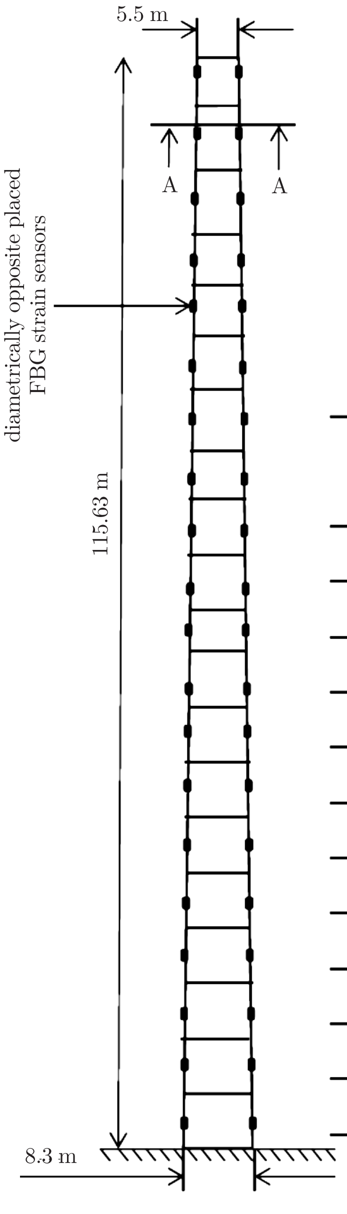
The sensor pairs are located perpendicular to each other, as indicated in Figure 3 and at the center of each element. If the damage is at any location not in the vicinity, the observability of the damage is in the form of the sine and the cosine component. Furthermore, due to the non-linearity, the damage may be detected, but the isolation of the damage may be a problem. Thus, the bi-axial NA tracking data should be combined in order to get more realistic damage isolation. The intuitive way of combination is by taking the inverse tan ratio of the change in the NA locations. Although this may yield an approximate estimate of the location, it cannot be applied directly. It should be kept in mind that the periodicity for sine and cosine is 2π while that for tan ratio is π thus leading to loss of directionality. Thus, a decision level data fusion is necessary, where the change in the directionality is overcome by proper study of the change in the NA location along both the sensor axes. A detailed discussion of the decision level data fusion strategy may be found in [18].

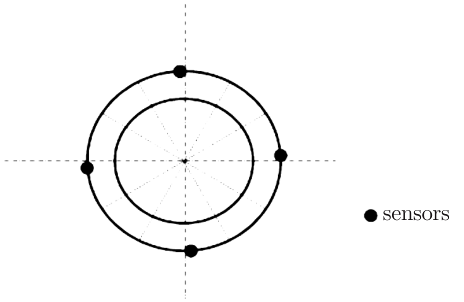
3. Finite Element Modeling

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 modeling software ABAQUS [25] based on the design data available in the reference [22].

The tower is a 115.630 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 into 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/m^3.

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 [26]. 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





Section A–A

height (m)	outer diameter (m)	thickness (mm)
0	8.3	38
11.5	8.015	36
23	7.743	34
34.5	7.484	32
45	7.186	30
57.5	6.908	28
69	6.629	26
80.5	6.351	24
92	6.072	22
103.5	5.795	20
115.6	5.5	20

Figure 3. FE modeling details of the tower

brake position to ensure minimal rotor motion and consequent change in mass distribution which may affect the NA [27].

The dynamic direct analysis was carried out using the modal superposition for estimating the displacements and the strain, so the number of extracted mode shapes was 50 in order to achieve accurate results and limit the computational load. The mesh size of the element was then chosen in order to achieve stable and smooth mode shapes for the extracted modes.

The seam based crack was simulated with line spring elements embedded in the shell elements Figure 4. This approach is simple and computationally inexpensive and is not significantly more complicated than an analysis using shell elements alone [28]. This approach may be used where the crack depth does not vary rapidly and the structure is not subjected to high frequency excitation [29]. Also, the focus of this particular study is on global strain changes and not in the immediate vicinity of the crack (fracture zone), and hence the simplified modeling approach may be used [30, 31]. In order to have stable convergence, the element size was varied uniformly to ensure a denser mesh in the crack vicinity and avoid sudden changes in the element size.

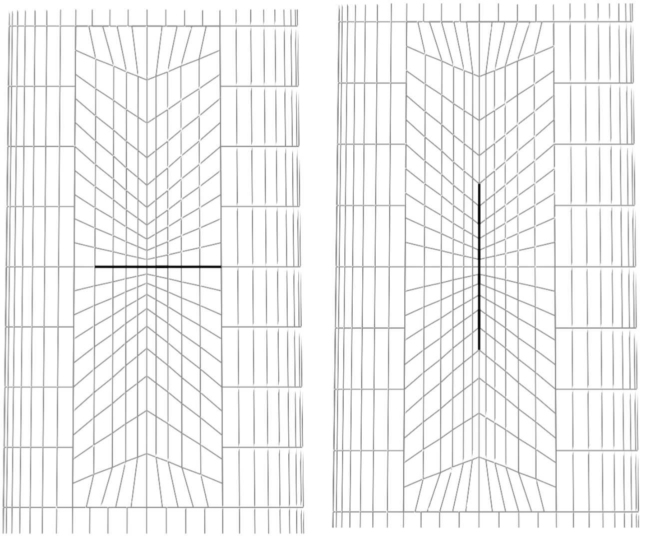


Figure 4. Crack FE modeling details

4. Numerical Simulation

Numerical simulations were carried out on the FE model described in the previous section. The numerical simulations were carried out to

- Demonstrate the use of NAE as a damage sensitive feature for accurate crack detection and isolation.
- Demonstrate the sensitivity of NAE to different crack orientations.
- Demonstrate the sensitivity of NAE to different crack lengths and crack depths.

4.1. NA based Damage Detection

In order to study the robustness of the Bi-Axial NA tracking based SHM strategy, four damage scenarios were simulated as shown in Figure 5. The crack was located at the center of each of the elements. The crack length was constant

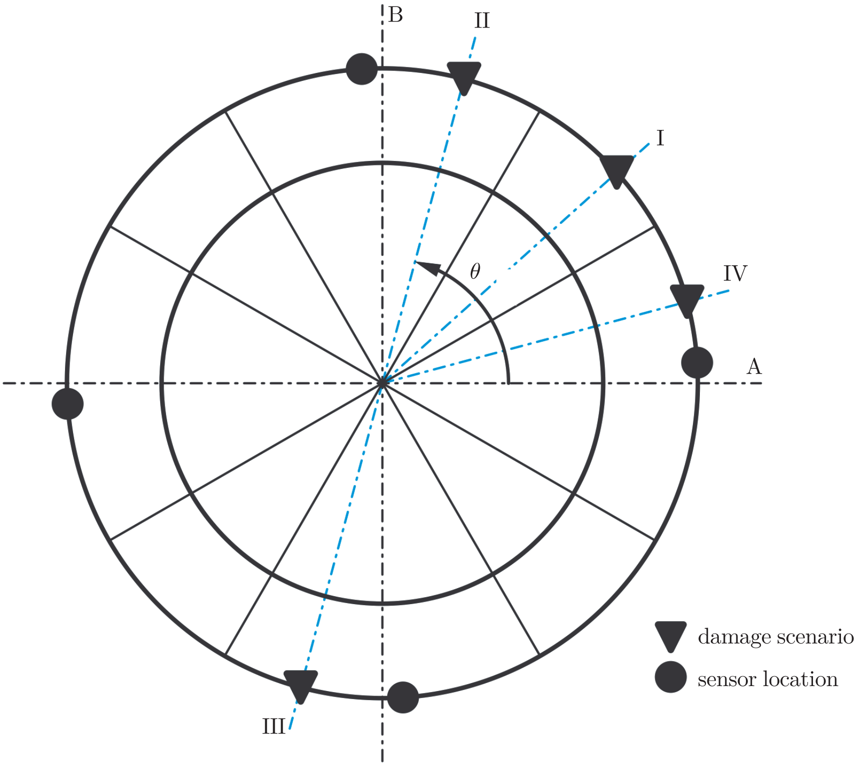


Figure 5. Damage scenarios indicating the need for bi-axial NA tracking

at 0.25 m (50% of the element width) and the depth was kept constant at 15 mm (50% of the element thickness).

Table 1 and Table 2 show the NAE estimates for horizontal and vertical orientations of the crack. The tables quantitatively show that the approach of using NAE as a damage sensitive feature is valid, as damage is accurately detected in all the four scenarios. In addition, it is seen that, when the decision level data fusion is not used, there is false detection of the location which is consistent with the results obtained in [18].

In Figure 6, it can be seen that the damage is clearly indicated by the change in ΔNAE. It is only in the vicinity of the damage that the change in NAE exceeds the selected threshold. Also, as indicated by Table 1 the angle determined by the data fusion is correct and accurate level II damage detection [32] is possible using the decision level data fusion.

The study of the two different orientations shows that both types of cracks can be detected. It should be noted that the horizontally oriented crack results in strain reconfiguration on a larger scale as the loading is in the direction perpendicular to the crack. This allows higher observability of the change in the NA location, as seen by the change in the value for the ΔNAE_B in the damage scenario IV. The authors acknowledge that the crack simulated is an open crack

Table 1. Bi-Axial NA tracking for crack detection (Horizontal Orientation)

Damage scenario	ΔNAE_A (%)	ΔNAE_B (%)	Damage location (°)	Damage location predicted (°)		Error in detection (°)	
				fusion	w/o fusion	fusion	w/o fusion
I	2.2646	2.0491	42	42.13	42.13	0.13	0.13
II	1.1856	3.8157	75	72.7	72.7	2.3	2.3
III	−1.2658	−4.886	−105	−104.52	75.47	0.48	−180.47
IV	5.1331	1.0029	15	11.05	11.05	3.95	3.95

Table 2. Bi-Axial NA tracking for crack detection (Vertical Orientation)

Damage scenario	ΔNAE_A (%)	ΔNAE_B (%)	Damage location (°)	Damage location predicted (°)		Error in detection (°)	
				fusion	w/o fusion	fusion	w/o fusion
I	2.2347	2.0166	42	42.06	42.06	0.06	0.06
II	1.1024	3.8215	75	73.9	73.9	1.1	1.1
III	−1.0658	−4.9383	−105	−102.17	77.82	2.83	−182.82
IV	5.1256	0.9523	15	10.26	10.26	4.74	4.74

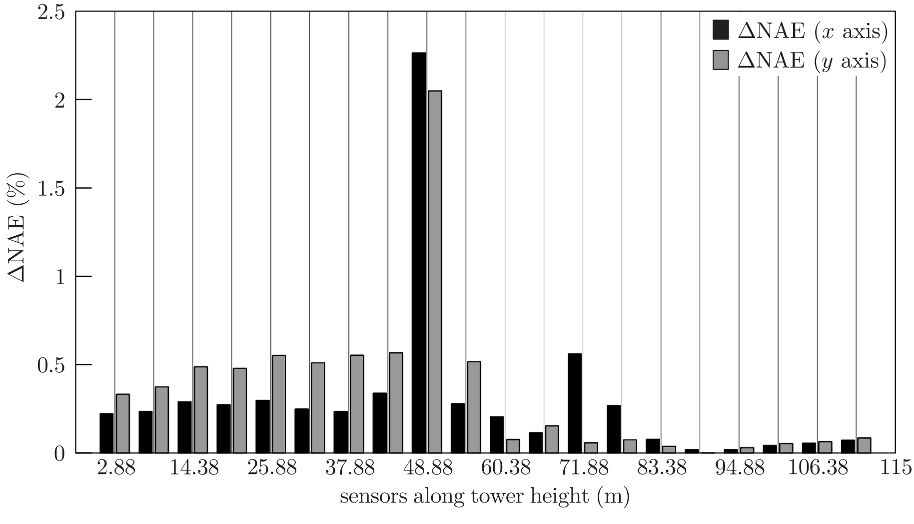


Figure 6. ΔNAE along the tower height for damage scenario I

only, and a breathing crack may be a challenge for detection. The breathing crack will be experienced when the cracked section is experiencing compressive loads, but it is believed that failure due to the crack will not occur during this phase as the strength of the material is higher in compression, also due to the yawing and change in the wind directions, the crack section will at some point experience tensile loads which will result in a constant opening of the crack which can be detected as shown in the studies above.

4.2. NAE Sensitivity to crack severity

As mentioned in section 1, the damage detection methodology should be sensitive to low levels of damage, and as such the robustness of ΔNAE for detecting cracks with different severities needs to be determined. The crack severity can be varied both in terms of the depth of the crack as well as its length. The different damage scenarios simulated are indicated in Table 3. The location of the horizontal crack is kept constant (scenario I) and the length is varied in terms of the % width of the chosen element. The crack depth is indicated as the % of the shell element thickness.

Table 3. Performance of NA with changing crack severity

Damage scenario	Crack length (% of element width)	Crack depth (% of element thickness)	ΔNAE_A (%)	ΔNAE_B (%)
i	20	50	1.5345	1.3383
ii	50	50	2.2646	2.0491
iii	80	50	3.7218	3.6574
iv	50	20	1.8937	1.6782
vi	50	80	4.0854	3.9667

As can be seen, even a small crack can be easily determined using the ΔNAE as a damage sensitive feature. It can be observed that the strain distribution in the vicinity of the crack varies both as a function of the crack length and depth. The change in the NA location is more significant for the increase in the crack depth. On the other hand, as the crack length increases, it results in strain redistribution in larger areas, and hence, it can be detected even if the damage occurs further away from the sensors.

5. Conclusions

The paper builds on the previous work of the authors and validates the methodology proposed by the authors on a more realistic damage scenario. In the paper, bi-axial NA tracking and decision level data fusion for damage localization has been employed for crack detection on a FE model of a wind turbine tower with a surface crack. The methodology is based on tracking of the NA along two perpendicular axes, using a KF based estimator.

The study indicates that the NA is a property of the condition of the structure and is sensitive to cracks in the structure. Furthermore, the robustness of the metric was studied for different crack depths and crack lengths and for vertical and horizontal orientations of the crack. From the results obtained it can be seen that the bi-axial NA tracking is a promising SHM methodology for improved damage isolation.

The present study aims at giving a proof of concept and the validity of the use of data fusion for NA tracking for crack detection in tower structures. The authors acknowledge that the actual loading conditions in-service as well as the pitching and the rotation of the blades may increase the complexity for the use of the metric. The rotation of the blades will change the load distribution in bending which in turn will affect the strains measured; these effects may be compensated for by fusing the rotation speed of the wind turbine in the estimation process. Similarly, pitch angle also affects the strain response of the tower, as shown in [33]. Thus, a more inclusive fusion of data from all the different sensors available is necessary to compensate for these effects. Hence, comprehensive data fusion taking into consideration the wind speed, pitching and the rotation of blades and experimental validation based on real data is identified as the next step of the research.

Acknowledgements

The authors would like to acknowledge the European Commission for their research grant under the project FP7-PEOPLE-2012 ITN 309395 "MARE-WINT" (new Materials and REliablity in offshore WINd Turbines technology).

The authors would 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 possibility to use their computational resources. The authors will also like acknowledge Katarzyna Majewska Ph. D. for her help with the artwork. 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, Yang S, Jo H, Spencer B F, Nagayama T and Seo J W 2012 *Bridge Maintenance, Safety, Management and Life-Cycle Optimization: Proceedings of the Fifth International IABMAS Conference, Philadelphia, USA*, Frangopol D, Sause R and Kusko Ch, (editors)

[2] Doebling S W, Farrar C R, Prime M B *et al.* 1998 *Shock and vibration digest* **30** (2) 91

[3] Adewuyi A P, Wu Z and Serker N H M K 2009 *Structural Health Monitoring* **8** (6) 443

[4] Cawley P and Adams R D 1979 *The Journal of Strain Analysis for Engineering Design* **14** (2) 49

[5] Hunt D L 1992 *10th International modal analysis conference* **1** 66

[6] Pandey A K, Biswas M and Samman M M 1991 *Journal of sound and vibration* **145** (2) 321

[7] Pandey A K and Biswas M 1994 *Journal of sound and vibration* **169** (1) 3

[8] Chakraborty S and DeWolf J T 2006 *Journal of Bridge Engineering* **11** (6) 753

[9] Zonta D and Bernal D 2006 *Proc. of IMAC XXIV, St. Louis* **197**

[10] Benedetti M, Fontanari V and Zonta D 2011 *Smart Materials and Structures* **20** (5), 055009

[11] Adewuyi A P and Wu Z S 2011 *Structural Control and Health Monitoring* **18** (3) 341

[12] Ciang Ch Ch, Lee J-R and Bang H-J 2008 *Measurement Science and Technology* **19** (12) 122001

[13] Faulstich S, Hahn B and Tavner P J 2011 *Wind Energy* **14** (3) 327

[14] Soman R, Malinowski P and Ostachowicz W 2014 *Neutral axis tracking for damage detection in wind turbine towers*, *Proceedings of the European Wind Energy Association Conference, Barcelona, Spain*

[15] Soman R, Malinowski P H and Ostachowicz W 2014 *Kalman-filter based data fusion for neutral axis tracking for damage detection in wind-turbine towers*, *Proceedings of the 7th European Workshop on Structural Health Monitoring (EWSHM), Nantes, France*

[16] Soman R, Malinowski P, Ostachowicz W and Paulsen U S 2015 *Proc. SPIE* **9438**, 94381B

[17] Soman R, Malinowski P H and Ostachowicz W 2015 *Threshold determination for neutral axis tracking based damage detection in wind turbine towers*, *Proceedings of the Offshore European Wind Energy Association Conference, Copenhagen, Denmark*

[18] Soman R, Malinowski P H and Ostachowicz W 2015 *Bi-axial neutral axis tracking for damage detection in wind-turbine towers*, *Wind Energy* (in press)

[19] Welch G and Bishop G 2014 *An introduction to the Kalman filter*, [online on 24/01/2014 at http://clubs.ens-cachan.fr/krobot/old/data/positionnement/kalman.pdf]

[20] Schmidt Paulsen U 2011 *Verification of long-term load measurement technique*, Work Package 1B.2 under the European Commission, Integrated Wind Turbine Design (UPWIND)

[21] Jang Sh, Jo H, Cho S, Mechitov K, Rice J A, Sim S-H, Jung H-J, Yun Ch-B, Spencer Jr B F and Agha G 2010 *Smart Structures and Systems* **6** (5–6) 439

[22] Bak C, Zahle F, Bitsche R, Kim T, Yde A, Henriksen L C, Natarajan A and Hansen M 2013 *Description of the DTU 10 MW reference wind turbine*, *DTU Wind Energy Report-I-0092*

[23] Xia H W, Ni Y Q and Ye X W 2012 *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

[24] Brown R G, Hwang P Y C *et al.* 1992 *Introduction to random signals and applied Kalman filtering*, Wiley New York, **3**

[25] ABAQUS 2013 *Analysis User's manual*, version 6.12-3

[26] Eurocode 2009 *NS-EN 1991-1-4, "General actions – Wind actions"*, *Standards Norway* **2005+NA**

[27] Bas J, Carriveau R, Cheng S and Newson T 2012 *Strain response of a wind turbine tower as a function of nacelle orientation*, BIONATURE 2012, The Third International Conference on Bioenvironment, Biodiversity and Renewable Energies 12

[28] Cao J J, Yang G J, Packer J A and Burdekin F M 1998 *Engineering Fracture Mechanics* **61** (5) 537

[29] Chondros T G, Dimarogonas A D and Yao J 2001 *Journal of Sound and vibration* **239** (1) 57

[30] Skallerud B 1995 *Fatigue and Fracture of Engineering Materials and Structures* **18** (4) 463

[31] Wu S and Abel A 1991 *Analysis of fatigue surface crack growth in tubular joints used in offshore structures*, The First International Offshore and Polar Engineering Conference

[32] Rytter A 1993 *Vibrational based inspection of civil engineering structures*, PhD thesis

[33] Bas J, Smith J, Carriveau R, Cheng Sh, Ting D S K and Newson T 2012 *Wind Engineering* **36** (5) 553