Kalman Filter based Neutral Axis tracking under varying temperature conditions

Rohan SOMAN [1], Katarzyna MAJEWSKA [1], Magdalena MIELOSZYK [1], Pawel MALINOWSKI [1], Wieslaw OSTACHOWICZ [1, 2]

[1]Institute of Fluid Flow Machinery, PAN. Fiszera 14, 80-231 Gdansk, Poland.
rsoman@imp.gda.pl
[2] Warsaw University of Technology, Narbutta 84, 02-524 Warsaw, Poland.

Abstract

Structural Health Monitoring (SHM) is no longer a luxury but a necessity. Thus the search for an SHM strategy that is suitable for low level damage detection, is low cost, and is insensitive to ambient loading condition and environmental conditions is still on going. The use of Neutral Axis (NA) location as a damage sensitive feature has been proposed by few researchers. This paper thus helps to establish the robustness of NA, through the study of the temperature effects on its estimation.

The paper presents results from an experiment on a simple composite beam, and shows that through advance mathematical tools, the effect of the temperature changes can be easily compensated and the NA as a damage indicator is robust and stable. The paper also presents the stability of NA under varying temperatures on a Finite Element (FE) model of a validated Nordtank NTK 500/41 wind turbine under simulated real damage conditions.

Keywords: Neutral axis (NA), Temperature effect, Kalman filter (KF), Composite, Data fusion, Wind turbine tower, Fiber Bragg grating (FBG) sensors.

1. INTRODUCTION

Man through his ingenuity has developed unparalleled technological systems to enrich his life and make it comfortable. These technological systems range from structures like bridges, buildings, tunnels dams etc., to mechanical systems like the wind turbine, automobiles, airplanes etc. His dependence on his inventions and the structures has steadily grown, and a life without them seems impossible. Thus the proper functioning of these technological systems is essential for civilization as we know it to exist and progress. Structural Health Monitoring (SHM) thus becomes an essential part of the system to ensure its smooth functioning. Hence SHM system for structures is no longer a luxury but a necessity.

SHM is defined as monitoring the structure through the evaluation of its in-service performance [1]. Most of the SHM 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 [2]. 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 [3].

The SHM system should be low cost, suitable for continuous measurement, insensitive to the presence of measurement noise, insensitive to the ambient conditions like temperature humidity, loading etc. and should be able to detect damage at an early stage. Keeping in mind these requirements several damage detection strategies have been proposed in the literature, which make use of many different damage sensitive features. A more recent trend in structures is to use the change in the Neutral Axis (NA) position of beam type structures as the damage sensitive feature [3-9]. It has been shown that the change in NA is the function of the condition of the structure alone. NA of a structure may be estimated by measuring the dynamic strains on the structure at two points in a cross section and through extrapolating the line to get the NA point of the cross section. It can be shown that the NA location is insensitive to ambient loading conditions. Also, through the use of proper numerical tools like the Kalman Filter (KF) the NA estimation can be made robust even in the presence of measurement noise. Thus the NA location seems to be a good damage sensitive feature for SHM. The NA has been used for SHM in bridges [4-7] and wind turbine tower structures [3, 8, 9]. These structures are often subjected to ambient temperature changes. Thus the robustness of the NA estimation in the presence of ambient temperature changes needs to be studied.

Thus, this paper presents the study of the effect of temperature changes on the NA location in composites and metallic structures. Firstly, an experimental study is undertaken on a simple composite beam subject to temperature changes in a heating chamber, and the strain response of the beam to static loading is used for the NA tracking. The methodology is also employed on a metallic structure in the form of a validated finite element (FE) model of the wind turbine tower under various simulated damage scenarios to check the suitability. The present study is limited to the bulk temperature effects. But it is envisaged, that the relationship of the strain to temperature is linear and hence the KF is ideally suited to tackle the gradient temperature effects which may be seen in real structures.

2. THOERETICAL BACKGROUND

2.1 Neutral Axis

A transverse load applied to beam-like structure as shown in Figure 1 leads to the bending of the structure.

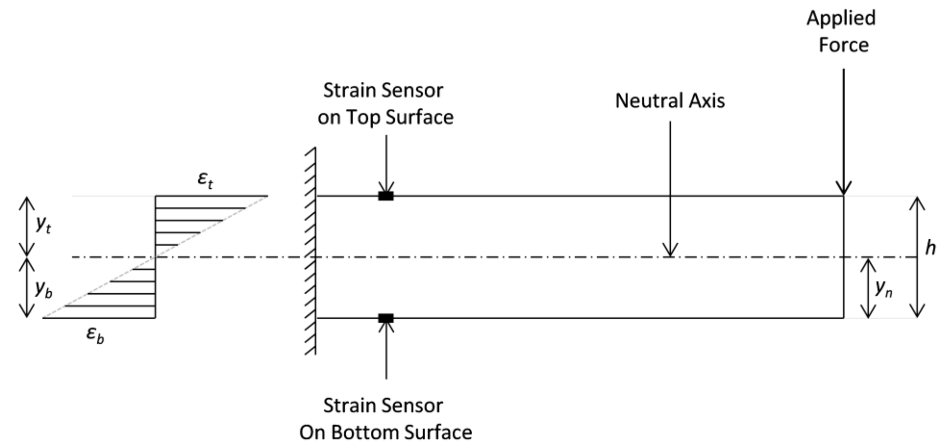


Figure 1: Flexural strain distribution over the beam cross section.

The bending strains are given by Equation (1)

$$\varepsilon = \frac{M_b y}{EI} \tag{1}$$

Where, ε is the longitudinal strain in bending, M_b is the bending moment at the cross section, E is the Young's modulus and I is the area moment of inertia, y is the distance from the NA [7]. This bending strain will be tensile at one of the surfaces, and compressive at the opposite surface. In between, this top and bottom edge is the NA of the cross section. 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 neutral axis can be located, using Equation (2) which in turn may be an indicator of the damage.

$$NA = \frac{\varepsilon_t}{\varepsilon_b + \varepsilon_t} = \frac{y_n}{h} \tag{2}$$

Where, ε_t is the strain at the top surface, ε_b is the strain at the bottom surface, h is the height of the beam and y_n is the NA location.
The Figure 1 explains the concept. The NA location can thus be estimated based on the strain measurements.

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 [10]. Figure 2 concisely explains the implementation of the KF. In the figure, 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.

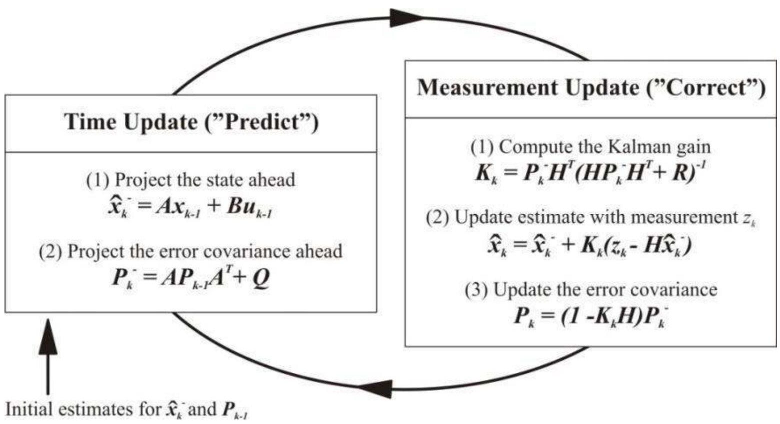


Figure 2: Flow chart for the implementation of the KF [11].

In the present application, the state estimate variable is a 2 × 1 vector consisting of the, ratio, $\frac{y_n}{h}$ which in undamaged condition should remain constant independent of the applied loads and the other variable tracking the 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 relation of the measured strain to the ambient temperature is linear in the temperature range and as such the temperature compensation can be easily incorporated in the KF by introducing the state estimation variables for the temperature. Also the measurement variable which in the simplest case consists of the measured strain at the top and the bottom can be expanded to include the measured temperature in the vicinity of the sensors.

3. COMPOSITE STRUCTURE

3.1 Experimental Setup

The NA was tracked for simple composite beam (35cm × 5cm × 0.29cm) shown in Figure 3 under static loading of 100g (0.98N) and 200g (1.96N) for a range of temperatures from 20°C to 60°C.

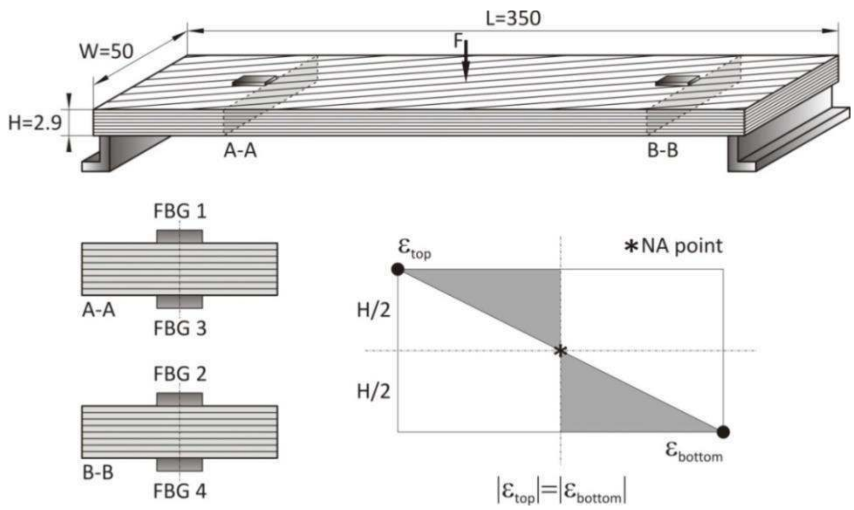


Figure 3: Experimental setup for composite beam.

The composite beam was made from 8 layers of woven fabric of glass fibers with the weave (+45/-45) each of which is 0.02cm thick. The layers are placed to maintain the symmetry of the composite sample and ensure that the NA will be at the middle. The composite beam was then instrumented with 2 pairs of Fiber Bragg Grating (FBG) sensors with gauge length 1mm. The basics of the FBG strain sensors are given in detail by Majewska et al. [12]. The FBG sensors were chosen as they offer several benefits over the conventional strain gauges like the ability to be multiplexed, the relatively low weight and the higher sampling frequency. In addition, the electrical neutrality, and the ability to transport the signal over long distance with minimal loss in intensity make the FBG sensors more attractive and it is expected they will replace the conventional sensors in the next few decades.

The beam was placed in a heating chamber to ensure stable temperature during measurement. The strain measurements were made by the Micron Optics si425-500 interrogator with the sampling frequency of 250Hz. The temperature was measured by Micron Optics os4200 temperature probe using the Fiber Sensing FS4100 interrogator at a sampling frequency of 1Hz. The lower sampling frequency was acceptable as the measurements were supposed to be made under stable temperature conditions.

The Figure 4 shows the strain measured at 20°C for 100g static loading. The measured strain for 2 and 4 is more or less equal in magnitude but opposite in sense, which is expected. But in the case of sensor pair 1 and 3, this is not seen. This can be attributed either to damage or disbond in the composite or improper gluing of the sensor. But the behavior of the sensor is linear, in the sense the measured strain increases linearly as the load on the structure as well as in the presence of temperature change. Thus the sensor can still be used for the NA tracking but, in principle the quantity will not be the actual NA of the beam but in fact the observable NA of the system.

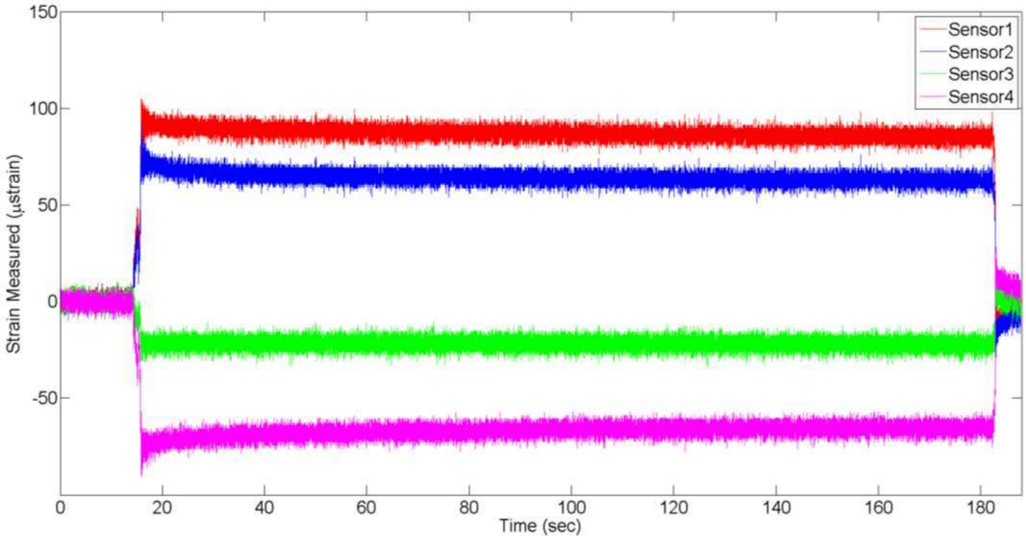


Figure 4: Measured strain in composite beam.

3.2 Results and discussion

The NA was tracked for each of the loading conditions based on the measured strains at the sensor pairs (1-3) and (2-4). The method focusses only on the strain measured in the composite as a result of the temperature, and the effect of the expansion of the FBG on the measured strain was accounted for in each case. When the influences of temperature on the measured strain in the material is not temperature compensated, the observed NA location changes linearly as shown in Figure 5(a) and 5(b). This linear behavior is expected, as the NA location will undergo a change proportional to the increase in the axial strains caused due to the change in the temperature. Also, it has to be noted that, the FBG sensors are nearly 10 times more sensitive to temperature than the loading and without the compensation of the effect of the temperature on the sensors itself, the results obtained will lead to a wrong estimation of the NA. Thus as long as the dependence of the measured strains on the temperature is linear the change in the NA location is linear.
Curves were fitted to the data and the slopes of the fitted curves are shown in Table 1. As can be seen for the same loading scenario the slopes for the tension and compression are equal in magnitude but opposite in sign, for the same sensor pair. Also the slope changes for different loading scenarios and is scaled inversely as the load on the structure.

Sensor Pair	100g		200g	
	tension	compression	tension	compression
1-3	0.00093	-0.00092	0.00046	-0.00046
2-4	0.00105	-0.00104	0.00053	-0.00052

Table 1: Average slope of plots under different scenarios.

Ideally for the sensor locations and the symmetric loading at the center, the slopes for the different pairs would equal, but due to the improper gluing of the third sensor, the strain transfer is not perfect leading to the errors. Although analytically the slopes in tension and compression for the same loading should be the equal, the minor differences may be attributed to the uncertainty in the temperature distribution within the chamber and imperfect support conditions.

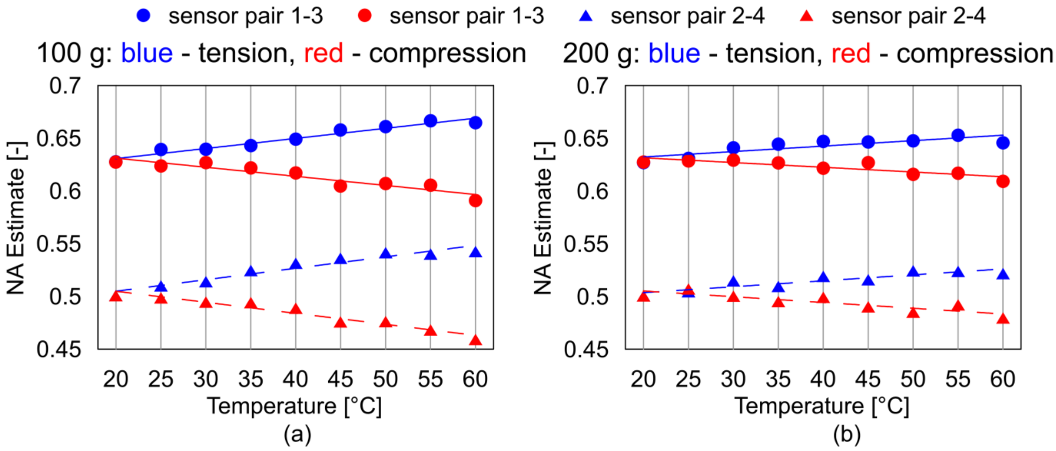


Figure 5: Estimated NA without temperature compensation under varying temperature conditions.
(a) 100g static loading (b) 200g static loading

On the other hand when, temperature information was incorporated in the NA tracking algorithm, the effects of the change in the temperature were easily overcome leading to a stable NA estimation in all loading scenarios for both sensor pairs as shown in Figure 6.

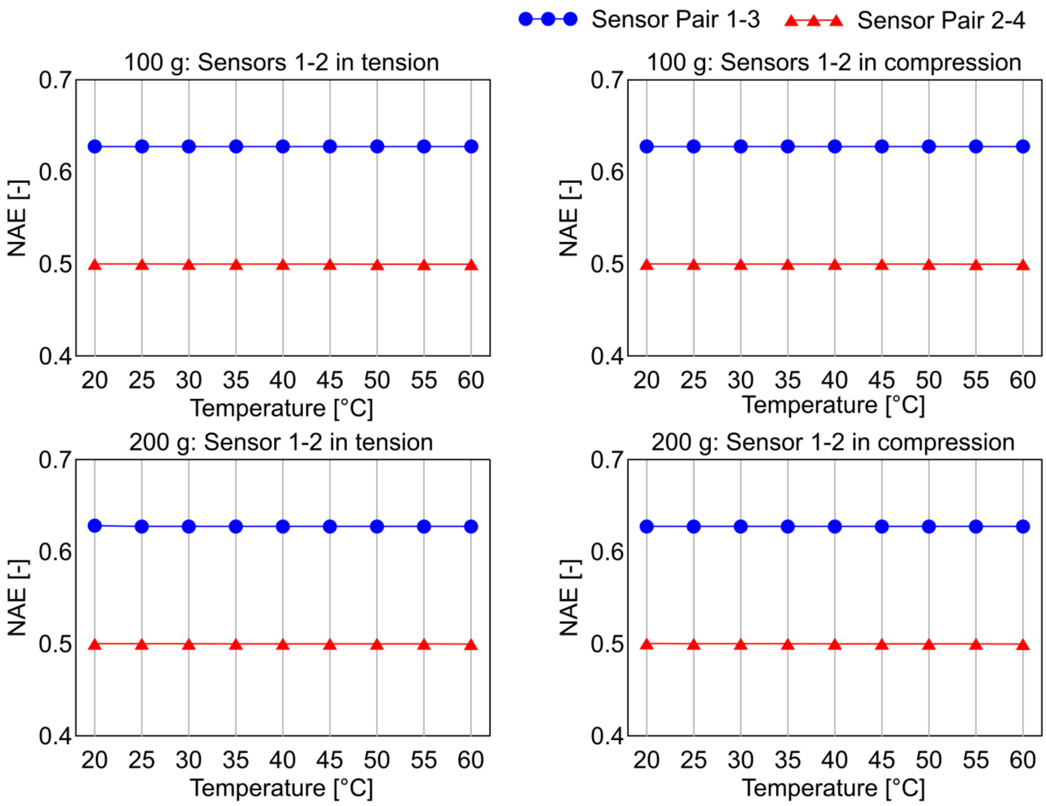


Figure 6: Estimated NA with temperature compensation under static loading of 100g and 200g under varying. temperature conditions

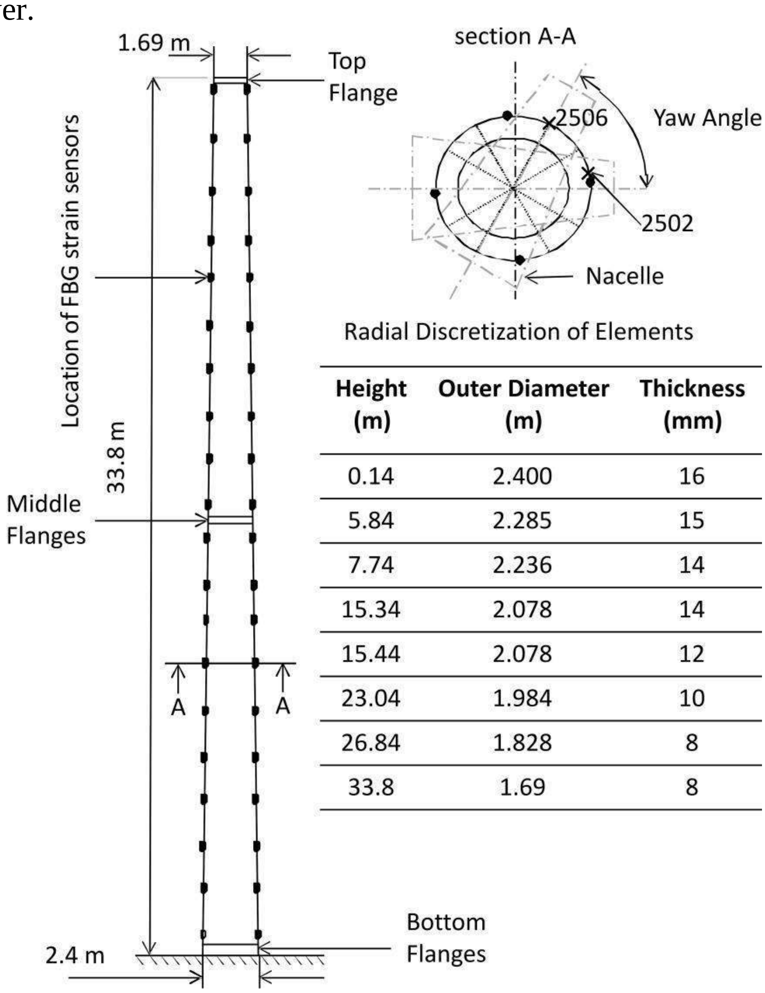
Thus the NA estimate with the temperature compensation in the KF allows robust tracking of the NA location under changing temperature conditions.

4. METALLIC STRUCTURE

The application of the KF based NA tracking method under changing temperature conditions is hence undertaken for damage detection. The methodology was employed on a validated FE model of the NTK 500/41 Wind Turbine subjected to some simulated damage scenarios. The idea behind the chosen structure was to see the effectiveness of the methodology on a damaged metallic structure. The metallic structure being a good conductor of heat minimizes the gradient effects induced due to temperature. Also, the wind turbine structures are subjected to large seasonal temperature variations and as such the robustness of the methodology for wind applications needs to be studied.

4.1 Finite Element Modelling

The FE model of the NTK 500/41 wind turbine [8] was developed in ABAQUS based on the design drawings and the available data in reports. The Figure 7 shows the dimensions of the NTK 500/41 tower.



Height (m)	Outer Diameter (m)	Thickness (mm)
0.14	2.400	16
5.84	2.285	15
7.74	2.236	14
15.34	2.078	14
15.44	2.078	12
23.04	1.984	10
26.84	1.828	8
33.8	1.69	8

Figure 7: FE modelling details of Nordtank NTK 500/41 wind turbine [8].

The tower is modelled as shell elements with S4R elements. The tower is divided in 72 elements along the height of the tower and 32 elements along the circumference. This is done in order to maintain the aspect ratio of the elements in the range where the simulation results are reliable. In addition, the flanges were modelled with solid elements. The welds of the flanges were modeled as tie constraints in the regions of the solid and shell element interactions. The tower top mass was simulated as point load with the selected eccentricity according to the design drawings. The wind loads were simulated using the wind measurements from the sensors at the hub height and then interpolating using the power law [13]. The blades were assumed to be in braked condition to avoid any rotation and the resulting changing of center of mass due to the rotation. The strain values at the middle of the element obtained through simulations were compared with those from the experiment and were found to be in good agreement. Also, the natural frequencies of the structure were within 1% of those obtained through experiments.

Some damage scenarios were introduced in the FE model. The simplest damage introduced was through the reduction of the flexural rigidity of 1 element of the tower by 20%. The crack was modelled by the linear spring; the failure of the connection between the flanges was modelled by removing the tie constraint between the solid and shell elements. Effect of ambient temperature changes were then introduced in the FE model as described in [14]. The NA was then estimated using the measured strains for each of the damage scenarios.

4.2 Results and Discussion

For each of the damage scenarios the estimated NA, using the temperature compensation is shown in Figure 8.

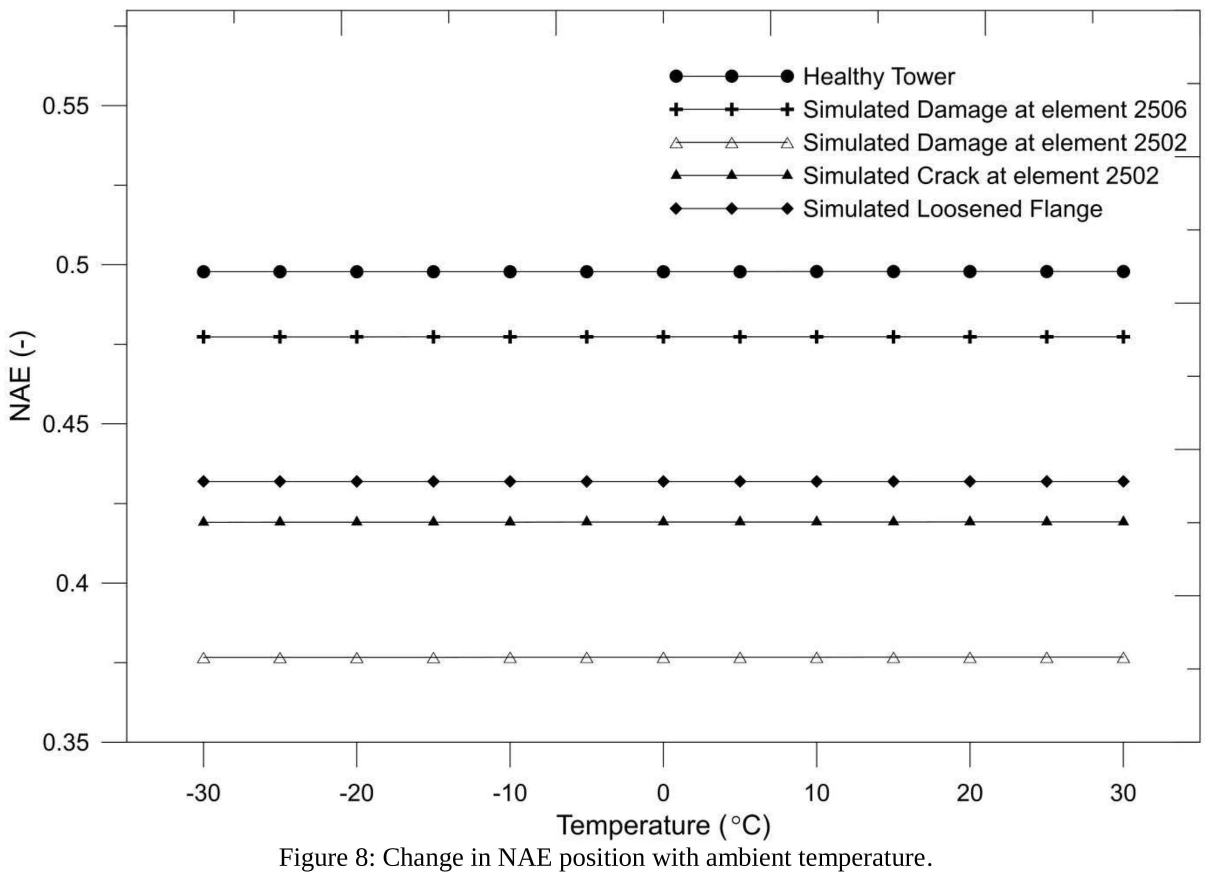


Figure 8: Change in NAE position with ambient temperature.

As can be seen, in each case the NA is stable even in changing temperature conditions. Also, one can see that for the healthy and each of the damaged condition of the tower, there is a significant change in the NA estimate of the tower and as a result damage can be easily detected.

5. CONCLUSIONS

The paper aims at studying the effect of ambient temperature changes on the observability of NA. The paper presents the results for the composite structure from experiments carried out on a simple composite beam and metallic structure through simulated studies. The paper shows the need for use of KF with the temperature compensation for accurate tracking of the NA location. It also highlights the pitfalls if the temperature information is not included in the data fusion strategy.

The paper also shows the robustness of the NA as damage sensitive feature in simulated damage scenarios of a wind turbine tower structure. The stability of the NA location is shown in variety of simulated damage scenarios which are anticipated in the real application of the structure like, fatigue cracking, loosening of the flange and reduction in flexural rigidity due to corrosion. The authors acknowledge that only the bulk temperature changes are considered in this paper, although due to the linear nature of the strain dependence on the temperature, the gradient effects may be easily compensated for as well. But the validation of this hypothesis is marked as an area for future work along with the field validation of the methodology on a real structure.

ACKNOWLEDGMENTS

The authors would like to acknowledge the European Commission for their research grant under the project FP7-PEOPLE-2012 ITN 309395 “MARE-WINT”, the National Science Center, Poland for their project grant no. 2015/17/N/ST8/01166, and National Centre for Research and Development in Poland - Project No. PBS1/B6/8/2012. The authors would also like to thank DTU Wind Energy, for providing valuable information for the modeling of the Nordtank NTK 500/41 wind turbine for the purpose of this study. The authors are also grateful to TASK-CI for allowing the use of their computational resources.

REFERENCES

[1] Cho, S., Park, J., Jung, H-J., Yun, C-B., Jang, S., Jo, H., Spencer Jr, B.F., Nagayama, T., Seo, J.W., 2010, Structural health monitoring of cable-stayed bridge using acceleration data via wireless smart sensor network, Bridge Maintenance, Safety, Management and Life Cycle Optimization. pp 158-164

[2] Adewuyi, A., Wu, Z., Serker, N. H. K. M., ”Assessment of Vibration-based Damage Identification Methods using Displacement and Distributed Strain Measurement”, Structural Health Monitoring 2009

[3] 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.

[4] Sigurdardottir, D., and Glisic, B., "Neutral axis as damage sensitive feature" Smart Materials and Structures 22, no. 7 (2013): 075030.

[5] Sigurdardottir, D and Glisic, B., 2015. The neutral axis location for structural health monitoring: an overview. Journal of Civil Structural Health Monitoring, 5(5), pp.703-

713.
[6] Sigurdardottir, D, and Glisic, B. "Detecting minute damage in beam-like structures using the neutral axis location." Smart Materials and Structures 23, no. 12 (2014): 125042.
[7] Xia, H. W., Y. Q. Ni, and X. W. Ye. "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.
[8] Soman R., Malinowski, P., Ostachowicz, W., Paulsen, U., Kalman filter based data fusion for neutral axis tracking in wind turbine towers. Proc. SPIE 9438, Health Monitoring of Structural and Biological Systems 2015, 94381B (23 March 2015); doi: 10.1117/12.2084145
[9] Soman, R, Malinowski, P and Ostachowicz, W, 2016. Bi-axial neutral axis tracking for damage detection in wind-turbine towers. Wind Energy 19 (4): 639-650
[10] Brown, R.G., Hwang, P. Y. C., "Introduction to Random Signals and Applied Kalman Filtering," 3rd Edition, John Wiley & Sons, New York, 1997.
[11] Welch, G and Bishop, G, An introduction to the Kalman filter. [online on 25/04/2016 at http://www.cs.unc.edu/~tracker/media/pdf/SIGGRAPH2001_CoursePack_08.pdf], 2016.
[12] Majewska, K., Mieloszyk, M., Ostachowicz, W., and Krol, A., Experimental method of strain/stress measurements on tall sailing ships using fibre bragg grating sensors" Applied Ocean Research 47, 270-283 (2014).
[13] Sen, Z., Altunkaynak, A., and Erdik, T., "Wind velocity vertical extrapolation by extended power law," Advances in Meteorology, vol. 2012, 2012.
[14] Soman, R., P. Malinowski, and W. Ostachowicz., Comparative study of performance of neutral axis tracking based damage detection. Journal of Physics: Conference Series. Vol. 628. No. 1. IOP Publishing, 2015.