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# Damage Detection of Wind Turbine Tower Structures Using Multimetric Sensor Data Fusion

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## ABSTRACT

Wind power systems have gained much attention due to the relatively high reliability, maturity in technology and cost competitiveness compared to other renewable alternatives. Advances have been made to increase the power efficiency of the wind turbines while less attention has been focused on structural integrity assessment of the structural systems. Vibration-based damage detection has widely been researched to identify damages on a structure based on change in dynamic characteristics. Widely spread methods are natural frequency-based, mode shape-based, and curvature mode shape-based methods. The natural frequency-based methods are convenient but vulnerable to environmental temperature variation which degrades damage detection capability; mode shapes are less influenced by temperature variation and able to locate damage but requires extensive sensor instrumentation which is costly and vulnerable to signal noises. This study proposes novelty of damage factor based on sensor fusion to exclude effect of temperature variation. The combined use of an accelerometer and an inclinometer was considered and damage factor was defined as a change in relationship between those two measurements. The advantages of the proposed method are: (1) requirement of small number of sensor, (2) robustness to change in temperature and signal noise and (3) ability to roughly locate damage. Validation of the proposed method is carried out through numerical simulation on a simplified 5MW wind turbine model.

## 1. INTRODUCTION

Wind energy is drawing popularity as a practical alternative renewable source of energy available today. With rise in popularity, advances have been made to increase the power efficiency of the wind turbines but less attention has been focused on structural integrity assessment. Damage in a wind turbine structure includes foundation failures, and fatigue cracking in the steel turbine tower and corrosion for intertidal area of an offshore wind turbine (Hau 2006). A presence of damage in the structure may result in long periods of turbine standstill with great economic loss and threatening the long-term viability of the wind turbine technology.

In order to continuous and timely monitoring of a wind turbine, structural health monitoring (SHM) can play an important role. Past researches for damage identification for a large-scale structure has utilized vibration-based condition monitoring strategies: natural frequency-based, mode shape-based and curvature mode shape-based methods. Natural frequency-based methods require use of single sensor for capturing dynamic characteristics (i.e., natural frequency) and use it as a basic feature for damage identification. Changes in resonant frequencies can be quickly conducted and are often reliable. While it is efficient in sensor configuration, the natural frequency-based damage detection has significant drawback. Critical limitation is that the frequency changes caused by damage are usually very small and may be buried in the changes caused by environmental and operational conditions. The damage may be identified if measurements to be compared are made at the same time of the year which needs long-period of measurement records (Askegaard and Mossing 1998).

Damage detection method such as mode shape-based and curvature mode shape-based method uses mode shapes and their derivatives as a basic feature for damage. As mode shapes contain local information which is more sensitive to local damages, locating for multiple damage detection is possible. Also, mode shapes are less sensitive to temperature variation than natural frequency (Farrar and James 1997). While there are many advantages, the drawback is also apparent. First, measurement of the mode shapes requires a set of sensor instrumentation with more sensors while natural frequency-based method relies on measurement of single sensor. Extensive sensor instrumentation of an operational turbine is prohibited due to cost restrictions (Swartz *et al.* 2010) and difficulty in maintenance. Second, the measured mode shapes are more prone to noise contamination than natural frequencies (Fan and Qiao 2011)

Sensor fusion is a technique for combining sensory data or data derived from sensory data from different sources so that the processed information would be possible better than those sources were used individually. In the field of SHM, the sensor fusion technique has been used for estimating displacement by combining incomplete displacement from two different sources (Park *et al.* 2013, Smyth and Wu 2007, Hong *et al.* 2013).

This study proposes a novelty of damage factor based on the assumption that relationship between measured data at a location from a different type of sensor has nothing to do with environmental effect but is influenced by a structural condition. In this study, the combined use of an accelerometer and an inclinometer was considered and damage factor was defined as a change in relationship between those two measurements. The advantages of the proposed method are: (1) inexpensive instrumentation with small number of sensors, (2) robustness to change in temperature and (3) ability to roughly locate damage. Validation of the proposed method is carried out through numerical simulation on a simplified 5MW wind turbine model.

## 2. PROPOSED METHOD

The proposed damage factor is based on modal approach. The second-differential of inclination vector $\{\theta''\}$ and acceleration vector $\{acc\}$ can be approximated using the linear combination of the finite number of modes and generalized coordinates as in Eqs (1) and (2), respectively.

$$\{acc\}_{m\times 1} = \Phi_{m\times r}\,\{q\}_{r\times 1}. \tag{1}$$

$$\{\theta''\}_{m\times 1} = \Psi_{m\times r}\,\{q\}_{r\times 1}. \tag{2}$$

where $\Phi_{m\times r}$ and $\Psi_{m\times r}$ are respective displacement and rotation mode shape matrices, m and n are the numbers of measurements of acceleration and inclination, respectively. $\{q\}_{r\times 1}$ is the modal coordinate, and $r$ is the number of used modes. When $n \geq r$, the modal coordinate $\{q\}$ can be obtained from Eq. (3) as

$$\{q\} = \Psi^{+}_{r\times n}\,\{\theta''\}_{n\times 1}. \tag{3}$$

where the superscript + stands for the Moore-Penrose pseudo inverse. A linear relationship between the second order differential of inclination and acceleration responses can be formulated using the modal approach by substituting $\{q\}_{r\times 1}$ in Eq. (1) with (3).

$$\{acc\}_{m\times 1} = \alpha_{m\times m}\,\Phi_{m\times r}\,\Psi^{+}_{r\times n}\,\{\theta''\}_{n\times 1}. \tag{4}$$

where $\alpha$ is diagonal matrix for compensating error in mode shapes from displacement and rotation. As $\alpha$ is solely dependent on modal information and only changed by the presence of damage in a structure that causes the variation of the modal properties, hereafter α is defined as damage factor.

This study proposes a simple and straightforward way of obtaining a damage factor is formulated in Eq. (5). The damage factor is obtained in frequency domain by matching the power spectral density of the measured acceleration and estimated acceleration at the $i$-th location which are supposed to have the same magnitude at the dominant frequency region.

$$\alpha_{ii} = \sqrt{\frac{S_{acc,i}(f_1)}{S^{acc,i}_{\theta''}(f_1)}} \tag{5}$$

where $S_{acc}$ and $S_{\theta''}^{acc}$ are the respective power spectral densities of the acceleration and estimated acceleration at the $i$-th location from a set of second differential of inclination. f1 is the first natural frequency which is the most dominant mode. The damage factor can be normalized as Eq. (6) so that zero can stand for intact condition of the structure.

$$Normalized\,Damage\,Factor(NDF) = \left\{\frac{\alpha_{DAMAGED,i}}{E(\alpha_{INTACT}, i)} - 1\right\} \times 100 \tag{6}$$

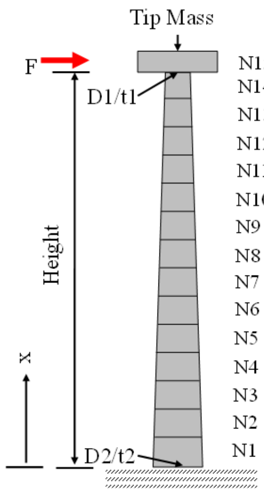
## 3. NUMERICAL VALIDATION

Numerical validation was carried out to investigate the effect of number and location of sensors; sensitivity of normalized damage factor (NDF) was then investigated with determined sensor configuration. Based on the numerical results, a wind turbine with a various severity of damage near the support was simulated and the effect of temperature variation and signal noise were studied.

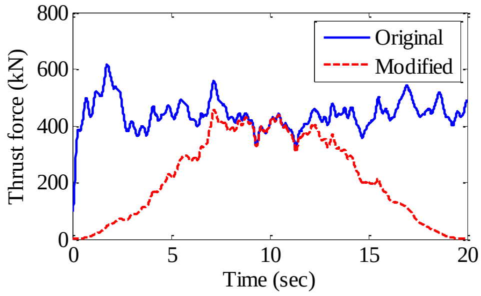
### *3.1 Simulation Setup*

The wind turbine (see Fig. 1) was modeled with 15 Euler-Bernoulli beam elements; the design specification of 5 MW wind turbine was provided by NREL (National Renewable Energy Laboratory) (Jonkman *et al*. 2009) as shown in Table 1. The height of the tower is 90 m, and two major natural frequencies are 0.31 Hz, 3.16 Hz, respectively. The top of the tower (RNA, rotor nacelle assembly) was modeled as a concentrated tip mass including masses from blades, a hub and a nacelle; the thrust force acting on the top of the structure was simulated using FAST (Jonkman and Buhl 2005) developed by NREL. The TurbSIM, turbulent-wind simulator was also used to generate wind data with mean velocity at 20m/s in 150 m x 150 m plane from the center of the blades considering temporal and spatial turbulence effect (Jonkman and Kilcher 2012). Based on the wind inflow data, the thrust force was obtained by FAST. In order to simulate wind data from 0 m/s, the Hanning window was applied as shown in Fig .1(b).

The effect of temperature and signal noise to damage identification was considered. The modulus of elasticity (E) of the steel tower was assumed to have linear relationship with temperature as shown in Fig. 2 (Ledbetter and Austun 1985). On the simulation, the temperature was varied from -30˚C to 40˚C randomly and corresponding modulus of elasticity was applied.




(a) 5MW wind turbine model




(b) Thrust force

Fig. 1 Simplified wind turbine model and thrust force

Table 1. Properties of 5MW Wind Turbine Model

| | |
|---|---|
| Height | 90 m |
| t1/t2 | 19/27 mm |
| D1/D2 | Φ3.87m/Φ6m |
| Tip Mass | 251.2 ton |
| Density | 7850 kg/m3 |
| Natural Frequency | 0.31 Hz, 3.16Hz |

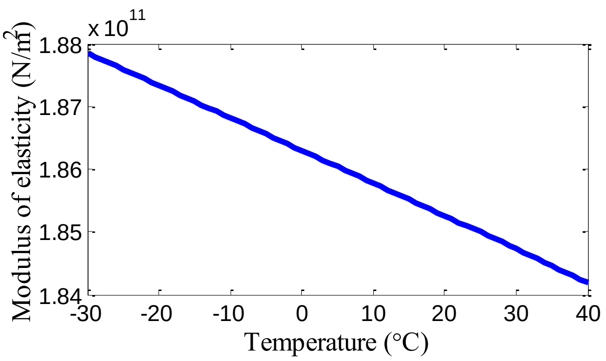



Fig. 2 Temperature versus modulus of elasticity

The 5 % RMS (Root Mean Square) error of acceleration and inclination was considered as signal noise. The damage was represented as reduction in stiffness; N1 which is close to support was chosen as a damaged element. The sampling rate was set to 20 Hz and 1000 sec of data was collected.

*3.2 Sensor Placement*

The four different numbers of sensor configurations were considered to estimate the acceleration at N15 from a set of inclination measurement. The discrepancy between the exact and estimated acceleration is expressed as RMS error as shown in Table 2. The exact acceleration is low-pass filtered at 1Hz to reduce the high frequency component noise above 1 Hz as frequency spectrum at the 1st natural frequency is region of interest.

Four cases of estimated acceleration agreed very well with the reference. Even use of single inclinometer at N15 could estimate the acceleration with less than 3% of error; the exact and estimated acceleration using single inclinometer is shown in Fig. 3.

In this study, one acceleration and inclination at N15 which is the nacelle location of the turbine is utilized; as the nacelle rotates toward wind direction, responses at N15 can have maximum amplitude over external wind load.

Table 2. Configuration of Inclinometers

| Number of inclinometer | 1 | 3 | 5 | 15 |
|---|---|---|---|---|
| Location | 15 | 1,7,15 | 1,5,8,11,15 | 1 ~ 15 |
| RMS error (%) | 2.97 | 1.79 | 1.20 | 1.11 |

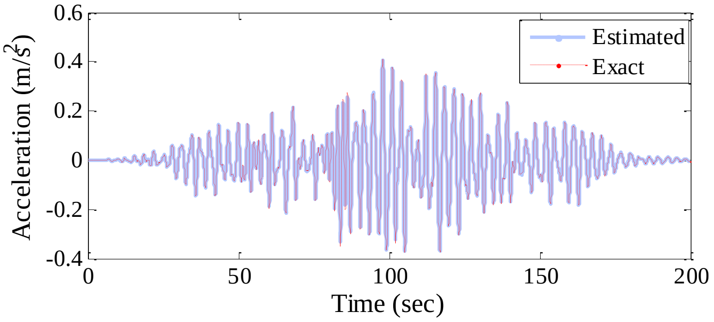



Figure 3. Comparison of the exact and estimated acceleration

*3.3 Sensitivity of the NDF to a Damage Location*

The sensitivity of the NDF with sensor configuration of acceleration and inclination measurement at N15 is investigated. The stiffness of each 15 element was reduced 50% step by step to observe the sensitivity to damage and temperature was constant at 25 °c. The proposed method was very sensitive to damage occurred at lower and upper part of the structure as shown in Fig. 4. A positive or negative sign of the NDF indicates the presence of damage as well as rough location of damage on the structure.

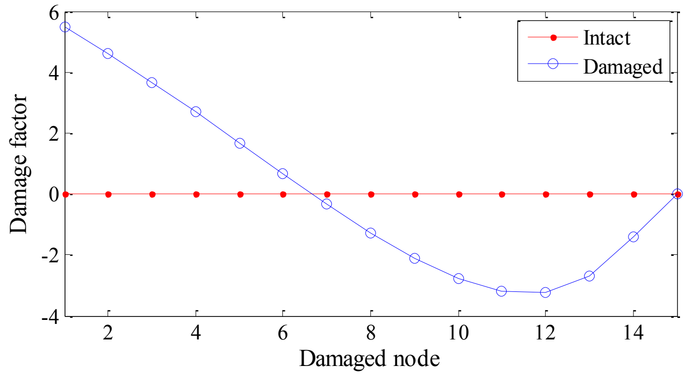



Fig. 4 Sensitivity of damage factor to 50% of damage severity

The change in natural frequency due to damage is shown in Fig. 5. The natural frequency was extracted through eigen-system realization algorithm (ERA) (Juang and Pappa 1985). The presence of damage could be identified but damage locating was impossible. Although the NDF is insensitive to damage occurred in the middle of the structure, the change in natural frequency can be adjunctively used for identifying these types of damage as it always changes with the presence of damage.

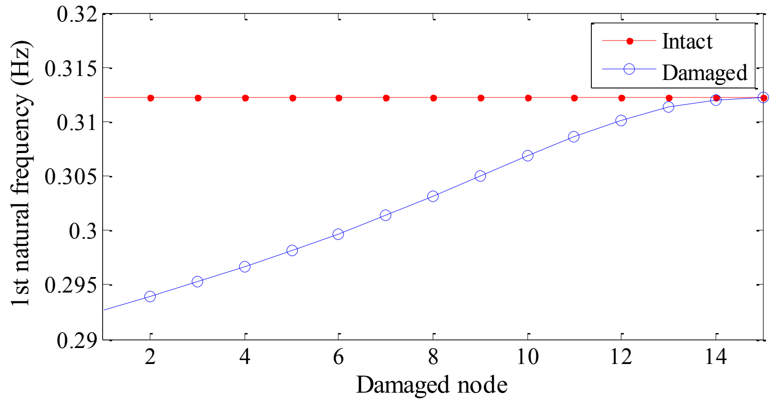



Fig. 5 Variation of natural frequency

*3.4 Effect of Temperature Variation*

The relationship between temperature and the NDF was carried out. The damage was simulated on N1 as it is the most vulnerable part of the tower due to significant bending moment. The stiffness at N1 was reduced to 1%, 5%, 10% and 20% with temperature variance from -30°c to 40°c. Fig. 6 shows the relationship between the NDF with four cases of damage severity and temperature. The slope for the NDF was close to zero; the NDF was little influenced by change in temperature. Even 1% of damage was clearly distinguished as shown in Fig. 6.

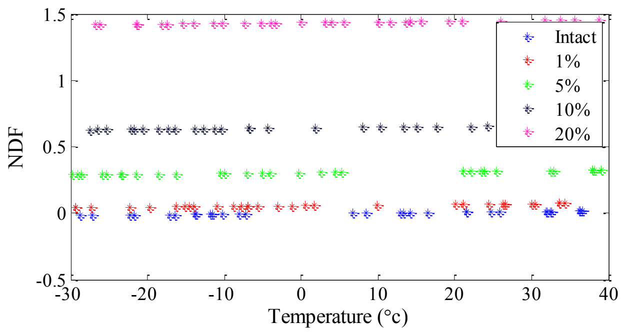



Fig. 6 Temperature versus NDF

On the other hand, the natural frequency is vulnerable to temperature change (see Fig .7). The 1st natural frequency versus temperature had a strong relationship and made it difficult to determine the damage severity only by change on frequency; 5% of damage was managed to be detected.

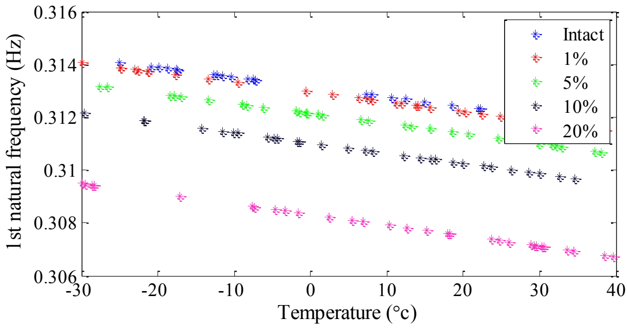


Fig. 7 Temperature versus 1st natural frequency

## 3. CONCLUSION

This study proposed a novelty of damage factor based on sensor fusion technique that not only detect damage but also roughly locate damage with use of minimum number of sensors. To validate the proposed method for damage identification of a wind turbine structure, numerical simulation on a simplified 5MW wind turbine model was carried out. The result of numerical simulation can be summarized as follows:

- Numerical simulations were carried on 4 cases of sensor deployment. Even single use of inclinometer at N15 was possible to accurately estimate acceleration at N15 with RMS error less than 3%.
- The use of an inclinometer and accelerometer at N15 was determined in the simulation.
- Sensitivity analysis was conducted with determined sensor configuration (i.e., acceleration and inclination at N15); the normalized damage factor (NDF) was sensitive to lower and upper part of the structure while it was close to zero for damage in the middle of the structure.
- NDF was able to not only detect but also roughly locate damage on the structure. Positive and negative sign indicated presence of damage in lower and upper part of the tower, respectively.
- A growing damage for 1 % ~ 20% reductions in stiffness was simulated at N1 and effect of temperature. The NDF had little effect on temperature change and even 1% of damage could be identified.

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