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Structural Health Monitoring of Composite Wind Turbine Blades: Challenges, Issues and Potential Solutions

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Abstract

Wind turbine (WT) blades are vulnerable to failure as they are exposed to direct harsh environment, suffering constantly varying loads by wind and cyclic fatigue load due to self-weight, experiencing extreme temperature and humidity changes, erosion and corrosion. As a consequence, blades show high failure rate and share significant downtime, which highlight the significance and essentiality of the research, develop and application of blade Structural Health Monitoring (SHM) techniques. To fulfil reliable SHM of WT blades, much effort has been spent in the past years as reported in literature. But to date, how to realize reliable WT blade SHM is still an open question. The previous reviews enumerate the non-destructive testing techniques that are potentially applicable to blade SHM, but they fail to give a clear suggestion on how to implement reliable SHM of a WT blade. To fill this gap, instead of replicating technique enumeration the present paper is oriented to investigate the pros and cons of existing blade SHM techniques and based on which, a newly developed blade SHM technique that is effective in both damage detection and location is discussed.

Key Words: wind turbine, blade, structural health monitoring, composite material

1. Background

Wind power industry is quickly growing worldwide although at present, wind turbine (WT) systems still suffer many reliability issues particularly in harsh offshore environment [1, 2]. Among WT components, rotor blades, made of fiberglass composite material, are more susceptible to being damaged as they are exposed to direct harsh environment and subjected to significant fatigue loads. The survey of over 700 onshore WTs in Sweden during 1997 to

2005 indicates that rotor blades contribute 13.4% of WT failures, ahead of gearboxes (9.8%) and generators (5.5%) [3]; Another survey of 1,500 onshore WTs over 15 years suggests that rotor blades are responsible for 7% of WT failures, also ahead of gearboxes (4%) and generators (4%) [4]. These figures are in agreement with the conclusions obtained in [5] as well. In addition, it is reported that in 2015, in worldwide range WT rotor blades are failing at a rate of around 3,800 a year, equivalent 0.54% of the 700,000 blades that are in operation around the world today [6]. As a consequence of these high failure rate figures, blade failures have become a primary cause of insurance claims. In American onshore wind market, they account for over 40% of claims, ahead of gearboxes (35%) and generators (10%) [6]. This figure matches very well with the 'Wind Energy Report 2005' by ISET, which reveals that the Mean Time between Failures (MTBF) of WT blades is 5 years. This means that 20 out of 100 WTs will suffer blade failures in one year of operation [7].

Blade failures are often associated with significant financial loss. For example, a sudden blade failure experienced by an onshore WT in Dunbar, Scotland in 2005 resulted in £1.25 million of repair cost and significant downtime [8]. The figure would be even larger in offshore scenario due to site-accessing difficulties and the challenges of conducting blade repair/replacement over sea. Therefore, to improve the safe operation of WT blades is of importance to fulfil successful wind power generation. Structural Health Monitoring (SHM) is one of effective approaches to reaching such a purpose. However, compared to the large amount of research on WT drive train condition monitoring techniques [9-11], the research on blade SHM technique is much less despite a few attempts to extend laboratory methods as in-situ SHM system [12]. These methods developed in laboratory did have potential as blade SHM tools. But how to apply them to in-situ SHM of WT blades is still challenging. Thus, a reliable in-situ WT blade SHM technique is still expected today.

The paper consists of two parts. In the first part, the state-of-the-art blade SHM techniques are reviewed. The effort will be focused on investigating the in-situ feasibility of the existing laboratory techniques through discussing their pros and cons in in-situ application; in the second part, a newly developed WT blade SHM and damage location technique based on the concept of Transmissibility of Frequency Response Functions (TFRF) will be discussed and commented. Finally, the paper will be concluded with the suggestions to the future research on blade SHM.

2. State-of-the-art WT blade SHM techniques

WT blade SHM is intrinsically for increasing safety, reducing downtime and lowering revenue loss by blade failures. But the significance of its in-situ application is far more than this. For example, defective blades could encounter sudden and catastrophic failure without any indication in advance when experiencing wind gusts. That would cause fatal damage to the whole WT system and neighbouring devices. The material pieces flying away from rotor blades could cause personal injury and damage to other wind farm facilities as well. For this reason, to avoid catastrophic failure a blade SHM technique should be vigilant to the incipient defects occurring in blade structure.

Due to external loads, environment and the peculiarities of blade materials and structures, WT rotor blades can be damaged by various means [12]. The major failure modes include:

- failure of adhesive joints;
- delamination of the load carrying laminates; and
- damage in laminate involving fibre rupture.

To detect these failures, many non-destructive testing techniques have been attempted [13-21]. Their capabilities, pros and cons are reviewed in the following.

2.1 Vibration analysis

Vibration analysis investigates the structural health condition of blades through analysing their dynamic responses that are exhibited when being excited by external forces [15]. Since the dynamic responses of the blades are partially determined by their material and structural properties (e.g. mass, stiffness and damping), any property change due to damage should be detectable from dynamic responses. As the dynamic responses can be characterized by some vibration features and modal parameters, a vibration analysis based blade SHM can be achieved via monitoring the variation tendencies of these vibration features and modal parameters.

Usually, vibration analysis is used for achieving a general assessment of the health condition of blade structures. It can be used for damage location as well if multiple vibration transducers are used in combination. The reason of using multiple vibration transducers is that WT blade is made of fiberglass composite material. The high damping of composite can significantly inhibit the dynamic response. As a consequence, only those transducers that situates near the position of defect can respond correctly to the crack propagation in blade. Thus, damage location requires the collaboration of multiple vibration transducers. So far, such a vibration analysis based blade SHM technique has been tried in the static and fatigue tests of WT blades in laboratory. But its in-situ application to blade SHM is not realistic because it is unlikely to install so many number of vibration transducers on an operating WT blade. For this reason, an alternative vibration analysis based blade SHM method is developed in [17]. Instead of performing blade SHM through the transducers mounted directly on blade, Ref.[17] suggested to accomplish blade SHM via monitoring the vibration of WT main shaft. Defective blades do have potential to change the vibration of main shaft. But it is worthy to note that main shaft vibration can be influenced not only by defective blades. It can be affected by many other factors as well, such as main bearing. For this reason, abnormal main shaft vibration does not necessarily mean the presence of a blade failure. Moreover, the snow and ice that are unevenly built up on three WT blades can alter shaft vibration as well, although they are not damage related. Thus, from this point of view vibration analysis is not a reliable approach to performing blade SHM.

2.2 Strain measurement

Strain gauges, usually made of piezoelectric ceramic materials, are popularly used in commercial tests of full scale WT blades [12]. In the tests, they are attached on blade surface to measure the local strain of blade surface due to bending and stretching loads. So far, strain gauge is the cheapest and also the most reliable approach to detecting and locating the defect on or near the surface of WT blade (e.g. surface cracks and skin delamination). However, it is inefficient in detecting joint failure. Moreover, owing to the reliability issues of piezoelectric ceramic material, strain gauges are rarely used to perform long-term blade SHM missions.

The distributed strain transducer provides an alternative method for measuring the strain along blade span direction. However, the distributed strain transducer needs to be embedded in blade in advance during manufacturing process. Thus, it is not applicable to the SHM of existing blades. Moreover, whether the installation of distributed strain transducer is harmful to the integrity of blade structure is also an issue worthy to concern.

2.3 Bending moment measurement

Bending moment measurement using optical Fibre Bragg Grating (FBG) sensors gives a new hope to develop in-situ blade SHM technique [16]. Up to date, the kind of blade SHM systems have been developed and some of them, for example the Moog Insensys' Blade Load Sensing System [18], have been commercialized and installed on operating WTs for demonstration.

Attributed to optical FBG sensors are immune to the disturbance of eternal environment (e.g. background noise, vibration, temperature, humidity, electromagnetic interference, etc.), they provide a very reliable tool for measuring the bending moment at blade root section. However, at the moment such a technique is still very expensive [9], which limits its extensive application in wind power industry. Moreover, it is worthy to note that bending moment measurement was initially designed for the purpose of load control, not for blade SHM. The bending moment measured from the root section of blade is affected not only by the integrity of blade structure but also by external loads. Moreover, as both factors are difficult to decouple, the reliability of the SHM conclusion drawn from bending moment analysis is questioned. In addition, a minor damage to the blade does not necessarily change the value of bending moment. Therefore, bending moment measurement could be ineffective in detecting incipient defect in blade. Beside this, the bending moment measurement cannot locate damage either.

2.4 Acoustic emission

Acoustic emission is to detect the energy of transitory elastic waves that are generated when crack initiates and propagates within the blade [22]. Different from strain measurement that is only able to detect local change in strain on blade surface, acoustic emission allows a global assessment of the structural integrity of the blade. In other words, one acoustic emission transducer is able to monitor the structural integrity of a part of the blade rather than a local area. But due to the high damping of composite blade material, the energy of the elastic waves due to defect initiation and propagation will decay quickly with distance. Thus, multiple acoustic emission transducers are usually needed when carrying out damage location. In addition, it is found that both changes in blade geometry and material interfaces can absorb the energy of elastic waves as well. As a consequence, the defect resultant elastic waves can be detected from blade surface only when the acoustic emission transducers are placed at 'right positions', which are close to the position of defect and moreover there is not material interface on the pathways from the defect to the transducers. However, in reality these 'right positions' are very difficult to be found. In addition to acoustic emission signals are often seriously polluted by noise, the effectiveness and reliability of damage detection by the approach of acoustic emission is an issue worthy to investigate in the future.

2.5 Ultrasonic detection

Ultrasonic detection is a well-established technique for detecting defects in composite and other kind of materials [23]. In the application to WT blade SHM, the ultrasonic signal/image allows both damage detection and damage location. For example, it allows to inspect the laminate for dry glass fibres and de-lamination under blade surface. Moreover, ultrasonic detection is less affected by external environment (e.g. background temperature, vibration, noise, etc.). Thus, it can be said that ultrasonic detection provides an effective and reliable tool for blade SHM. Attributed to these merits, ultrasonic blade SHM techniques are being commercialized today. Moreover, the prototype system has been successfully applied to the indoor examination of full scale WT blade [24]. Nonetheless, the successful implementation of ultrasonic detection needs the aid of liquid couplant, which has low attenuation thus can enhance the detecting capability of the ultrasonic transducers. As it is difficult to apply liquid couplant to a rotating blade, the in-situ application of ultrasonic detection techniques is limited.

2.6 Infrared thermography

Infrared thermography is used to measure the temperature distribution on structure surface. Since the defect occurring in structure will change the continuity of the structure thus temperature distribution, it can be readily detected and located from the thermography image. Such a principle is equally applicable to blade SHM [25].

Attributed to intuitive detection results and effectiveness in detecting subsurface defects, infrared thermography has been widely applied to the condition monitoring of a wide range of machines and structures, such as bearings, gear boxes, power electronic convertors, motors, generators, etc. It is also successfully used to detect the subsurface defects occurring in WT blades [25]. As infrared thermography carried out the full-field measurement of blade, it enables efficient SHM of WT blade in laboratory. However, infrared thermography detection results are prone to be influenced by environmental temperature. That will challenge incipient defect detection in WT blade SHM practice, because the temperature change resulted by an incipient defect would be small and thus fully hided by high environmental temperature.

Apart from the aforementioned non-destructive testing techniques, there are many other techniques also show potential as WT blade SHM methods, such as X-rays, Laser Doppler vibrometer, electrical resistance-based damage detection and so on [12, 19, 21]. But considering they are not popular methods, they will not be discussed any more in order to keep a concise context of the paper.

From the above discussion, it can be summarized that a successful blade SHM technique should satisfy at least three basic conditions, i.e.

- alert to minor damage
- reliable to assess damage
- capable to locate damage

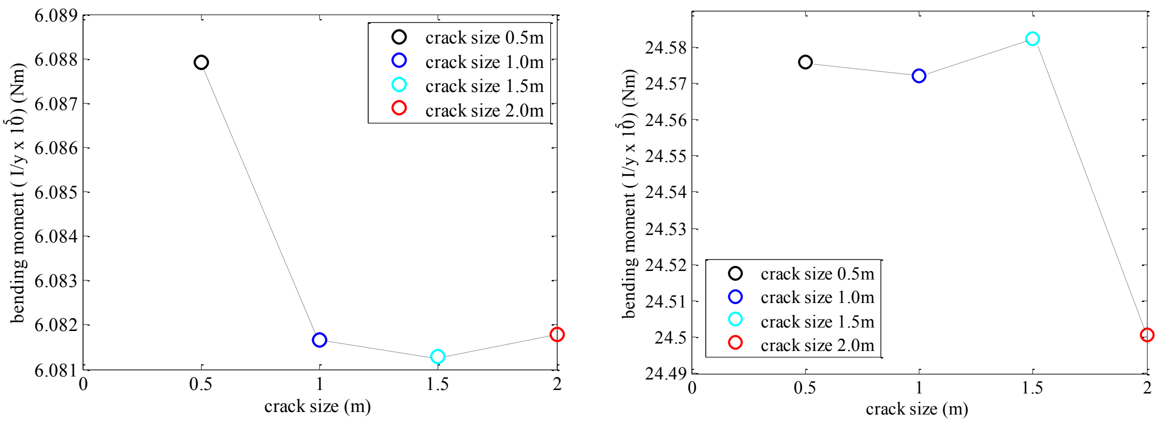
The aforementioned non-destructive testing techniques do promote blade SHM. However, none of them has fully satisfied these three conditions, which motivates the further research on blade SHM.

3. Blade SHM using Transmissibility of Frequency Response Function (TFRF)

3.1 Reason for developing a TFRF-based blade SHM technique

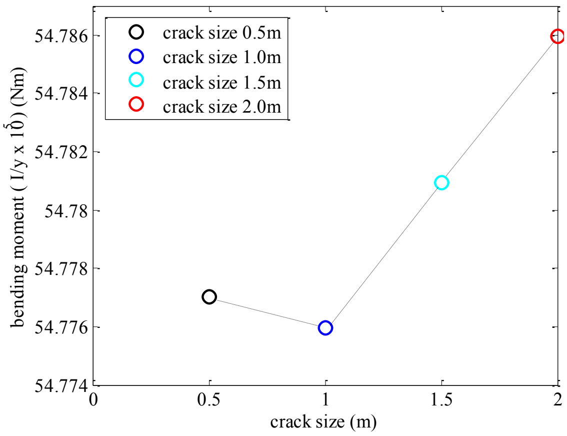
Considering external loads have significant influence on blade SHM result, their effects are investigated below. Assume a 80 m long WT blade that is subjected to different wind loads, a lateral surface crack is present at the position 26 m away from blade root. When wind speed is 5, 10 and 15 m/s, respectively, and the crack is 0.5, 1, 1.5 and 2 m long, the calculated bending moment at the root section of the blade is shown in Fig.1 [26].

From Fig.1, it is found that despite the health condition of the blade, the calculated bending moment does give a right response to the variation of wind load, i.e. the higher wind speed the larger the bending moment tends to be. This enables bending moment to be a reliable criterion for load control. However, the bending moment fails to correctly respond to crack size under all three wind load conditions. This example suggests that bending moment is not a reliable indicator of the structural health condition of the blade.



(a) when U =5m/s

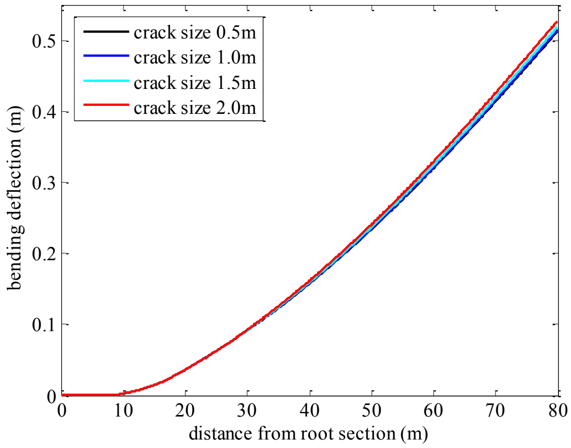
(b) when U =10m/s



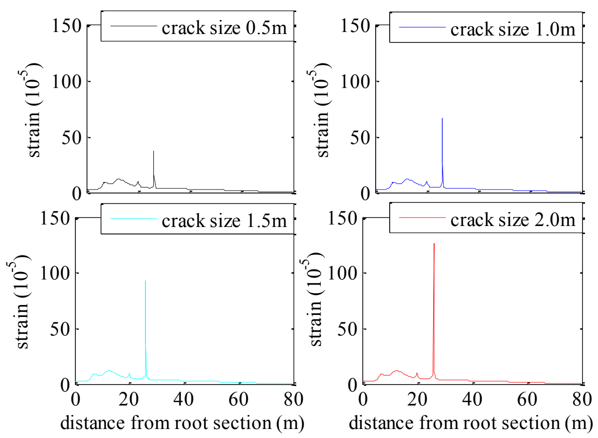
(c) when U =15m/s

Fig.1 Bending moment at the root section of the blade

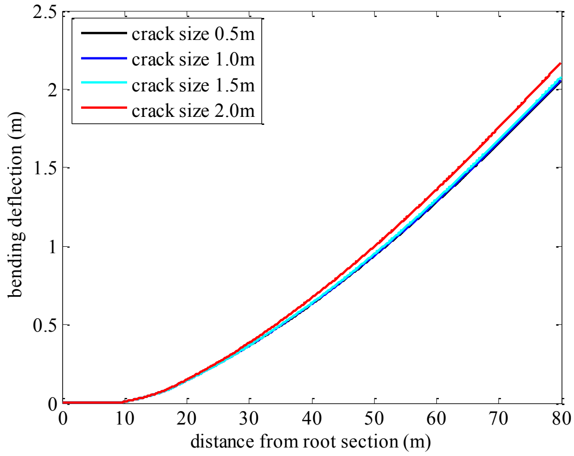
To explore a more reliable blade SHM method, the deflection of the blade and corresponding strain distribution along blade span are investigated. The numerical calculation results are shown in Fig.2.



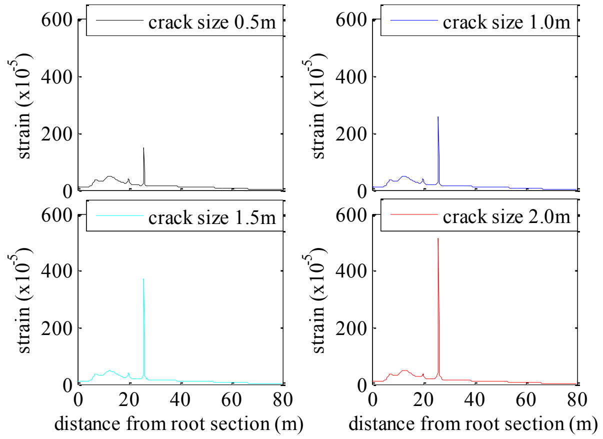
(a) deflection when U =5m/s



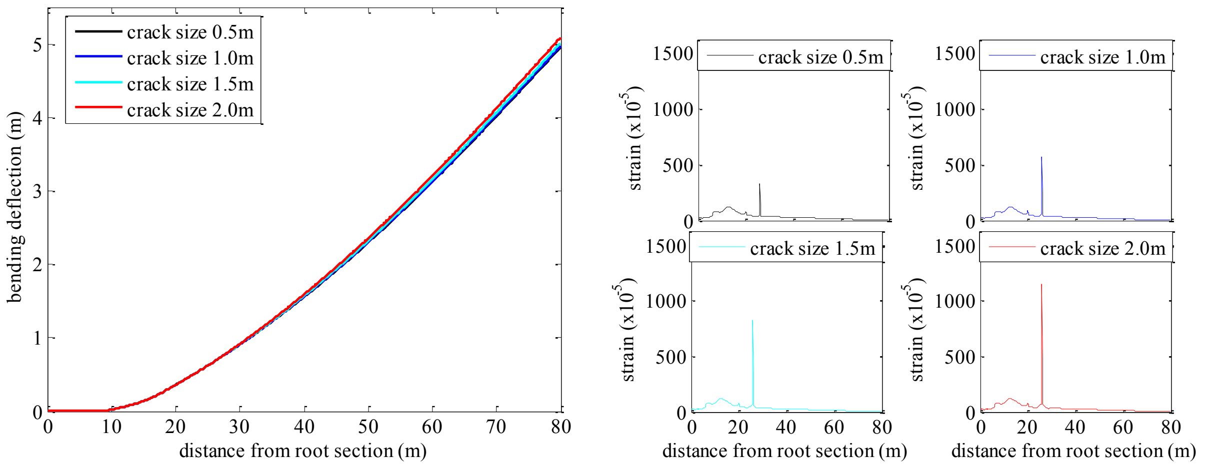
(b) surface strain when U =5m/s



(c) deflection when U =10m/s



(d) surface strain when U =10m/s



(e) deflection when U =15m/s (f) surface strain when U =15m/s

Fig.2 Bending deflection and surface strain

From Figs.2a, 2c and 2e, it is found that both wind load and crack size have influence on blade deflection. However, wind load dominates the deflection, while the influence of crack size is too small to be accepted as a convincing proof for performing blade SHM. Moreover, blade deflection fails to give any indication to location of the crack. By contrast, Figs.2(b), (d) and (f) suggest that in spite of wind loads, not only crack size but also its location is indicated by surface strain. Apparently, surface strain is a more effective indicator of the health condition of the WT blade. However, in real life it is unrealistic to map over the entire blade surface with transducers to measure the strain distribution. Hence, a TFRF-based blade SHM technique, which was inspired by the concept of transmissibility [27], was developed in [28].

3.2 The TFRF-based blade SHM technique

The TFRF-based blade SHM technique was developed in order to detect and locate the damage to blade in a more effective and reliable way [28]. Assume three blade sections S_{i-1}, S_i and S_{i+1} respectively with masses m_{i-1}, m_i and m_{i+1}, see Fig.3. Where, the sections S_{i-1} and S_i are connected via stiffness $k_{i-1,i}$ and damping $c_{i-1,i}$, and the sections S_i and S_{i+1} are connected via stiffness $k_{i,i+1}$ and damping $c_{i,i+1}$.

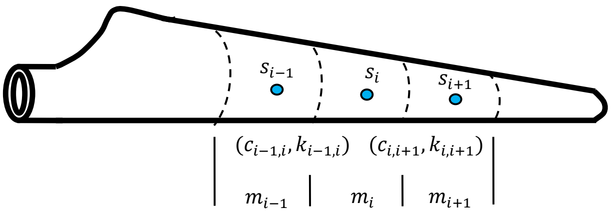


Fig.3 Three neighbouring sections of the blade

It can be inferred that when a defect occurs in section S_i, both $(c_{i-1,i}, c_{i,i+1})$ and $(k_{i-1,i}, k_{i,i+1})$ will respond correspondingly, whilst the damping and stiffness connecting other blade sections will not respond. This inspires the TFRF-based blade SHM technique. Since structural damping and stiffness rely on structural integrity, the TFRF-based blade SHM is intrinsically immune to the influences of external factors, such as wind loads, snow/ice on blade surface, etc. Therefore, the TFRF-based blade SHM is reliable in the sense of theory.

Assume $x_i(t)$ and $x_k(t)$ $(t = t_0, t_1, \ldots, t_{N-1})$ are the blade response data measured from two neighbouring sensors when an external exciting force $f(t)$ is applied to the blade. The frequency spectra of $f(t)$, $x_i(t)$ and $x_k(t)$ are

$$\begin{cases} \mathcal{F}_f(j\omega) = \sum_{n=0}^{N-1} f(t_n) e^{-jn\omega/f_s} \\ \mathcal{F}_{x_i}(j\omega) = \sum_{n=0}^{N-1} x_i(t_n) e^{-jn\omega/f_s} \\ \mathcal{F}_{x_k}(j\omega) = \sum_{n=0}^{N-1} x_k(t_n) e^{-jn\omega/f_s} \end{cases} \tag{1}$$

where f_s refers to data sampling frequency, N is the total number of data included in data series $f(t)$, $x_i(t)$ and $x_k(t)$.

Assume the Frequency Response Functions (FRFs) of the i-th and k-th blade sections are $R_{x_i}(j\omega)$ and $R_{x_k}(j\omega)$, the following relationships exist at frequency ω_r.

$$\begin{cases} \mathcal{F}_{x_i}(j\omega_r) = R_{x_i}(j\omega_r)\mathcal{F}_f(j\omega_r) \\ \mathcal{F}_{x_k}(j\omega_r) = R_{x_k}(j\omega_r)\mathcal{F}_f(j\omega_r) \end{cases} \tag{2}$$

Then, the transmissibility of the FRFs at frequency ω_r can be described as

$$T_{i,k}(j\omega_r) = \frac{R_{x_i}(j\omega_r)}{R_{x_k}(j\omega_r)} = \frac{\mathcal{F}_{x_i}(j\omega_r)/\mathcal{F}_f(j\omega_r)}{\mathcal{F}_{x_k}(j\omega_r)/\mathcal{F}_f(j\omega_r)} = \frac{\mathcal{F}_{x_i}(j\omega_r)}{\mathcal{F}_{x_k}(j\omega_r)} \tag{3}$$

which shows that $T_{i,k}(j\omega_r)$ can be estimated directly from $\mathcal{F}_{x_i}(j\omega_r)$ and $\mathcal{F}_{x_k}(j\omega_r)$. In practice, multiple times of tests are often performed to minimize the negative effects of measurement errors, i.e.

$$T_{i,k}(j\omega_r) = \frac{1}{M}\sum_{m=1}^{M} T_{i,k}^m(j\omega_r) = \frac{1}{M}\sum_{m=1}^{M}\left(\frac{\mathcal{F}_{x_i}^m(j\omega_r)}{\mathcal{F}_{x_k}^m(j\omega_r)}\right) \tag{4}$$

where, the superscript $m = 1,2,\ldots,M$ indicates the number of tests.

Use the transmissibility of the FRFs obtained when the blade has perfect structural integrity as a benchmark, then a blade SHM criterion $C_{i,k}$ can be defined as

$$C_{i,k} = \frac{1}{N}\sum_{r=1}^{N}\left[T_{i,k}(j\omega_r) - T_{i,k}^*(j\omega_r)\right] \tag{5}$$

where $T^*_{i,k}(j\omega_r)$ refers to the transmissibility of the FRFs obtained when the blade is perfect in structural integrity.

From the above equations, it can be inferred that:

- The criterion $C_{i,k}$ is less affected by environmental factors. Thus, it has potential as a reliable indicator of the structural health condition of WT blades;
- The growth of the defect can be indicated by the increasing tendency of $C_{i,k}$;
- As the transmissibility of the FRFs reflects the correlation of the structural and material properties of neighbouring sections, the increase of both $C_{a,b}$ and $C_{b,c}$ suggests that a defect is present at the position near sensor ‘b’. So, the TFRF-based blade SHM technique possesses attractive damage location function. Moreover, more accurate damage location can be done through comparing the values of $C_{a,b}$ and $C_{b,c}$.

All these merits have been experimentally demonstrated in [28]. Fig.4 shows a blade in fatigue test. Where, 9 FBG sensors and 6 accelerometers were installed along blade span to monitor the blade. In the test, cracks initiated and propagated near sensors FBG5 and ACC3. The corresponding SHM results are shown in Fig.5.

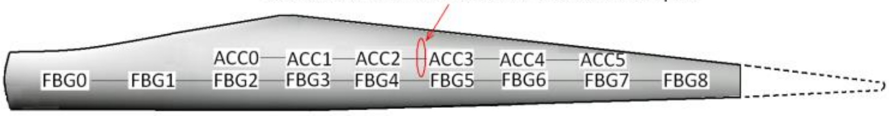
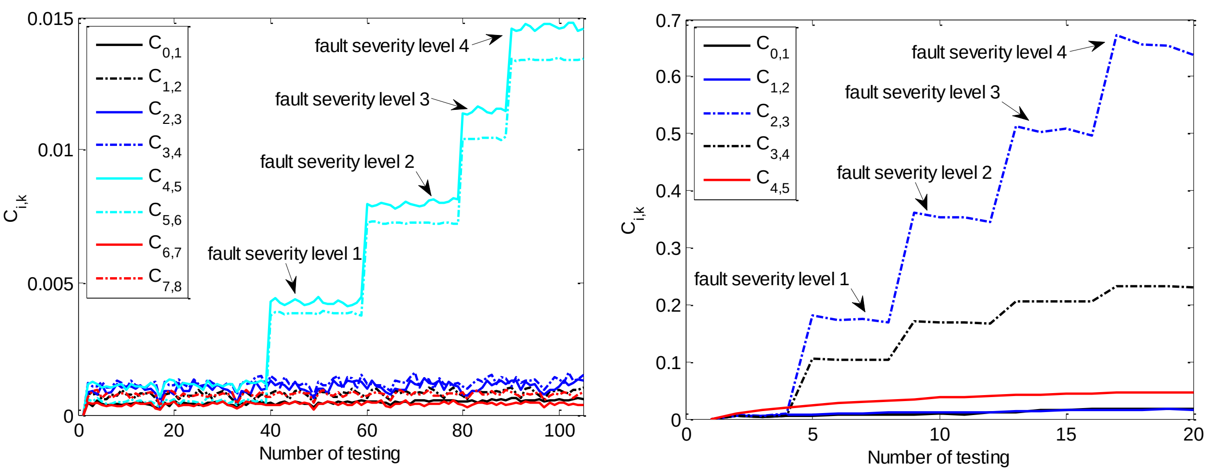


Fig.4 Blade used for fatigue test



(a) results from FBG strain gauges (b) results from accelerometers

Fig.5 Blade SHM results

From Fig.5, it is found that the cracks can be readily detected by observing the variation tendency of the SHM criterion and moreover they can be accurately located by comparing the results of $C_{4,5}$ and $C_{5,6}$ in Fig.5a and $C_{2,3}$ and $C_{3,4}$ in Fig.5b. In the meantime, Fig.5 also proves that the TFRF-based blade SHM technique can work very well whatever the types of transducers are used for data acquisition.

Despite the aforementioned merits, the successful implementation of the TFRF-based blade SHM technique still relies on the responses of the blade along its span direction. So far, fibre-optic distributed strain sensor [29] and high resolution stereo imaging camera are two potential solutions, although further verification is still required in the future. As mentioned in Section 2.2, the distributed sensor needs to be embedded in blade in advance during blade manufacturing process, so it is not applicable to monitoring existing WT blades. But if it can be embedded in future blades, it will be an effective and very reliable tool for performing WT blade SHM attributed to its robust performance against environmental disturbances. By contrast, stereo imaging camera can be used to monitor operating blades if it can be installed at the top of WT nacelle. The sampling rate of the stereo imaging camera can be over 125 frames per second (i.e. >125 Hz), which is much higher than sampling frequency 20 Hz that is usually adopted for strain measurement in commercial tests of WT blades [12]. But it is worthy to note that the practical application of the stereo imaging camera could be affected by weather conditions. Thus, associated protection measures should be developed synchronously. With respect to capital cost, the present market price for a fibre-optic distributed strain sensor and data acquisition hardware system is about £100,000. A high resolution stereo imaging camera could cost approximate £40,000, depending on quality. Therefore, the costs of both techniques are affordable compared to the in total capital cost of a Mega-watt scale WT and the finance benefit attributed to the application of them.

4. Concluding remarks

Based on the discussions depicted above, the following comments are given:

- Survey has shown that blade causes more troubles than WT gearbox and generator. To date, condition monitoring of WT gearbox and generator has been fully researched. A reliable blade SHM technique has not been achieved today. Thus, more effort is still required to develop reliable blade SHM techniques to ensure the safe operation of blades and lower the downtime and revenue loss due to their failures;

- Both vibration analysis and acoustic emission are well-established techniques. They are applicable to perform the general assessment and damage location of WT blade. However, their reliability is prone to be affected by external factors (e.g. external varying loads, background noise, vibration, etc.). How to improve their reliability is an issue needs to deal with in the future;
- Strain gauges have been popularly used in laboratory tests of WT blades to detect and locate the damage occurring near blade surface. However, they are unable to detect those defects that are far from blade surface (e.g. joint failures). In addition, its in-situ application is limited owing to the reliability issues of piezoelectric material and impossibility of mapping over the entire blade surface with strain transducers for strain measurement. The distributed strain transducer gives a glimmer of hope to address this issue, but needs further demonstration;
- Ultrasonic detection is a reliable blade SHM technique, which has been successfully applied to the laboratory examination of WT blades. However, its in-situ application is constrained by its expensive hardware system and inconvenience of using liquid couplant;
- The application of infrared thermography to blade SHM has been successfully demonstrated in laboratory. However, its in-situ application is still limited because an incipient defect in composite WT blade is unable to change the temperature significantly;
- The newly developed TFRF-based blade SHM technique is reliable in both damage detection and location. It is a promising blade SHM technique if it can be successfully commercialized in the future. Nonetheless, its successful implementation still relies on the measurement of the dynamic responses along blade span. Distributed strain sensor and high resolution stereo imaging camera are two potential tools for fulfilling the measurement, but need more verification in the future.

Acknowledgment

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