Ultrasonic Guided Wave Based Damage Detection of Engine Composite Fan Blades

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ABSTRACT

Engine composite fan blades are subjected to tremendous centrifugal and aerodynamic forces for long periods of time, resulting in blade cracking and delamination. Ultrasonic guided wave detection technology in structural health inspection technology has the advantages of wide coverage and high detection accuracy, and has a very high potential for application in the health monitoring of blades. However, the variable curvature and material anisotropy of the blade can affect the propagation of the guided wave, which in turn affects the accuracy of damage quantification and localization. In order to mitigate this effect, an ultrasonic guided wave detection method applicable to engine blade structures is proposed in this paper to localize and quantify the damage. The damage likelihood lines were determined based on the ratio of the damage index(DI) of the signals acquired by each pair of sensors, and the damage was localized by the intersection of multiple damage likelihood lines. The size of the damage was assessed as the mean value of the two largest damage factors. This method was validated on a test platform simulating the rotating operating environment of an engine blade, where damage was simulated by bonding a vacuum sealant to the blade. The results show that the proposed method for damage localization and quantification is effective and suitable for damage detection of composite blades.

1. INTRODUCTION

The composite fan blade has become the core technology breakthrough direction for the new generation of aero-engine due to its light weight, high specific strength and excellent fatigue resistance. However, composite blades are prone to internal delamination, fiber fracture, matrix cracking and other damages after long-term

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service, which have no obvious traces on the blade surface and are difficult to be detected by conventional visual or penetration testing [1-3]. Therefore, the development of monitoring technology for composite blades is of great significance to ensure the safe operation of engines and reduce maintenance costs.

The ultrasonic guided wave technology in structural health monitoring technology in composites has the advantages of high monitoring accuracy and wide coverage area, which is extremely advantageous for monitoring the tiny damage inside the composites [4-6]. Since sensors can be permanently embedded in the composite material, this makes the application of this technology on composite blades more promising [7-9]. The composites are fabricated in processes such as layup and prepreg curing for sensor embedding. The embedded sensors are protected by carbon fiber to withstand harsh service environments such as high temperatures, heat and humidity, and salt spray. In addition, the blade is extremely sensitive to the aerodynamic profile and the embedded sensors do not affect the blade surface streamlines [10-12]. In conclusion, the development and application of composite blade damage detection technology based on ultrasonic guided waves is of great significance. However, the current damage detection methods are mostly for regular structures, and there are fewer studies on the detection of composite blades with variable curvature. Moreover, the sensors used in the proposed methods are bonded to the surface of the object to be measured, and these methods have not been validated on blades that have embedded sensors. Therefore, the ultrasonic guided wave detection technology suitable for blades is still to be developed.

For the damage detection of composite blades, an ultrasonic guided wave detection technology is proposed to reduce the influence of variable curvature and thickness structures on the detection results. This method is based on the damage index(DI) calculated from the mutual excitation and reception signals of all sensors, the DI ratio to localize the damage, and the maximum DI to evaluate the damage size. The composite blades embedded with piezoelectric sensors were fabricated and a rotating blade test platform was built and used to validate the feasibility of the method for application on engine blades. The blades were clamped on a rotating test platform and rotated, and the localization and quantification accuracy of the damage detection was tested before and after the rotation.

2. METHODOLOGY

2.1 Damage localization

The DI ratio calculated from the mutual excitation and received signals of each pair of sensors was used to calculate the damage likelihood line, and the intersection of the likelihood lines was used to localize the damage. Where DI is expressed as the difference between the signal under damaged structure and the signal under healthy structure, which is often used to assess the health status of the structure[13]. The DI is as follows:

$$\mathrm{DI} = \frac{\int \left| u_d(t) - u_b(t) \right| dt}{\int u_b(t) dt} \tag{1}$$

where $u_b(t)$ is the baseline signal, and $u_d(t)$ is the damage signal. The main modes of ultrasonic guided waves under low-frequency conditions contain S_0 and A_0 modes, which have different propagation speeds and attenuation characteristics

[14-16]. Therefore, when damage occurs in the structure, each pair of sensors has a different DI of the signal received after excitation of each other. The closer the damage is to the sensor receiving the signal, the larger the DI calculated for the corresponding signal. From this, a point can be solved for on the line connecting each pair of sensors based on the ratio of DI, where a vertical line is made set as the damage likelihood line. When sensor *i* and sensor *j* excite and receive signals from each other, the intersection of the damage likelihood line and the connecting line between the sensors is:

$$(x_{ij}, y_{ij}) = \left((x_i - x_j)\frac{\mathrm{DI}_{ji}}{\mathrm{DI}_{ij} + \mathrm{DI}_{ji}}, (y_i - y_j)\frac{\mathrm{DI}_{ji}}{\mathrm{DI}_{ij} + \mathrm{DI}_{ji}} \right) \tag{2}$$

where DI_{ij} is the damage factor of the path from sensor i to j; x_i and y_i are the sensor coordinates. The sensor coordinates are known and the damage likelihood line can be solved after obtaining the intersection point. Since the damage location is closer to the path with the largest damage coefficient, the damage localization results are compensated for by moving the localization point closer to this path to reduce the localization error. Then the distance moved is:

$$l' = \frac{\sum_{\mathrm{n}=1}^{N} (\mathrm{DI}_{\max} - \mathrm{DI}_{\mathrm{n}})}{(N-1)\cdot \mathrm{DI}_{\max}} \cdot l \tag{3}$$

where N is the number of paths, DI_{n} is the sum of the two damage indexes for each path, $\mathrm{DI}_{\max}$ is the maximum value in DI_{n}, and l is the distance from the localization point to the path with the maximum damage index. Compensation for damage localization is achieved by moving the localization point a distance of l' along the direction normal to the path of maximum DI.

2.2 Damage quantification

The closer the damage is to the link between the sensors when the damage occurs, the greater the DI calculated for the signals received by that pair of sensors. Therefore, the size of the damage is evaluated based on the DI of the sensor path closest to the damage. The rate of change of curvature and thickness of fan blades with small area is very small, and the effect of this structure on the reception of ultrasonic guided wave signals by all sensors can be approximated to be consistent. To further reduce this effect, the damage size was evaluated as the average of the two largest DI, allowing DI to more accurately characterize the damage. The DI value at the time of damage quantification is:

$$\mathrm{DI}_{\mathrm{s}} = \frac{\mathrm{DI}_{\max 1} + \mathrm{DI}_{\max 2}}{2} \tag{4}$$

where $\mathrm{DI}_{\max1}$ is the maximum damage index; $\mathrm{DI}_{\max2}$ is the submaximum damage index. The formula for converting DIs to size of damage is:

$$L = \frac{\mathrm{DI}_{\mathrm{s}}}{\beta} + b \tag{5}$$

where L is the maximum size of the damage; β is the ratio factor; and b is the adjustment factor. This Eq.5 sets the DI_{s} value to vary linearly with damage size. The conversion of DI_{s} to damage size using Eq. 5 has some accuracy when the damage size changes are small. In the case of large changes in damage dimensions, higher order equations have to be chosen to fit this relationship.

2. EXPERIMENTAL SETU

Both the blower fan blade and the engine fan blade are characterized by variable curvature and thickness, which have the same effect on ultrasonic guided wave propagation. Therefore the appearance of blower fan blades was simulated to create composite fan blades for the validation of damage detection methods. The fan blade is made of carbon fiber prepreg, and the fabrication process is vacuum hot pressing method. The sensors for excitation and reception of ultrasonic guided waves are piezoelectric ceramics PZT-5H. All sensors are embedded in the blade and the layout of these sensors in the blade is shown in Figure 1. Damage detection was performed on the rotating test platform shown in Figure 2, which was used to simulate the rotating components of the engine. The leads of the sensors are connected to the ultrasonic guided wave detection system through conductive slip rings to realize guided wave excitation and reception on the composite blades.

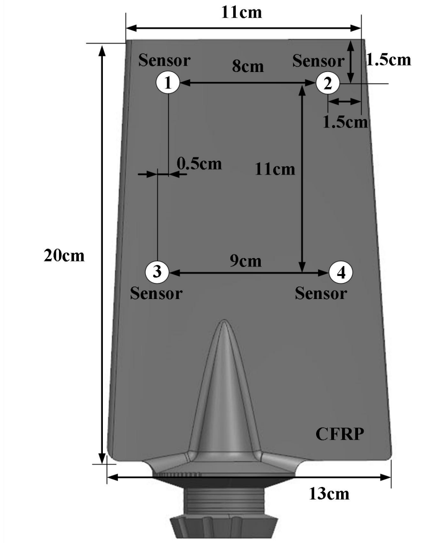

Figure 1. Layout of sensors in the blade.

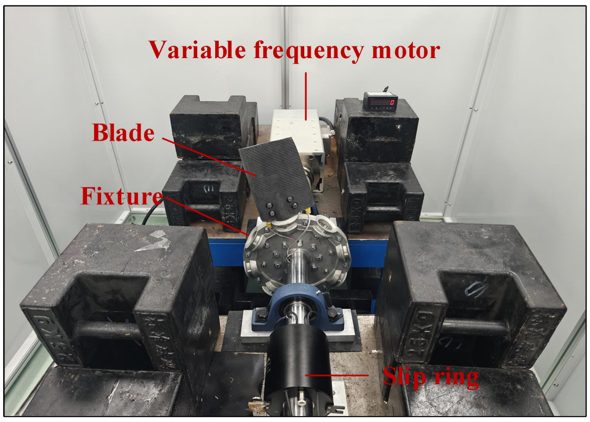

Figure 2. Rotary test platforms.

3 DAMAGE DTECTION EXPERIMENT

3.1 Baseline signal acquisition

Before damage can be detected, the baseline signal is acquired on undamaged blades, which is used to compare the signals when damage occurs. The 4 sensors take turns to individually excite the signals and the other sensors receive the signals, and a total of 12 signals are acquired. To test the repeatability of the baseline signal, the blade speed was increased to 1000 rpm and the rotation was stopped for signal acquisition after the rotation lasted for 10 minutes. The baseline signal excited at sensor 1 and received at sensor 2 is shown in Figure 3. The signal envelope is unchanged after the rotation, and the difference between the signals approximates a smooth line with good signal repeatability. The sensor detection signal embedded in the blade was stable and the use of conductive slip rings has not affected the baseline signal. Therefore, this experimental protocol can be used to simulate the damage detection of engine blades and it is feasible to use this acquisition signal as a baseline signal.

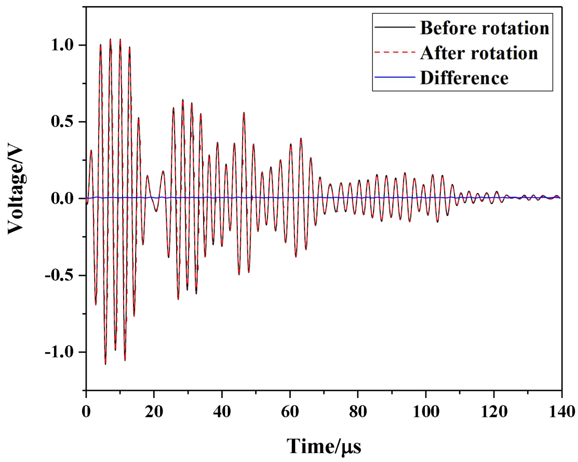

Figure 3. Baseline signal before and after rotation.

3.2 Damage localization

A vacuum sealant is bonded to the blade surface to simulate the damage, which can absorb the ultrasonic guided waves in the structure and cause changes in the guided waves to simulate the damage. This sealant has a top view shape of a square with a side length of 8mm and a thickness of 3mm. Four locations on the blade were selected to bond the sealant to simulate the damage, and it was pasted at the locations shown in Figure 4. The DI was calculated by the method of Section 2.1 and the DI was transformed into a damage likelihood line. Since signals with larger DIs contain more damage information, the intersection of the damage likelihood lines corresponding to the three largest DIs was used to localize the damage. The localization results obtained after further compensating this intersection through Eq. 3 are shown in Table I. The results of the damage localization were in the vicinity of the actual damage location and the maximum error was 10 mm, which demonstrated that the damage localization was effective. The localization method is applicable to composite blades with variable curvature and thickness.

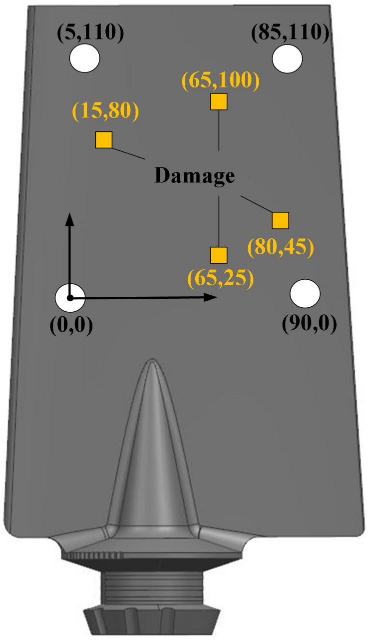

Figure 4. Location of prefabricated damage.

TABLE I. DAMAGE LOCALIZATION RESULTS AND ERRORS

Number	Damage(mm)	Localization(mm)	Error(mm)
1	(15,80)	（18.63，89.25）	9.94
2	(65,100)	（61.57，92.66）	8.10
3	(65,25)	（60.65，34.14）	10.12
4	(80,45)	（70.72，46.56）	9.41

3.3 Damage quantification

The edge length of the vacuum sealant was changed to 10mm and 12mm, and the damage was quantified after it was pasted again on the original prefabricated damage location. The DI_s calculated by Eq. 4 for different damage locations with different damage sizes is shown in Figure 5. The values of DI_s and the fitted parameters are shown in Table II. The quantitative results show that the DI_s rises gradually as the damage size increases, with a similar gradient of change in the DI_s value at each location. The change in the scale factor for a linear fit to the relationship between DI_s and damage size using Eq. 5 floated within 0.0027, which demonstrated a similar linear relationship between damage size and DI_s at multiple locations. Therefore, the structure of variable curvature and thickness has less influence on the results of damage quantification when damage is detected on a small area of composite blades. The damage quantification results consistently demonstrate that the method is effective for quantifying blade damage for variable curvature and thickness.

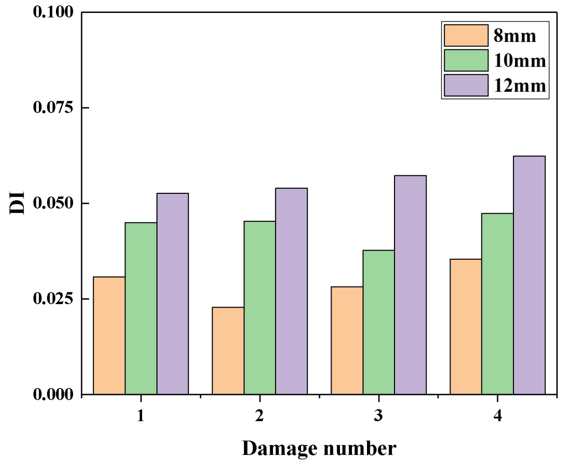

Figure 5. The DI_s for different locations and sizes of damage.

TABLE II. THE DI_s VALUES AND FITTING PARAMETERS

Damage location number	DI_s at 8mm	DI_s at 10mm	DI_s at 12mm	β	b
1	0.0308	0.045	0.0526	0.0056	2.38
2	0.0228	0.0453	0.0540	0.0083	5.10
3	0.0282	0.0377	0.0573	0.0075	4.57
4	0.0354	0.0474	0.0624	0.0068	2.86

4. CONCLUSION

The proposed damage localization methods and quantitative methods for the inspection of composite blades with variable curvature and thickness are effective. The accuracy of damage detection is better on small areas of the blade, while for large areas of the blade detection, the number of sensors needs to be increased. The ultrasonic guided waves attenuate very strongly in composite blades with variable curvature and thickness. When sensor deployment is carried out over a large blade area, attention should be paid to the effective detection distance between sensors.

The proposed detection method is carried out under engine shutdown, and it is still to be explored for damage detection of blades under rotating conditions. In addition, the propagation of ultrasonic guided waves is affected by temperature resulting in changes in the baseline signal. In the future, the ultrasonic guided wave signals under variable speed and variable temperature conditions will be acquired to analyze the changing characteristics of the ultrasonic guided waves. Based on these influence characteristics the corresponding compensation scheme and detection method will be proposed.

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