Rapid Detection of Cracks in Turbine Blades Using Ultrasonic Infrared Thermography

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Abstract. Ultrasonic infrared thermography was used to detect the crack in the turbine blades in this work. In order to explore the effect of couplant on the detection results, three groups of comparative test were carried out respectively by using no couplant, sheet metal and medical adhesive plaster as couplant. On this basis, infrared image sequences and temperature data were analyzed. The results obtained show that couplant is the key factor to the detection efficiency of ultrasonic infrared thermography, and the medical adhesive plaster is a type of better couplant compared to the sheet metal. Additionally, ultrasonic infrared thermography can effectively detect the crack in the blade with the detection time of 1s, which demonstrates that the ultrasonic infrared thermography is very suitable for the situation of rapid detection.

1. Introduction

Blades are the key components in the turbine to realize the energy conversion. During the working process, the blades are subjected to a variety of forces such as static centrifugal stress, bending stress, torsion force and exciting force, and are prone to cracking [1]. Therefore, it is of great significance for improving the safety and reliability of the turbine to detect the crack in the blade accurately and effectively. Many techniques have been applied to detect the crack of blade, among which the most common detection methods are based on penetration inspection [2] and ultrasonic inspection [3]. However, the penetration inspection can only detect the surface opening defects, and the penetrant is toxic and volatile. The ultrasonic inspection has low detection efficiency for complex structures, and the detection results are not intuitive. So it is necessary to explore the effective detection method.

Ultrasonic infrared thermography possesses superior performances such as high-speed, great structural adaptability, large area inspection and intuitional results in detecting the internal defect of object and attracts extensive attention in the world [4-9]. In the 1970s, E. G. Henneke et al [10] found that the defect of the sample may generate the thermal mode when the high frequency vibration excitation was applied to the sample. On this basis, Adams R. D et al [11] proposed the ultrasonic infrared thermography detection method. However, the simulation calculation and experimental verification were difficult to carry out due to the limitations of computer performance and infrared camera capability. Afterwards, with the improvement of computer performance and the measurement accuracy of infrared camera, the research of ultrasonic infrared thermography detection entered a completely new stage. In 2000, L. D. Favro et al [12] detected micro-cracks of aluminum alloy sample using ultrasonic infrared thermography and pointed out its ability to inspect contact interface type of defects with high sensitivity and great speed. In 2007, X. Han et al [13] studied the relationship between the crack surface closed state and the crack heat generation, and explored the detectability of ultrasonic infrared thermography. In 2013, Guo-feng Jin et al [14] used numerical method to study the feasibility of detecting cracks in sample with curvature using ultrasonic infrared thermography. Therefore, ultrasonic infrared thermography can effectively detect the micro-cracks in metal materials and has great complex structure adaptability. At present ultrasonic infrared thermography technology is mostly used for the sample-level inspection. Involving the advantages of the ultrasonic infrared thermography technology, this work tries to use this method to detect of blade with crack.

Firstly, this work analyzes the non-destructive testing principle of ultrasonic infrared thermography and the heat generation law in the internal damage region of component. On this basis, a set of experiments were carried out to detect the crack in the blade by using no couplant, sheet metal and medical adhesive plaster as couplant. Then, the effect of couplant on the test results was analyzed by comparing the experimental results.

2. The detection principle of ultrasonic infrared thermography

Ultrasonic infrared thermography detection system consists of ultrasonic excitation source, infrared camera and computer processing system. Its detection principle and composition can be showed in Figure 1. Ultrasonic infrared thermography is an active detection technology with ultrasonic pulse excitation. The ultrasonic wave enters the detected object through the tip of the ultrasonic probe, and it will produce scattered reflection when encounters discontinuity or interface, while it makes the damage contact interface to generate heat that the particles rub each other due to the viscosity of the propagation medium. The mechanical energy is converted into heat, which is transmitted to the surface of the object in the form of thermal waves, the changeable temperature of the surface of the object will be generated and recorded by the infrared camera. Detection of the defect inside the object can be realized after the infrared image sequences collection and analysis.

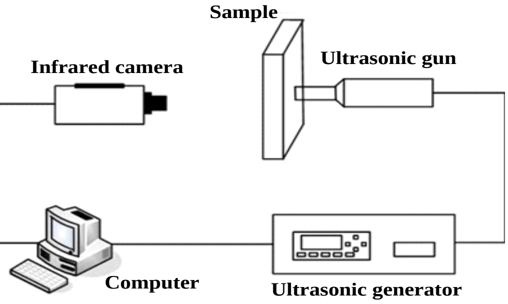


Figure 1. The detection system of the ultrasonic infrared thermography.

It can be seen from the above analysis that the damage contact interfaces are collided during the ultrasonic excitation, where can be regarded as the multiple-degree freedom vibration system. And the ultrasonic mechanical energy is converted into heat. The control equation of forced vibration under ultrasonic stimulation can be described as follow [15]:

$$M\frac{d^2U}{dt^2}+C\frac{dU}{dt}+KU=F+R \tag{1}$$

According to Newton third law and the first law of thermodynamics, it is known that the heat flux density at the damage is:

$$q(t)=\gamma\cdot\left[\mu_{\mathrm{d}}+(\mu_{\mathrm{s}}-\mu_{\mathrm{d}})e^{-\beta|v|}\right]R_{\mathrm{N}}(t)\cdot v_{\mathrm{T}}(t) \tag{2}$$

The meaning of each physical quantity in the above formula is shown in Table 1.

Table 1. The meaning of the physical quantities.

Symbol	Name	Unit
U	Nodal displacement matrix	m

M	Mass matrix	kg
C	Damping matrix	kg/s
K	Stiffness matrix	kg/s^2
F	External load matrix	N
R	Contact force matrix	N
t	Time	s
$R_N\,(t)$	Normal friction	N
$V_T(t)$	Tangential relative speed difference	m/s
γ	Friction heat transfer ratio coefficient	
β	Static and dynamic friction conversion factor	
μ_s	Static friction coefficient	
μ_d	Dynamic friction coefficient	

3. Experimental investigation

3.1. Test Overview

The sample studied in this work is a turbine blade made of alloy steel, as shown in Figure 2.

Figure 2. The turbine blade used in the test.

Experimental ultrasonic infrared thermography detection system, as shown in Figure 3, consists of ultrasonic excitation system, sample fixture, infrared camera and computer processing system. The ultrasonic excitation system is mainly composed of an ultrasonic gun and a test parameter control panel. The infrared image collection equipment is the Vhr680 uncooled infrared camera manufactured by InfraTec. Its temperature measurement range is from -40 to 1200℃ and the image resolution is 320×240.

In the experiment, the ultrasonic excitation power is set to 800w, the amplitude of vibration output is 70%, the pre-tightening force between the ultrasonic gun and the blade is 440N, and the infrared camera acquisition frequency is 50Hz. In addition, in order to explore the effect of couplant on the detection results, three groups of comparative test were carried out respectively by using no couplant, sheet metal and medical adhesive plaster as couplant.

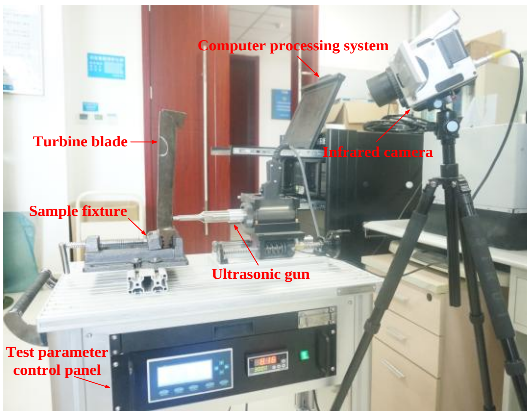
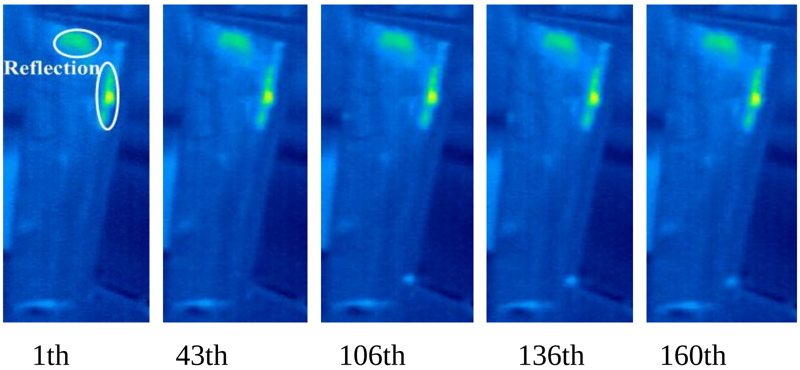


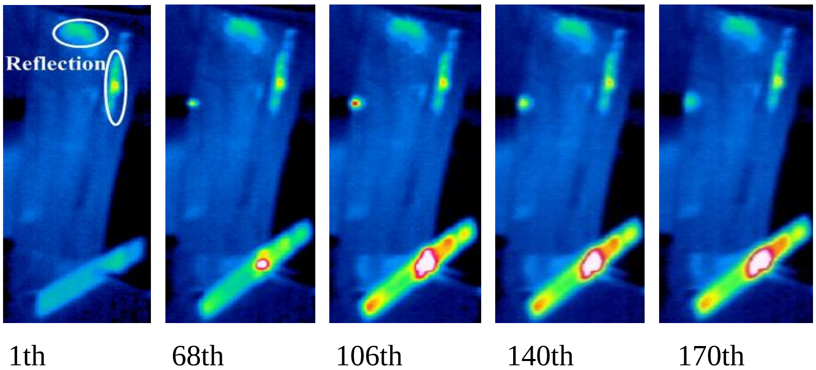
Figure 3. The detection system of the ultrasonic infrared thermography.

3.2. Results and analysis

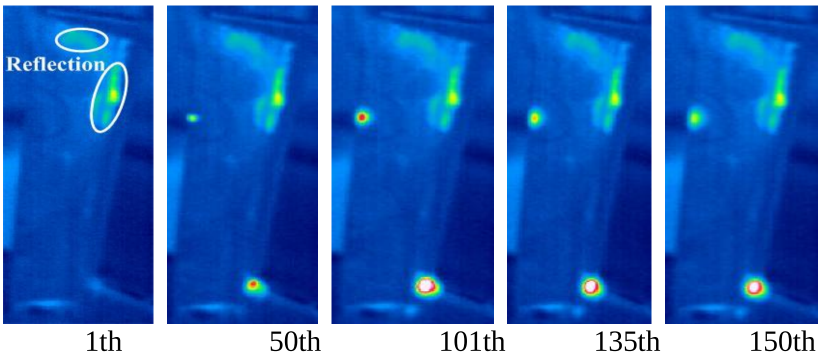
Figure 4 shows the detection results of blade using ultrasonic infrared thermography. The bright spots on the upper and right of blade are all surface reflection, the hot spots on the lower right corner are the excitation position of the ultrasonic gun, and the hot spots on the upper left are the damage region. The results show that there is no hot spot on the surface of the blade without the couplant. When the couplant is used, there are hot spots in the damage region and no hot spot in the non-damage region. Therefore, the couplant is the key factor to the detection efficiency of ultrasonic infrared thermography. Ultrasonic infrared thermography can effectively detect the crack in the blade with the characteristics of selective heating.



(a) Using no couplant



(b) Using sheet metal as couplant



(c) Using medical adhesive plaster as couplant

Figure 4. Detection results of blade using ultrasonic infrared thermography method.

In Figure 4 (a), the ultrasonic wave cannot be effectively injected into the blade, as a result, the damage region cannot be selectively heated. So there is no hot spot in the infrared image sequences collected. Figure 4 (b) and (c) show the detection results by using sheet metal and medical adhesive

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plaster as couplant respectively. After ultrasonic excitation, hot spots appear in the upper left region of the blade, then extend around. It is related to the process of the vibration friction heat generation and heat conduction that hot spots appear from dark to bright and then to dark due to the effect of thermal diffusion. The reason why the hot spots turn from dark to bright is that friction occurs in the damage region due to the ultrasonic vibration and a great deal of heat is produced, leading to temperature rise. The reason why the hot spots turn from bright to dark is that heat dissipation leads to a gradual decrease of temperature during heat conduction process. The bright spots have no obvious change in the excitation process, which are marked in the infrared images, so they are the surface reflection. Comparing Figure 4 (b) and (c), the hot spots are larger and brighter in Figure 4 (c), so the medical adhesive plaster is more effective than the sheet metal.

Additionally, the hot spots in Figure 4 (c) appear in the 50th frame among the infrared image sequences, i.e., the crack in the blade was detected. According to the acquisition frequency of 50Hz in the experiment, it is concluded that ultrasonic infrared thermography can effectively detect the crack of the blade with the detection time of 1s.

3.3 Data processing

To directly analyze the detection results, we use maximum surface temperature difference to weigh the detection effect of ultrasonic infrared thermography in this section.

The surface temperature difference parameters, defined in Eq. (3), were used to investigate the effect of couplant on the detection results. The point P was selected in the damage region of blade and the point Q was selected in the non-damage region, as shown in Figure 5. The temperature data of P and Q were extracted, which represented by T1 and T2 respectively. The temperature difference between damage region and non-damage region is expressed byΔ T:

$$\Delta T = T_1 - T_2 \tag{3}$$

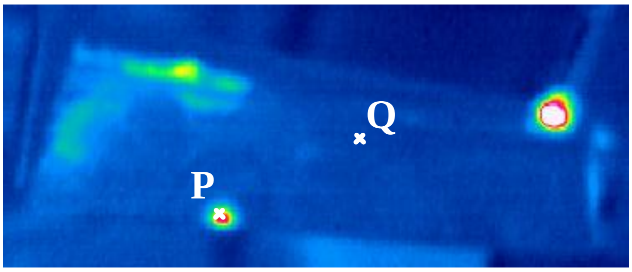
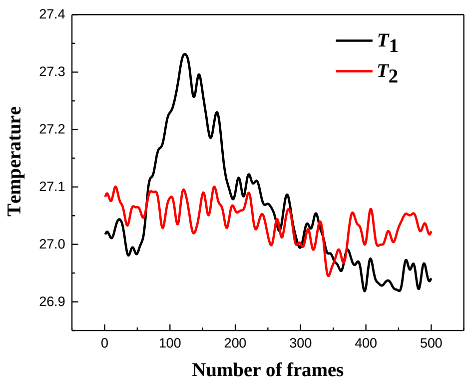
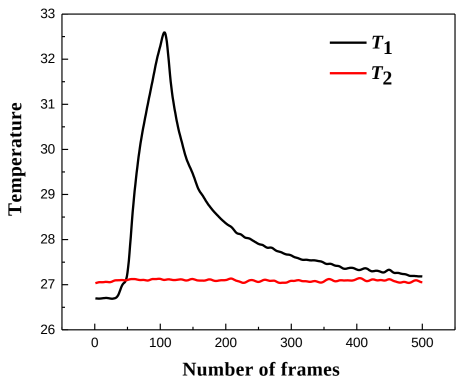


Figure 5. Selection of non-damage region and damage region of blade.

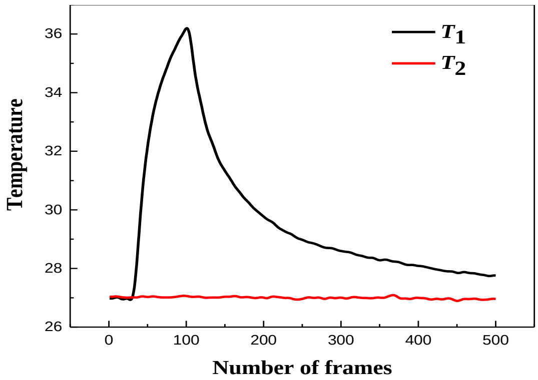
In the three groups of comparative test, the temperature data T1 and T2 were respectively extracted, and the temperature difference Δ T was obtained according to formula (3). The time curvest of T1, T2 and Δ T were drawn, as shown in Figure 6 and 7.



(a) Using no couplant



(b) Using sheet metal as couplant



(c) Using medical adhesive plaster as couplant

Figure 6. Temperature vs. time curve in non-damage region and damage region.

In Figure 6 (a), after ultrasonic excitation, the temperature increased by 0.4℃ in the damage region and it was not obvious, while the temperature fluctuated basically at 27.05℃ without significant increase and decrease in the non-damage region. So there is no hot spot in the corresponding infrared image sequences. This shows that the ultrasonic wave cannot be effectively injected into the blade without couplant. In Figure 6 (b), after ultrasonic excitation, the temperature increased rapidly by 6℃ in the damage region, while the temperature fluctuated basically at about 27℃ without obvious change in the non-damage region. So there are obvious hot spots in the corresponding infrared image sequences. In Figure 6 (c), after ultrasonic excitation, the temperature increased rapidly by 9℃ in the damage region, while the temperature fluctuated basically at about 27℃ without obvious change in the non-damage region. So there are larger and brighter hot spots in the corresponding infrared image sequences.

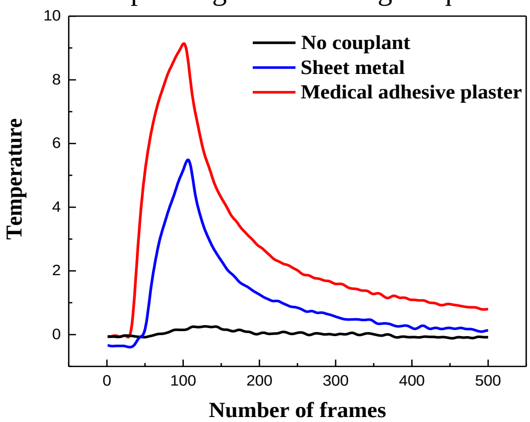


Figure 7. Temperature difference vs. time curve in non-damage region and damage region

It can be seen from Figure 7 that there is almost no temperature difference between the damage region and the non-damage region without couplant. When using sheet metal as couplant, the surface temperature difference reached a maximum of 5.5℃ in the 106th frame. When using medical adhesive plaster as couplant, the surface temperature difference reached a maximum of 9.1℃ in the 101th frame. Therefore, the defects of the blade cannot be detected without couplant and the medical adhesive plaster is a type of better couplant compared to the sheet metal.

4. Conclusion

In this work, ultrasonic infrared thermography was used to detect the crack in the blade, and three groups of comparative test were carried out respectively by using no couplant, sheet metal and medical adhesive plaster as couplant. The results obtained show that couplant is the key factor to the detection efficiency of ultrasonic infrared thermography, and the medical adhesive plaster is a type of better couplant compared to the sheet metal. Moreover, the ultrasonic infrared thermography can effectively detect the crack in the blade with the detection time of 1s, which has instructional significance for the rapid detection of various blades.

Acknowledgments
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