Air-coupled ultrasonic infrared thermography for inspecting impact damages in CFRP composite

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Ultrasonic thermography or thermosonics is proved to be an effective non-destructive testing (NDT) method for inspecting carbon-fiber-reinforced polymer (CFRP) composites; however, the potential damages for the structure cannot be ignored, because of the contact vibration between the ultrasonic horn and the specimen. This work aims at developing a new excitation method for ultrasonic thermography—air-coupled ultrasonic excitation. CFRP laminates with impact damages are tested by air-coupled ultrasonic thermography, and the theoretical model of heat conduction is given. Results demonstrate good excitation performance for impact damages detection in CFRP composites. Moreover, the conventional ultrasonic thermography results are shown, and the prospect of air-coupled ultrasonic thermography is discussed.

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In recent decade, ultrasonic thermography or thermosonics has been proved to be an effective non-destructively test and evaluate (NDT/E) method. It utilizes a pulse of 20–40-kHz ultrasound to cause the defect interfaces to clap or rub, the heating is then observed by an infrared (IR) camera. Subsurface defects become visible with time delays that are determined by diffusion of heat from the defects to surface.

Early studies are more concerned on metal defects detection. Han *et al.* did a good job about the detection for vertical micro metal cracks[1,2] and proposed the acoustic chaos theory in thermosonics[3]. In China, Liao *et al.* applied ultrasonic thermography to detect fatigue cracks in aluminum alloy and did numerical simulation about the heat generation in cracks[4].

Recent years, this technique is gradually applied for composites testing. In Ref. [5], long pulse and low power ultrasound is used to detect impact damage in carbon-fiber-reinforced polymer (CFRP) composites, try to whilst eliminating damage at the exciter attachment point[5]. Dillenz *et al.* used frequency modulated ultrasonic excitation to detect corrosion defects in sandwich structures and impact damages in laminates[6,7]. Han *et al.* used the thermosonics to detect sub-surface fatigue cracks in graphite/epoxy composites, and developed a finite element model for transient heat transfer analysis of the frictional heating in the crack[8].

However, the potential damages for composites can not be ignored. The reason is that ultrasonic horn has to be mechanical in contact with the structure by pressing against the specimen with a relatively large pressure, and the contact high frequency vibration could cause damage to the specimen in some degrees. Another problem is that the signal of defects would be confused by the frictional heating at the excitation location and the movement of the specimen caused by the impacting of

ultrasonic horn, maybe bring difficulties about the thermal signal reconstruction.

In this letter, a new excitation method, air-coupled ultrasonic excitation, for IR thermography is presented. This technique utilized a non-contact ultrasonic excitation (20 kHz) as a heat source, with an IR detector located in the vicinity of the specimen to monitor the surface temperature variation and distribution. CFRP laminates with impact damages are tested by air-coupled ultrasonic thermography, and the approximate theoretical model of heat conduction is given. At present, the power of the ultrasonic energy is relatively low in the following experiment, however, the impact damage in CFRP composite is astonishingly revealed in the thermal images. Moreover, the conventional ultrasonic thermography results are shown, and the prospect of air-coupled ultrasonic thermography is discussed. It is shown that air-coupled ultrasonic excitation thermography provided a potential technique for NDT/E.

The principle and experimental setup of air-coupled ultrasonic thermography is shown in Fig. 1, a specially
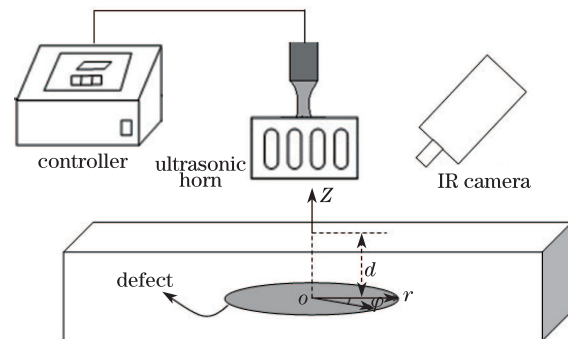

Fig. 1. Sketch map of air-coupled ultrasonic thermography.

manufactured ultrasonic horn connected with a piezoelectric transducer is used as a heat generator. Typically, the ultrasonic horn is positioned at a certain distance (Integral multiples of ultrasound half-wavelength in the air) from the sample so that the coupling of ultrasound to the sample can be enhanced. If the distance from the ultrasonic horn to the sample is changed, the signal of defects may be varied significantly.

The ultrasound vibration for several seconds caused the interfaces of the defects to clap or rub, the surface temperature rising is delayed by thermal diffusion from subsurface defects. The impact damage defect can be seen as a continuous heat source. The general heat diffusion equation is written as[9−11]

$$\nabla \cdot [\kappa \nabla T(r,t)] - \rho c \frac{\partial T(r,t)}{\partial t} = -f(r,t), \quad (1)$$

where $T(\boldsymbol{r},t)$ (K) is the temperature at position r and time t, $f(\boldsymbol{r},\ t)$ is the heat source function which gives how the heating is applied to a medium, $\kappa[\mathrm{W/(m \cdot K)}]$ is the thermal conductivity, $\rho(\mathrm{kg/m^3})$ is material density, and c (J/kg·K) is specific heat. The ratio of the thermal conductivity to the volumetric heat capacity is defined as the thermal diffusivity $(\mathrm{m^2/s})$:

$$\alpha = \frac{\kappa}{\rho c}. \quad (2)$$

To solve Eq. (1) across the interface between two materials Z=d, two general boundary conditions must be satisfied at all time. They are temperature continuity boundary condition $T1$=$T2$, and energy conservation boundary condition:

$$\frac{\partial T}{\partial z}\big|_{z=d} = 0. \quad (3)$$

The assumption is that the material is isotropic and homogeneous, and a continuous heat source is applied at t=0, z=0, with constant strength q and radius r_0. So the solution for Eq. (1) at r=0, z=d can be given as[12]

$$T(t) = \frac{q/(\pi r_0^2)}{2\rho c} \int_0^t \frac{1}{\sqrt{\pi \alpha(t-t')}} \left[1 - \exp\left(-\frac{r_0^2}{4\alpha(t-t')}\right)\right]$$
$$\cdot \exp\left(-\frac{d^2}{4\alpha(t-t')}\right) \mathrm{d}t'. \quad (4)$$

Figure 2 shows the experimental setup of air-coupled ultrasonic thermography, a specially manufactured ultrasonic horn (23×16×11 (cm)) which is made of aluminum alloys is applied. The underside of the horn must have definitely large size in order to provide uniform vibration amplitude and have an efficient ultrasound coupling. A Branson 2 000aed 20-kHz ultrasonic welding generator is used as the ultraosnic source. In the experiment, distance between the horn and specimen is approximately 8.5 cm. The position of the specimen is not critical, for it can be placed under or beside the horn. Maximum output power of the ultrasonic generator is a few hundreds of watt. The elastic wave is generated by ultrasonic transducer and propagates in the air where mechanical damping is enhanced rapidly. For efficiently coupling

the ultrasound into the sample, the output ultrasound pulse to the gun is continuously excited for a long time typically ranged from one second up to several seconds. The IR camera is CEDIP JadeIII which has a 320×240 focal plane detector with a sensitive wave range of 3.7–4.8 μm and a temperature resolution of 0.02 °C.

Figure 3 shows the photo of CFRP boards with size of 89×55×1.5 (mm). The center of the four CFRP boards are impacted by different energies (2J, 3J, 4J, 5J) to cause different degrees of damages.

Figure 4 shows the thermal images obtained by the same duration (several seconds) of 20-kHz air-coupled ultrasonic excitation. The frame rate of the IR camera is 60 Hz. As shown in Fig. 4, impact damages of different degrees are heated by the air-coupled vibration, and revealed as the bright areas (higher temperature) in the thermal images. It is also found that specimen with higher damage degrees has a larger heating area and a higher signal versus noise level.

Figure 5 shows the temperature versus time curve for the center of the defects, it is found that the specimen with higher impact damage degree has a higher peak temperature rise under the effect of air-coupled ultrasonic vibration.
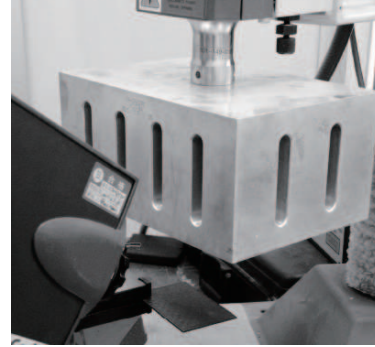

Fig. 2. Experimental setup for air-coupled ultrasonic thermography.

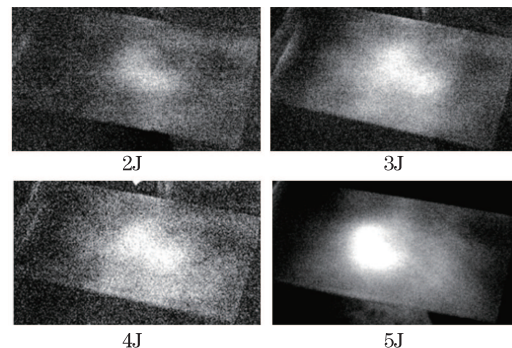Fig. 3. Photo of CFRP boards.

Fig. 4. Results of air-coupled ultrasonic thermography.

As comparison, Fig. 6 shows the results of conventional ultrasonic pulse excitation. The impact damages are revealed by the ultrasonic pulse excitation, but meanwhile a great heating is generated between the contact point of ultrasonic horn and the specimen. Though the signal versus noise is much higher than air-coupled excitation, it may cause new damages on the surface at the excitation point. The results also show that specimen with higher damage degrees has a larger heating area.

The temperature versus time curve for conventional ultrasonic thermography at the center of the defects is also shown in Fig. 7. As compared with Fig. 5, it is found that the peak temperature rise of contact ultrasonic excitation is about several times higher than that of air-coupled ultrasonic excitation.

As the comparison shown, both of the methods can realize the detection of impact damages in CFRP composite, the air-coupled method is non-contact and safety while the conventional method may cause new damage at the excitation point when the ultrasonic vabration is emitted. However, results of conventional method seem to be better than that of air-coupled method, as the signal versus noise of the thermal images and the peak temperature rise are considered. The main reason is that the excitation power is much lower in air-coupled ultrasonic thermography due to inefficiency coupling of ultrasound between the horn and air. Further work should consider improving the power of the ultrasound excitation and optimize the structure of the ultrasonic
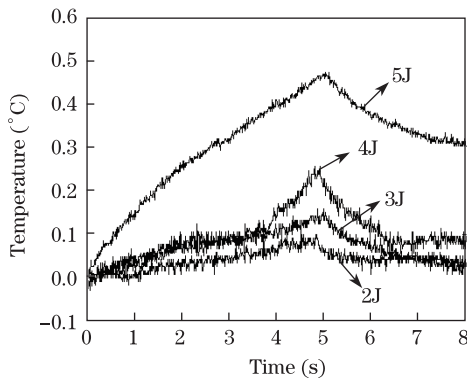

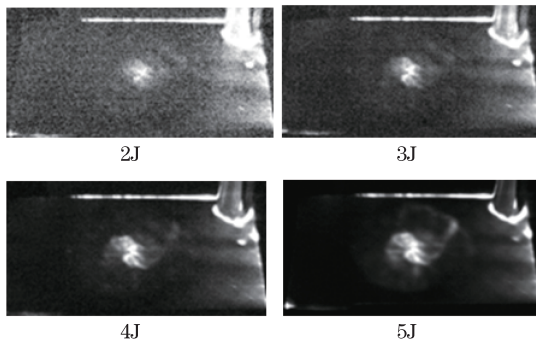Fig. 5. Temperature versus time curve of air coupled ultrasonic thermography.

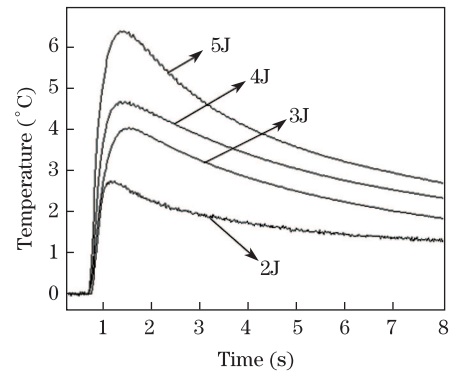Fig. 6. Results of conventional ultrasonic thermography.

Fig. 7. Temperature versus time curve of conventional ultrasonic thermograpghy.

horn. The ultrasound impedance matching between the horn and air should also be considered, maybe add some coupling materials to the end of the horn.

In conclusion, a new NDT method, air-coupled ultrasonic thermography is introduced. Four CFRP laminates with impact damages are tested with the theoretical model of heat conduction described. Results show efficient excitation for impact damage in CFRP. It is found that conventional ultrasonic thermography has a better signal versus noise level and a peak temperature rise, but may cause new damages on the surface at the excitation point. Further work about air-coupled ultrasonic thermography can focus on the structure optimizing of the ultrasonic horn and improving the impedance matching between the horn and air by adding some coupling materials.

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