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Effect of driving frequency on non-linear coupling between ultrasound transducer and target under inspection in Sonic Infrared Imaging

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HIGHLIGHTS

- The nonlinear effect of driving frequency on the Sonic IR imaging system is investigated.
- The 20 kHz transducer are the best among the three individuals: 20 kHz, 30 kHz, 40 kHz.
- The non-linear coupling effect between ultrasound transducer and target is observed.
- The duct tape coupling material is better than leather as coupling material.

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ABSTRACT

Sonic Infrared (IR) Imaging, also referred as vibrothermography, is a novel Nondestructive Evaluation (NDE) technology to find cracks through infrared imaging of vibration-induced crack heating. The vibration source plays an important role in the detection of cracks. In this paper, the effect of driving frequency on the ultrasound vibration to the thermal imaging is presented. The research is organized by using different frequency system and coupling materials on the same aluminum bar sample. The analysis is conducted by combination of the vibration waveforms with the IR images and signals. Correlation analysis between the acoustic energy and the thermal energy in the crack is discussed as well.

1. Introduction

Sonic Infrared (IR) Imaging technology has been demonstrated as a powerful and neat NDE technique [1–5]. It can detect surface and subsurface cracks, delaminations, and disbonds in metallic and composite materials successfully [6–9]. In this technique, the ultrasonic excitation power supply is employed to introduce very short period pulse (less than 1 s) to the test piece which causes relative motion of the defect surfaces, so generating heat by friction; the frictional heating is then detected by a modern infrared camera [10–12]. There are a lot of research on the relationship between heat generation mechanism and the driving frequency [13–15]. Zweschpher et al. [16] used frequency modulated ultrasound to improve the detectability of the cracks. Holland et al. [17,18] reported on the use of different resonant frequency or broadband actuator to increase of the heating of cracks. Previous papers from Han et al. [19–21] showed the nonlinear effect of different coupling materials to Sonic IR imaging techniques by choosing six common coupling materials used in the lab (Duct Tape, Laminated Business Card, Non-Laminated Business Card, Teflon, Gasket Materials, Leather) based on aluminum target sample. The difference of the acoustic transmission coefficient [22] between these coupling materials plays key impact to the nonlinear effect of the coupling. Song and Han [23] also presented succeeded research on different loading force by using only one driving frequency input for Sonic IR imaging system, the nonlinear effect of the loading force was explained. All the previous research did not touch the effect of the individual frequency to the Sonic IR imaging, which makes this research motivated. It will be a very interesting topic for the effect of individual frequency to Sonic IR imaging. As the effect of driving frequency to the Sonic IR imaging plays important role in industry for the crack detectability. In this paper, the research is mainly focused on three common used single frequency system (20 kHz, 30 kHz and 40 kHz) on aluminum (Al) bar sample separately. Due to the limitation of the facility in our lab, only these three individual frequencies are studied. The comparison between these three systems is reported. Quantitative relationship between the

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vibration acoustic energy and thermal energy in the crack with different frequency system are given by using two different coupling materials. The results will provide a comprehensive view and a guide of picking ultrasound transducer frequency for successful detection of cracks with Sonic IR technology.

2. Experimental setup

The experimental setup is shown in Fig. 1. The sample used to conduct all the experiments is an aluminum bar with an edge-through crack. The dimension of the sample is 230 × 40 × 2.4 mm, with the crack length of 10 mm, which is created by MTS machine. The size of crack is made big on purpose, in order to effectively measure the heating generated from the crack through IR camera and the vibration on both sides of the crack. The infrared camera has a focal plane of 640 × 512 pixel array. One end of the Al bar is clamped tightly to a rigid back in post, and the other end is pushed by the transducer also with a rigid backing post.

Two laser Doppler vibrometers (OFV 511) were pointed and focused at two points across the crack to measure the relative vibration of the crack, as shown in Fig. 2. The data acquisition sampling rate was set as 512 kHz for laser vibrometers. A coupling material was always placed between the ultrasound transducer tip and the sample. Three ultrasound sources are utilized in the system, with input frequency as 20 kHz, 30 kHz and 40 kHz. The power capacity of each of them are 750, 800 and 1000 W.

The transducer tip used in each power supply has same diameter of 19.05 mm. For each frequency system, the predefined loading force set as 168 N. The load force is measured from a load cell embedded in the housing fixture of the transducer after calibration as shown in Fig. 1. Such force level was chosen because there is highest temperature increase at crack tip, then the signal level at infrared camera is higher. At that loading force, the experiment is tested twice sequentially without releasing the transducer. Two type of coupling material (Duct Tape and Leather) were used in each Sonic IR experiment. The size of the coupling material typically is 25 × 25 × 0.60 mm. The duct tape is Nashua 357 premium grade duct tape; it has a high tensile strength (800 Kg/m) and is very durable. The Young's modulus of this material is 2000 Mpa, and density is about 1.1 g/cm^3. 2 Layers such tape is folded to make such coupling material (2LayerDT). Leather is cut from a used leather jacket. Its Young's modulus is 80 Mpa, and density is about 0.6 g/cm^3. According to the acoustic impedance theory [24,25], the acoustic transmission efficiency of the 2LayerDT for Al structure target is higher than that of leather. The photos of such materials are shown in Fig. 3.

In each experiment, the input ultrasound pulse length is set the same as 800 ms, the ultrasound transducer was placed at the same spot on the sample with a coupling material in between, and the camera position was also kept the same.

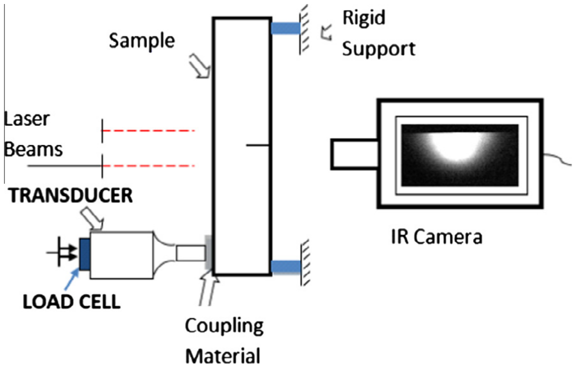


Fig. 1. Schematic drawing of experimental settings.

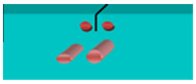
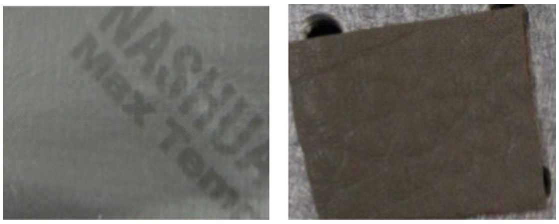


Fig. 2. Closed up view of the laser beam locations.



(a) 2Layer DT (b) Leather

Fig. 3. Coupling materials used in the experiment.

3. Experimental results and discussion

3.1. Quantity index characterization of coupling materials

According to Rayleigh's Theorem [26], the total energy of a vibration system is the integration over the velocity square and the excitation period. This energy can be used as a measurement of acoustic energy. Since the translation motion of the sample does not contribute heating to a defect, the relative velocity is used to calculate the acoustic energy here.

$$E = \int |V(t)|^2 dt$$

where $V(t)$ is relative velocity at time t.

The thermal energy can be calculated by the summation of the changes of IR signal for all the pixels for the duration of the ultrasonic pulse. To reduce the computing time, only regions of interest, for example, localized defect area are computed for the thermal energy.

$$\sum_i \sum_j P(i,j,t) - \sum_i \sum_j B(i,j,t_{0^-})$$

where $P(i,j,t)$ is the pixel value at location (i,j) at time t, and $B(i,j,t_{0^-})$ is the pixel value at same location for the initial background frame at t_{0^-}.

The energy calculated here are all quantitative index value, there is no physical meaning behind them, and so there is no unit for each of them, more details about the characterization and analysis of these quantities were presented in previous paper [27].

According to Plank's Law [28], the electromagnetic radiation emitted by a black body can be related to its definite temperature at thermal equilibrium. By using commercial black body calibrator, the pixel values of images in each frame in the infrared camera are calibrated to its temperature. The relationship between the pixel value and its corresponding temperature was calibrated using following formula. Assuming the room temperature was constant when the experiments were done, then all the pixel value changes in the infrared camera can be related to its corresponding temperature changes captured from point of interests in the camera view. From here, the temperature changes at crack tip via its surrounds can be calculated.

$$T = pixel\,value \times 4.19 \times 10^{-3} (1 \pm 1.35\%)$$

3.2. Acoustic energy on frequency dependence

Figs. 4 and 5 show the results of acoustic energy calculated at one spot of the crack for 2LayerDT and Leather as coupling