



Journal of
**Software
Engineering**

ISSN 1819-4311



Academic
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Design and Implementation of Infrared Thermal Wave Detection System Excited by Power Ultrasonic

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ABSTRACT

On the basis of the study and test of the infrared thermal imager and ultrasonic excitation system at home and abroad, ultrasonic thermal wave detection system was constructed depending on the uncooled focal plane infrared thermal imager and ultrasonic plastic welding machine with high frequency. Through designing reasonable loading device, the ultrasonic gun was realized to incent the structure perpendicular to the measured surface. It ensured that the ultrasonic energy could enter into the measured material effectively. Then the thermal imager was adjusted successfully and was focused in the whole detection surface field through a special transition piece. Industrial aluminum was determined to be used to set up above devices. At the same time, according to the characteristics of ultrasonic thermal wave detection technology, special tools were designed and implemented. Ultimately, experiment was carried out by using the system. The test results show that the controllable performance of the system is good as well as the operation performance which verifies the detection system can satisfy the design requirement.

Key words: Power ultrasonic, infrared thermal wave, detection system design

INTRODUCTION

According to the different thermal excitation, the infrared thermal wave detection technology is mainly including four methods shown as follows: (1) Pulsed Thermography (PT) which uses pulsed flash lamps with high energy to emit visible light wave in milliseconds. This mode of heating has been used widely in many areas due to the advantages of simple structure, fast detection speed and high efficiency. At present, the main works focus on the application and how to improve the detection capability of pulsed thermography technology (Yang *et al.*, 2010, 2011) (2) Swedish AGEMA company (Dillenz *et al.*, 2000). has proposed the Modulation Thermography (MT) detection method (also called "LOCK-IN" imaging technology), using thermal wave changed according to the sine or cosine law. Through the analysis of each point's phase and amplitude for the detected object surface temperature, the existence of defects and the corresponding characteristic parameters can be obtained. The advantages of this method are that the extraction of phase information is irrelevant with the detected object's surface radiation rate and the heating temperature is low, the measurement of the damage depth can be adjusted. But the drawbacks are that heating time is longer, hardware control system and realization of post processing are difficult which is not conducive to realize rapid on-site detection (3) Ultrasonic Thermography (UT). Favro *et al.* (2000) and Han *et al.* (2005) used an ultrasonic wave with low frequency and high energy as the excitation source, causing interfacial friction and slip phenomenon of the defects. Then, ultrasonic

energy is attenuated and transformed into heat energy. So, the existence of the defects can be evaluated according to the temperature change. This method heats the defect region selectively. So, the detection has high sensitivity and is especially suitable for micro-crack detection in the object or structure with irregular shapes (Han *et al.*, 2005), (4) Standing Heat method (ST), the method is mainly applied in reinforced concrete structure and the detection of interior and exterior wall brick for building. The abnormal surface temperature is caused by the change of diurnal temperature which realizes the detection of the internal structure of the building or concrete road. The most representative work was done by Virginia University (Chen *et al.*, 2012). But this method has more interference of external factors, only suitable for materials with poor heat transfer performance and also with long detection time. In addition to the above several detection methods of infrared thermal imaging, some other (Vasudevan, 2004; Safai, 2006; Renshaw *et al.*, 2011) detection methods has been proposed by the use of laser, mechanical vibration, terahertz wave as heat excitation source and also have been achieved for some preliminary applications.

In the above infrared thermal wave detection technologies, ultrasonic excitation based on infrared thermal imaging technology is especially suitable for detection of micro-crack and kissing defects. However, the contact force between ultrasonic transducer and the detected object is difficult to be accurately controlled which may cause the detection results with poor stability and is also difficult to realize quantitative detection. Therefore, this study takes the uncooled thermal imager as the core, constructs a fast and efficient infrared thermal imaging detection system excited by power ultrasonic. The work in this study can improve the system's detection stability and price and provide corresponding technical support for the rapid promotion and application of this technology in other areas.

MATERIALS AND METHODS

Detection principle of ultrasonic infrared thermal wave technique: The detection principle of ultrasonic infrared thermal wave technique is shown in Fig. 1. It can be seen that ultrasonic infrared thermal wave detection system mainly includes three parts: The ultrasonic excitation source (an ultrasonic gun), an infrared imager, computer control and processing system. Among them, the ultrasonic excitation source is used to generate power ultrasonic and transmit it to the detected object to excite damage information. The infrared imager is the core equipment which measures the surface temperature distribution of the detected object. The functions of the computer is to control the ultrasonic excitation source and the infrared imager and to process and analyze the images acquired by the infrared imager. Then, the images contrast is enhanced for realizing the quantitative recognition of damages or defects.

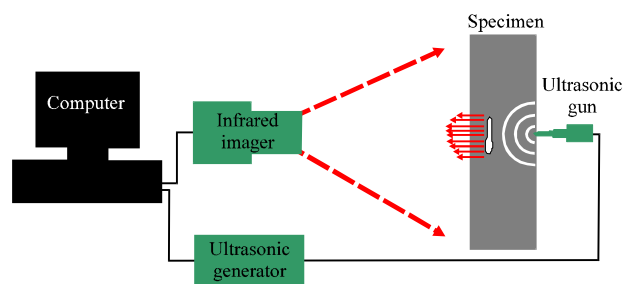


Fig. 1: Detection principle of ultrasonic infrared thermal wave technique

Design goals of the ultrasonic infrared thermal wave detection system: On the basis of theory study, numerical simulation analysis and summarizing the study status of ultrasonic infrared thermal wave at home and abroad, the design targets of ultrasonic infrared thermal wave detection system were determined as follows:

- **Fast speed:** It can detect the surface and shallow fatigue crack, internal delamination and impact damage fast and effectively
- **High reliability:** During detection, it must guarantee the ultrasonic energy can be coupled into the specimen effectively and stimulate the damage interface to produce heat which would not cause new damages
- **Strong adaptability:** It can effectively detect the different materials with different shapes
- **Strong operability:** The system can adjust the position of ultrasonic and the acquisition angle of infrared thermal imaging conveniently according to the different objects and damage characteristics
- **Excellent appearance:** Under the premise of ensuring the normal function, it can install all equipment properly and reduce the system volume

Whole function design of the detection system: Ultrasonic infrared thermal wave detection system mainly consists of three parts: Ultrasonic excitation source, infrared thermal imaging system, computer control and processing system.

There into, infrared imager with high performance, ultrasound thermal excitation device and compute need to be purchased. Layout diagram of the thermal imager and ultrasonic device needs to be designed by ourselves, as well as the special clamp for fastening the detected object. The whole structure design scheme can be seen in Fig. 2.

Design and type selection of ultrasonic thermal excitation device

Performance parameters: Due to the different area application, ultrasonic technology can be divided into two categories. First is the use of ultrasonic to acquire material information which is named so-called testing ultrasonic. At the application, the frequency range from 25 kHz to 10 MHz is always used for different materials. Another use is utilizing ultrasonic to produce power changes that called power ultrasonic, the frequency range is between 20 and 40 kHz. The former is mainly used for nondestructive testing, the latter is always used in ultrasonic cleaning, ultrasonic welding and other occasions. According to the design requirements of the detecting system, the ultrasonic plastic welding equipment at home and abroad is discussed, the main performance parameters were researched: The excitation frequency is $20\text{ kHz} \leq f \leq 40\text{ kHz}$, amplitude is $5\text{ }\mu\text{m} \leq A \leq 20\text{ }\mu\text{m}$ and activation time is $100\text{ msec} \leq t \leq 200\text{ msec}$.

Many domestic companies and foreign companies which manufacture ultrasonic plastic welding equipment were surveyed through comparison of technical parameters and price. The final selection is the type of 2000LPt ultrasonic plastic welding machine manufactured by Branson of USA. It mainly includes a type of HT-480 ultrasonic generator, an ultrasonic gun and a titanium alloy incentive head, as shown in Fig. 3. The device generates the ultrasonic frequency of 40 kHz. It can adjust the percentage of power output through changing the amplitude parameter. The effect of ultrasonic mode includes continuous output and output according to the time which duration time changes from 50 msec to 9.99 sec and the amplitude of the output is from 10-100%.

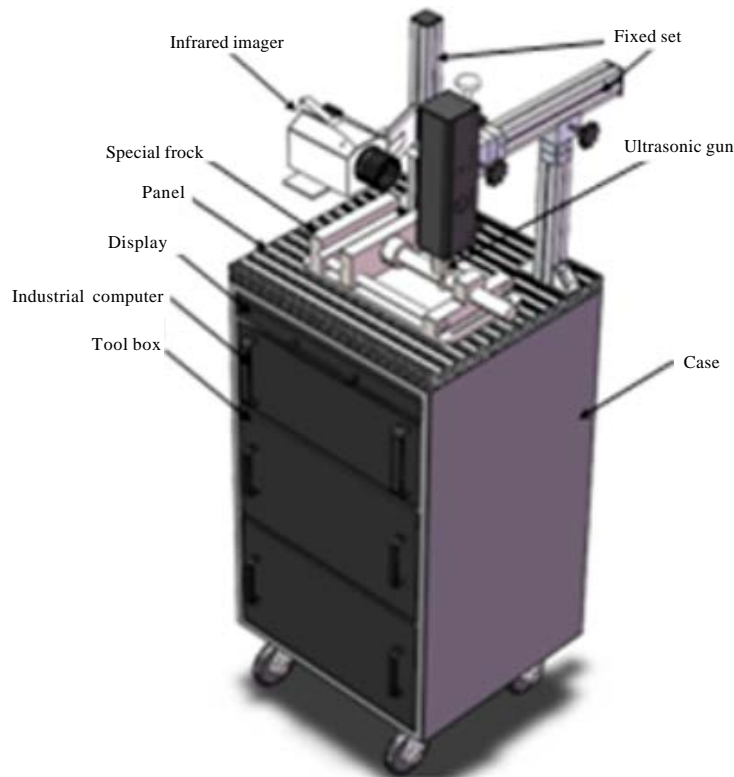


Fig. 2: Configuration appearance for the ultrasonic infrared thermal wave detection system



Fig. 3: Type of 2000 Lpt ultrasonic plastic welding equipment

The performance parameters are shown in Table 1.

Working principles of the equipment: The working principles of ultrasonic plastic welding equipment are shown in Fig. 4.

It can be seen from Fig. 4 that 220 V/50 Hz electrical energy is transformed into 20 kHz energy by ultrasonic generator. Then, electric energy with the frequency of 20 kHz is also transformed into

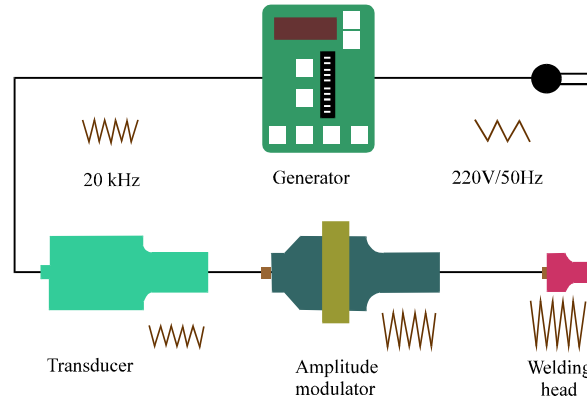


Fig. 4: Working principle of ultrasonic plastic welding equipment

Table 1: Performance parameters of the 2000LPt ultrasonic plastic welding equipment

Parameters	Values
Generator model	2000 LPt 40:0.50:4T
Ultrasonic gun model	HT-480
Frequency	40 kHz
Output power	500 W
Input voltage	200 V~240 V AC/50/60 Hz, 1 ph
Size	229×197×76 mm
Weight	7 kg

ultrasonic mechanical energy with the frequency of 20 kHz by the transducer. Ultrasonic amplitude is adjusted by changing the amplitude modulator and welding head. The transducer is a key element of the whole set of equipment which converses a form of energy to another form. The working principle is shown in Fig. 5.

It is can be seen in Fig. 5 that the current passes through the transducer to generate electromagnetic field. Then the electromagnetic field passes through the piezoelectric piece making it vibrate. Finally, vibration is reaching to the amplitude modulator by the metal head.

Infrared thermal imager: According to the working principle of infrared thermal imager, it mainly includes two kinds of types-cooled and uncooled. Thermal sensitivity of cooled type thermal imager is higher belonging to high-end thermal imager, so the price is more expensive. Therefore, uncooled thermal imagers were mainly investigated in this work, focusing on the following several technical indexes of the thermal sensitivity, frame rate, spatial resolution and whether it has secondary function development, etc.

Several production companies were chosen for investigation. Ultimately, the selection is the type of InfraTec Vhr 680 scientific infrared imager through technical parameters comparison, price comparison and the field test.

Design of the fixing device: The installation position of ultrasonic gun and infrared thermal imager would affect the detection results directly, so the fixing device should be designed to meet the following principles:

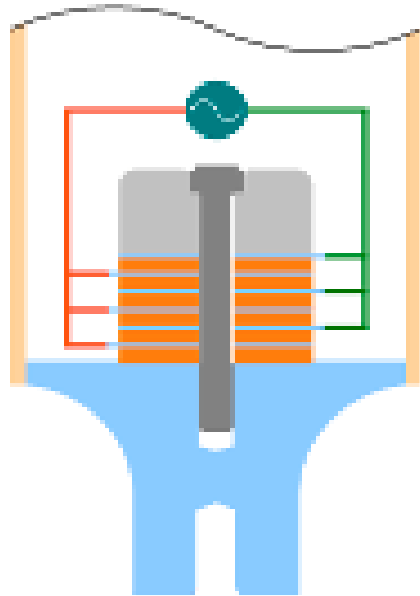


Fig. 5: Working principle of the transducer

- Multi degree of freedom, it can provide convenient conditions for thermal imager to focus and detection of different shapes
- Solid and reliable, to ensure that ultrasonic gun can keep vertical excitation in the detection without displacement
- It is also convenient to be assembled and disassembled. So, the thermography and ultrasonic gun can be removed conveniently, achieving in service detection for large equipment

According to above requirements, the design scheme is shown in Fig. 6.

In Fig. 6, the proposed scheme can achieve ultrasonic gun movement in the direction of x-axis and z-axis. The movement distances are 250 and 300 mm, respectively. In the xoy plane, the rotation angle can reach 180°. Under special circumstances, ultrasonic gun can move in the direction of y axis by adjusting a fixing piece in the base. Ultrasonic gun is fixed on the front of the device. During detection, the relative position of the ultrasonic gun and detected object is fixed by lock handle which makes the vibration direction of the gun head is vertical to the measured surface. Meantime, it also ensures that the ultrasonic gun works in the fixed state. In order to ensure the ultrasonic can be coupled into the object effectively, initial static pressure needs to be forced to the object. It also can be adjusted by the movement of the front-end device driven by the screw.

Infrared thermal imager moves in the direction of z-axis by the beam and the journey distance is 500 mm. It can also be rotated at any angle through the base and movement in the direction of y-axis is realized by adjusting the bottom fixing component.

Industrial aluminum has many excellent properties, such as perfect appearance, no need of welding and handling and carrying conveniently, it also meets the design principle of fixing device and mounting panel and the requirements of the system overall strength and stiffness. Through the comparison of domestic and foreign products price and performance parameters, the final selection is using APS-8-40160 aluminum to build installation panel, APS-8-4040 W aluminum to assemble the fixing device.

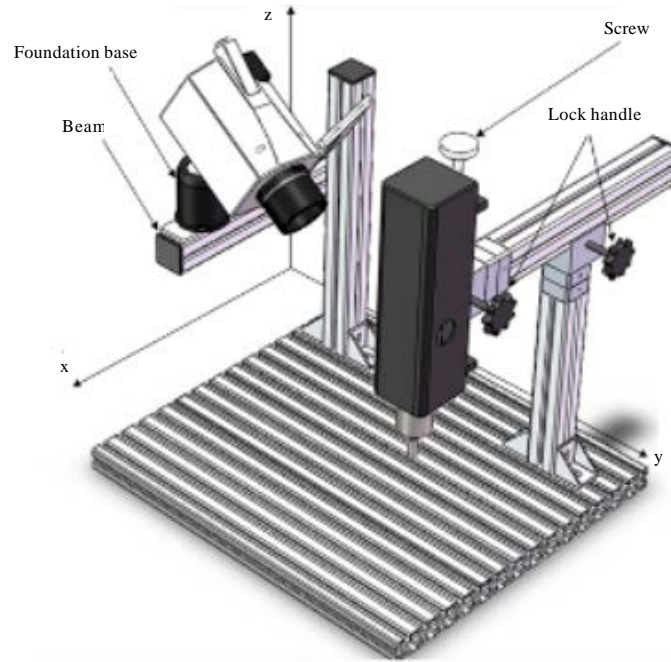


Fig. 6: Schematic diagram of the fixation device

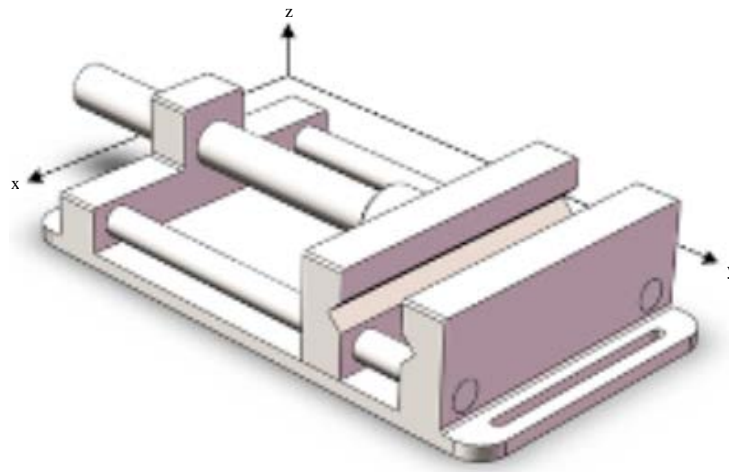


Fig. 7: Schematic diagram of the special frock

Design of the special frock

Design principle: It can be adjusted according to the different shapes of the detected objects. It can reliably fasten the detected object to make sure that the detected object would not move. The design scheme is shown in Fig. 7. It can be seen from Fig. 7 that the special frock only can be moved along the direction of y axis with the distance of 200 mm. A screw is used to control clamping degree of the special frock. Stainless steel material was chosen to manufacture the special frock.

RESULTS

On the basis of hardware system design, selection and production of the main components, combining with the design of the system structure, ultrasonic infrared thermal wave detection system was achieved which is shown in Fig. 8. Infrared thermal imager is connected to an industrial control computer through a 1394 interface card, controlling the acquisition of thermal wave images.

In order to verify the feasibility of the detection system, a specimen of glass fiber composite material was fabricated containing three prefabricated delamination damages. The excitation time is 200 msec, the amplitude of the output is set to 100%. The detection results are shown in Fig. 9.

Three fabricated defects can be seen clearly in Fig. 9. There into, the size of the first defect is the most maximal which is also displayed the most distinctly. But thermal images of the second defect are obviously affected by the environmental radiation (including the operator). The noise disturbs the temperature in evidence. The third defect is the minimum, so the resulting heat flux is also the minimum which made the heat spot fuzzy.

The detection results show that this system can detect the interface defects for the composite materials which can meet the design requirements. For the problem of thermal wave image noises, image processing methods need to be researched deeply, to realize the quantitative identification of defects by ultrasonic thermal wave detection.

DISCUSSION

Infrared thermal wave nondestructive detection system based on ultrasonic excitation was studied in this study. The design target and overall design plan of ultrasonic infrared thermal wave detection system were proposed firstly. According to the three parts of ultrasonic excitation source system, infrared thermal imaging system and computer control and processing system parts, concrete design requirements were also provided around the design goals.

Taking ultrasonic plastic welding gun and uncooled focal plane infrared imager with high accuracy as the core components of the system, the loading device of ultrasonic gun and installing



Fig. 8: Ultrasonic infrared thermal wave detection system

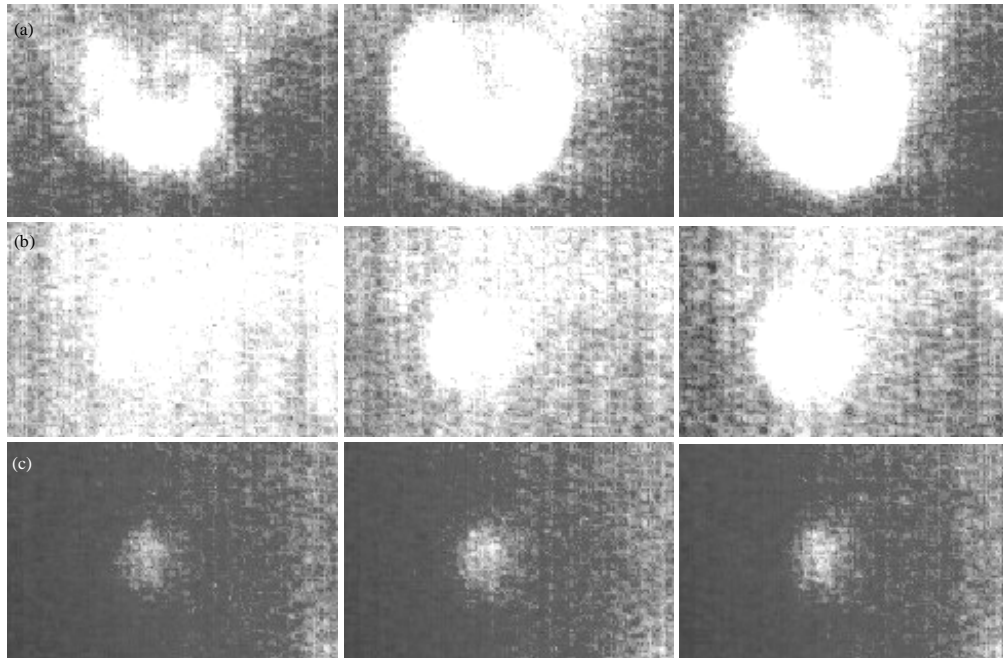


Fig. 9(a-c): Detection results of the glass composites specimen with three prefabricated delamination defects, Thermal wave sequence images of (a) 1 No. damage, (b) 2 No. damage and (c) 3 No. damage

equipment of thermal imager were fabricated. Then, the special frock was also designed and achieved. The system designed in this study has higher cost performance by taking uncooled infrared imager instead of previous cooled infrared imager. The stability and sensitivity of the detection system is also improved which is favorable for this technology to be used in engineering application.

CONCLUSION

At last, the system's overall construction and experimental verification were carried out. On the basis of the above study, the overall debugging and global optimization of the system were realized. A set of ultrasonic infrared nondestructive testing system is established successfully and the system was used to detect the delamination damages in composite specimens. The experimental results show that the system has good controllability, convenient operation and also can achieve the design goals of the detection system.

ACKNOWLEDGMENT

This study is supported by the National Natural Science Foundation of China (Grant No. 51305447, 51275518) and the Natural Science Basic Research Plan in Shaanxi Province of China (Program No. 2013JM7021).

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