

## Air Coupled Acoustic Thermography Inspection Technique

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Vibrothermography or Sonic Thermography is a technology in which acoustic energy is coupled to the structure, typically by means of an acoustic transducer in contact with the part. The conversion of acoustic energy to thermal energy is relatively higher at damage sites. The temperature increase at the surface is detected with an infrared camera. This technology enables detection of defects, such as cracks in metallic structures, which were heretofore undetectable with conventional flash thermography techniques. The scope of this effort is to determine the viability of a new heating technique using a non-contact acoustic excitation source. Because of low coupling between air and the structure, a synchronous detection method is employed. Any difference in the out-of-plane stiffness improves the acoustic coupling efficiency and as a result, defective areas have an increase in temperature relative to the surrounding area. Measurement results indicate that core damage that is difficult to detect in honeycomb sandwich structures with conventional flash thermography, is detectable using air coupled acoustic excitation. A vibrating membrane model is developed and compared with the experimental results.

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# AIR COUPLED ACOUSTIC THERMOGRAPHY (ACAT) INSPECTION TECHNIQUE

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**ABSTRACT.** The scope of this effort is to determine the viability of a new heating technique using a noncontact acoustic excitation source. Because of low coupling between air and the structure, a synchronous detection method is employed. Any reduction in the out of plane stiffness improves the acoustic coupling efficiency and as a result, defective areas have an increase in temperature relative to the surrounding area. Hence a new measurement system, based on air-coupled acoustic energy and synchronous detection is presented. An analytical model of a clamped circular plate is given, experimentally tested, and verified. Repeatability confirms the technique with a measurement uncertainty of +/- 6.2 percent. The range of frequencies used was 800 – 2,000 Hertz. Acoustic excitation and consequent thermal detection of flaws in a helicopter blade is examined and results indicate that air coupled acoustic excitation enables the detection of core damage in sandwich honeycomb structures.

**Keywords:** Thermography, Air Coupled Acoustic Thermography (ACAT), Sonic Thermography

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## INTRODUCTION

New aircraft designs are using more advanced composite sandwich structures [1]. Sandwich structures are typically made by bonding thin composite skins (facings) with a lightweight core in between. These structures are lower in cost, lightweight, repairable and can be molded into complex shapes. Sandwich structures require advanced inspection systems. Of concern is the detection of skin damage, the bond between the skin and core and damage to the core material. Currently ultrasound is an available inspection method for these structures, however this technology requires the use of a gel or water couplant. This inspection technology also requires contact with the structure and therefore curved surfaces are more difficult to inspect. As a result coin tap testing is still commonly used for inspection of sandwich structures because of its simplicity and ability to detect core damage. This technique is highly subjective and does not completely map out the damaged areas. Thermography is an inspection technique that has shown good potential for inspection of honeycomb structures [1].

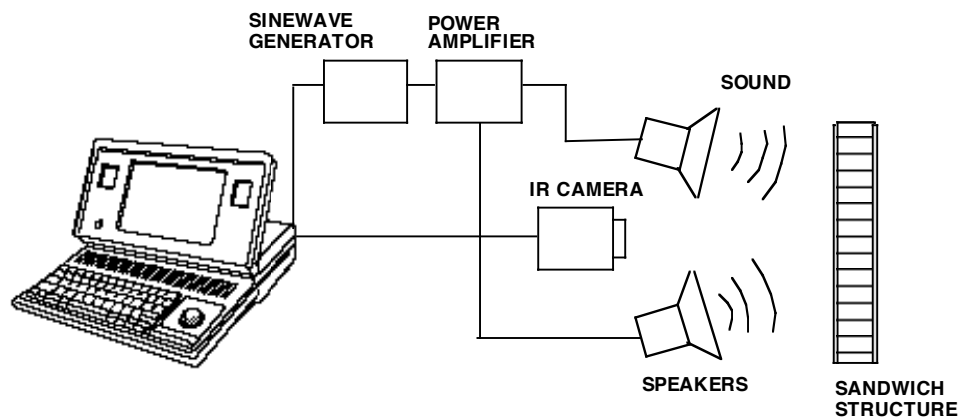
Thermography inspection systems, using flash lamp heating, have the advantage of being noncontact and are able to detect a wide variety of defects which effects the diffusion of heat into the structure. Defects, however such as surface normal cracks, do not significantly alter the heat diffusion and therefore can be difficult to detect. In addition, core damage in sandwich structures is difficult to detect with flash lamp heating methods because heat flow into the core is limited.

Vibrothermography or sonic thermography is able to detect cracks by exciting the structure with large amplitude high frequency elastic waves which causes the crack interfaces to rub and therefore generate heat [2-4]. In this case the defect acts as a heat source. This simplifies defect detection. A disadvantage of this technique is the source has to be mechanically coupled to the structure, and therefore the inspection requires a contact mechanism. Mechanical coupling of the large amplitude ultrasonic vibrations can be a problem because the ultrasonic transducer needs to be mounted securely and ideally the part should be isolated from any holders or fixtures [5]. All these parameters can affect the repeatability of the inspection. Another disadvantage is the potential for damaging the structure at the coupling point [6].

A new flaw detection technique based on an infrared imager and air coupled acoustic excitation using a wide area sound source has been developed. It is demonstrated that areas of damage on honeycomb sandwich structures, not normally detected with conventional flash thermography, are detected with this air coupled acoustic thermography (ACAT) technique. This technique uses large area noncontact coupling of the acoustic sound energy, and hence is capable of wide-area examination. The measured temperature changes are small due to the impedance mismatch between air and composites or metals. The small temperature increases are detected using synchronous detection. A reduction in the out of plane stiffness increases the coupling efficiency of the acoustic energy. Weak areas act like heat sources and thereby allow detection of defective areas. An analytical model of a clamped circular plate is given, experimentally tested, and verified using the ACAT system.

## MEASUREMENT SYSTEM DESCRIPTION

The ACAT system is shown in Figure 1. The system consists of an infrared camera operating in the 3–5 micrometer wavelength band, a computer with image data capture system, and an acoustic source. The acoustic source consists of a function generator, dual channel power amplifier, and an array of four compression horn driver loudspeakers. The loudspeaker array was positioned approximately 11.5 cm from the sample. The thermal detection system consists of a computer connected to the infrared



**FIGURE 1.** Air coupled acoustic thermography (ACAT) inspection system.

camera through a digital image acquisition card. During measurement the computer triggers the function generator, which is synchronized to the image acquisition card. The acquired data are composed of a series of 12 bit resolution digital images (256 x 320) captured at 1/15 of a second. For a typical measurement, 2400 images are acquired and the acoustic source is pulsed at 0.5 Hz for a total of 80 cycles. The acquired data is processed pixel by pixel in the time domain using a fast Fourier transform algorithm to produce magnitude images as a function of frequency. The sound pressure level in the laboratory was measured around 105 dBA 5 feet away from the array. The acoustic frequency was varied from 800 – 2,000 Hz. A maximum in the sound pressure level within this range was used to determine an optimal heating frequency.

## ACAT MODELING EFFORTS

To model the acoustic heating, a sample with a suspended circular aluminum plate was measured. The sample consisted of a 0.32 cm thick 2024 aluminum plate with a 6.4 cm diameter hole. A 0.05 cm thick 2024 aluminum plate was bonded to the thicker plate using an epoxy adhesive thus allowing the thin layer to be suspended with the outer edges bonded to the thicker plate. A drawing and picture of the sample are shown in Figure 2. The normal modes of vibration for a circular plate are well known in the literature [7]. The modes of vibration are obtained from the fourth order wave equation:

$$\nabla^4 z + \frac{3\rho(1-\sigma^2)}{Eh^2} \frac{\partial^2 z}{\partial t^2} = 0 \quad (1)$$

where h is the half thickness, E is the modulus of elasticity,  $\sigma$  is the Poisson's ratio,  $\rho$  is density and z is the out of plane displacement. The solution to the fourth order wave equation describes the modes of vibration. The modes of vibration or characteristic functions are obtained from [7] as:

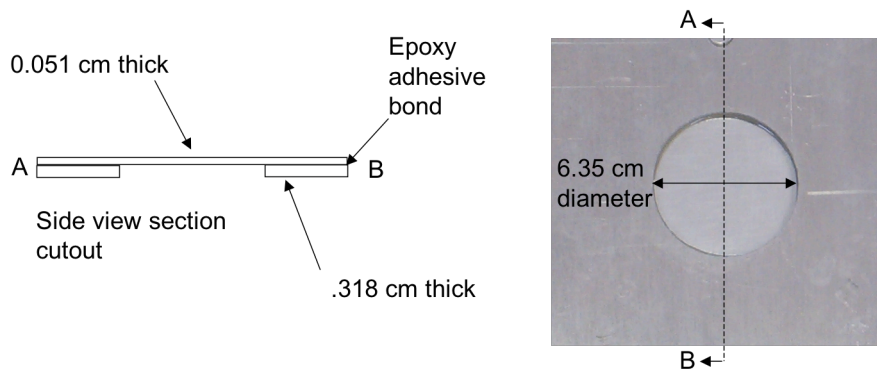
$$\text{Characteristic Functions} = \cos(m\theta) \left[ J_m\left(\frac{\pi\beta_{mn}r}{a}\right) - \frac{J_m(\pi\beta_{mn})}{I_m(\pi\beta_{mn})} I_m\left(\frac{\pi\beta_{mn}r}{a}\right) \right], \text{ where} \quad (2)$$

$\sin(m\theta)$  is used instead of  $\cos(m\theta)$  if  $m > 0$ .

The values of m and n are integers and define the vibration modes,  $J_m$  is the Bessel function of the first kind and  $I_m$  is the modified or hyperbolic Bessel function of the first kind, a is the radius of the circular plate, and  $\beta_{mn}$  is the mode factor. The roots of equation (2) provide the allowed frequencies of vibration and are given as:

$$\text{Frequency} = \frac{\pi h}{2a^2} \sqrt{\frac{E}{3\rho(1-\sigma^2)}} \beta_{nm}^2. \quad (3)$$

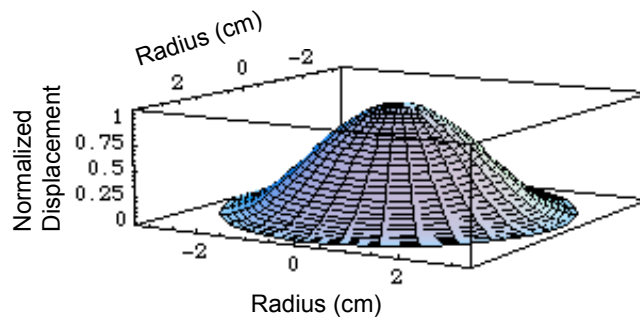
The fundamental mode vibration with  $m = 0$  and  $n = 1$ ,  $a = 0.032$  m,  $h = 0.00025$  m,  $\rho = 2.77 \times 10^3$  kg/m<sup>3</sup>, Poisson's ratio  $\sigma = 0.33$ ,  $\beta_{01} = 1.015$ , and modulus of elasticity  $E = 73.1$  GPa is calculated to be approximately 1,223 Hz using equation (3) for the sample described in Figure 2. The normalized fundamental mode displacement is shown in Figure 3.



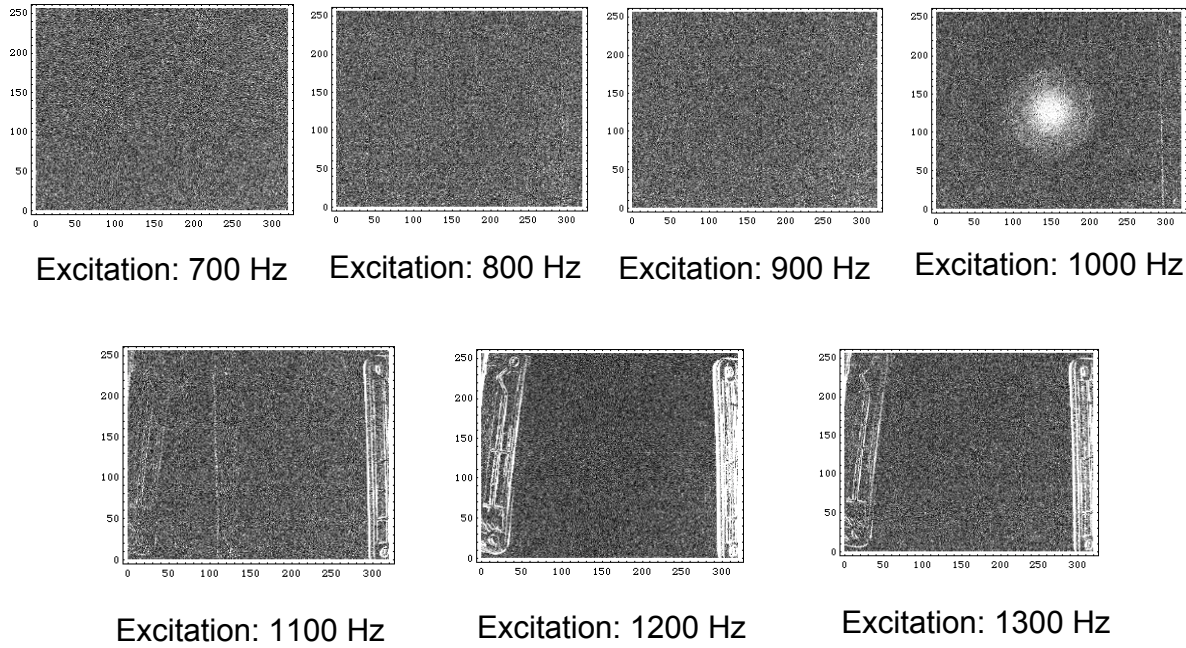
**FIGURE 2.** Drawing and picture of suspended circular plate sample.

## COMPARISON OF MODELING TO MEASUREMENTS

Using the system shown in Figure 1, the aluminum plate sample was tested with the camera frame rate set at 15 Hz. Total number of images acquired was 2400 and the acoustic source was pulsed at 0.5 Hz for a total of 80 cycles. The suspended plate was driven into vibration using a sound pressure level (measured at 5 feet away) of approximately 100 dBA and the frequency was varied from 700 – 1,300 Hz in increments of 100 Hz. The 0.5 Hz magnitude images as a function of frequency are shown in Figure 4. A resonance is detected at 1,000 Hz where significant heating is occurring. This temperature rise is due to the forced vibration from the acoustic source. The most likely mechanism of heating is internal friction. The modeled normalized displacement is compared to the measured temperature using line plots over the defect as shown in Figure 5. Since the plate is bonded at its edges minimal displacement and therefore minimal heating is occurring toward the edges. It is worth noting a halo effect in the 1,000 Hz image in Figure 4. This ring, at the edges where the plate is bonded, is likely due to the epoxy adhesive heating at the circular edge. This would also account for the difference between the model predicted resonance of 1,240 Hz and the actual measured resonance of 1,000 Hz. This difference is due to the adhesive bond, which does not allow for perfectly rigid clamping at the boundary edges assumed in the model. These results verify the heating is due to the displacements caused by the acoustic source.



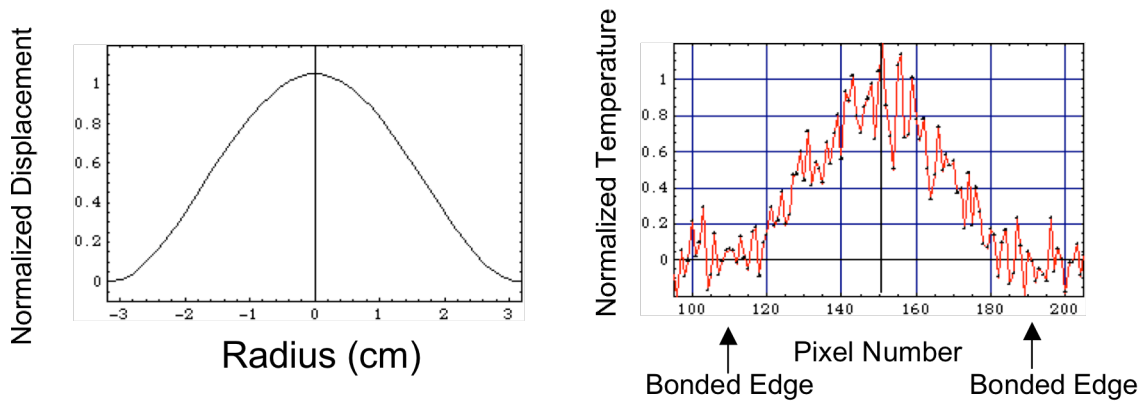
**FIGURE 3.** Fundamental mode vibration  $m = 0$ ,  $n = 1$ .



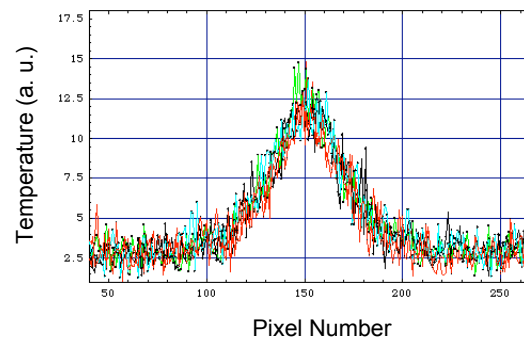
**FIGURE 4.** Resulting 0.5hz magnitude images using air coupled acoustic heating on aluminum plate.

## MEASUREMENT REPEATABILITY

To determine measurement repeatability, the defective area was measured with the same excitation parameters five times. Line plots over the defective area of the aluminum sample are shown in Figure 6. The defect peak value was obtained by averaging 5 x 11 pixels over the defect. The average peak value was measured to be 11.63  $\pm$  .72 for a measurement uncertainty of  $\pm$  6.2 percent. This result indicates good measurement repeatability.



**FIGURE 5.** Comparison of predicted displacement to measured temperature.



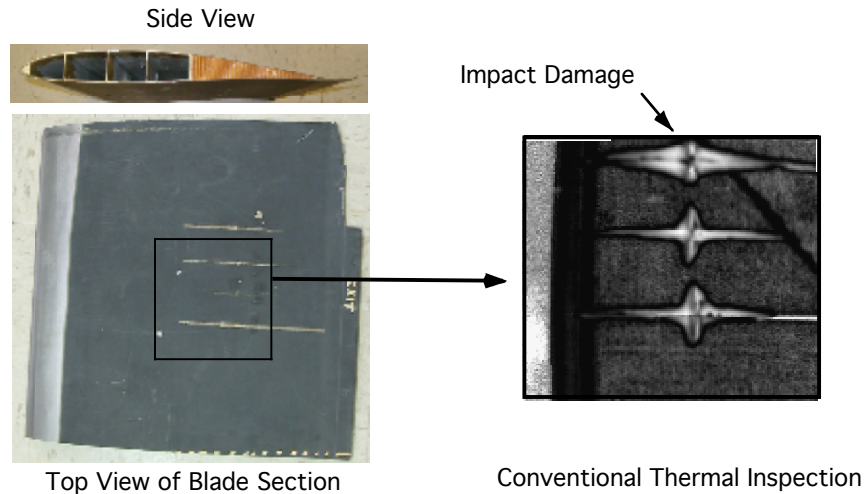
**FIGURE 6.** Line plot over suspended plate showing measurement repeatability.

## APPLICATION ON HONEYCOMB STRUCTURE

The capability of the ACAT system is tested on a sandwich honeycomb structure with ballistic damage and fabricated damage and the results are compared to conventional flash thermography. The sample, shown in Figure 7, is an AH-64 helicopter blade section with ballistic damage to the outer skin and core. The sandwich structure consists of outer layers of fiberglass bonded to a lightweight honeycomb core. Also shown in Figure 7 is a conventional thermal inspection showing three areas with ballistic damage. Delaminations from the ballistic damage show up as light areas.

The sample was inspected with the ACAT system. The acoustic source frequency was 1620 Hz pulsed at 0.5 Hz. The corresponding acoustic thermography magnitude images at 0.00625 Hz and 0.5 Hz are shown in Figure 8. The 0.00625 Hz magnitude image reveals a much larger area of damage between the top two delaminated areas. This damage corresponds to a disbond, between the skin and core, resulting from a ballistic impact on the opposite side that did not penetrate through. This area has reduced out of plane stiffness and therefore sound energy is able to vibrate this area resulting in a significantly higher temperature. Another interesting result is the 0.5 Hz magnitude image of Figure 8 where the image shows hot spots at the ballistic impact locations. This is again due to small delaminations in the outer skin weave cause by the impact event. The broken fiber/matrix allows the acoustic sound to more easily couple and vibrate thus acting as hot spots.

To verify the disbond detected between the skin and core, an edge cut on the blade sample was made along the core between the skin and core as shown in Figure 9. A comparison between conventional thermography and acoustic thermography images is also shown in Figure 9. The cut was made using a razor blade and was 4.4 cm long and penetrated approximately 1.9 cm into the core leaving some core material still attached to the skin. The cut area does not show up in the conventional thermography inspection image but clearly shows up (light area) using the acoustic technique. In addition, along the edge there appears to be additional damage. This small indication corresponds to some damaged core seen visually along the core edge. Using the ACAT system, skin to core disbonds not detectable with conventional thermography, are detected.



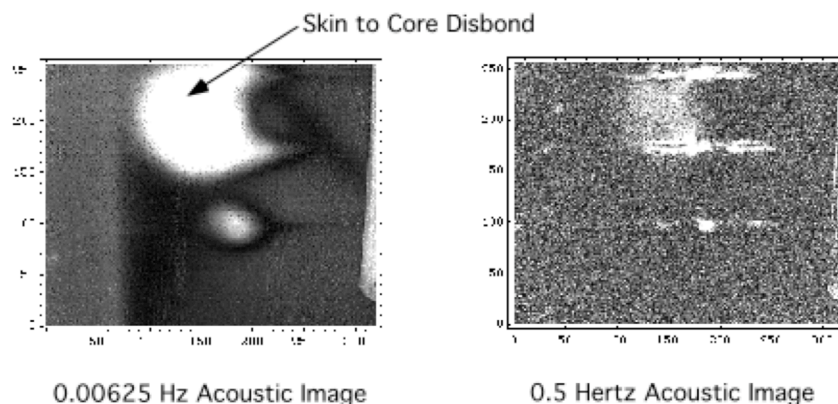
**FIGURE 7.** Helicopter blade sandwich structure with skin/core damage and corresponding flash thermography inspection.

## CONCLUSIONS

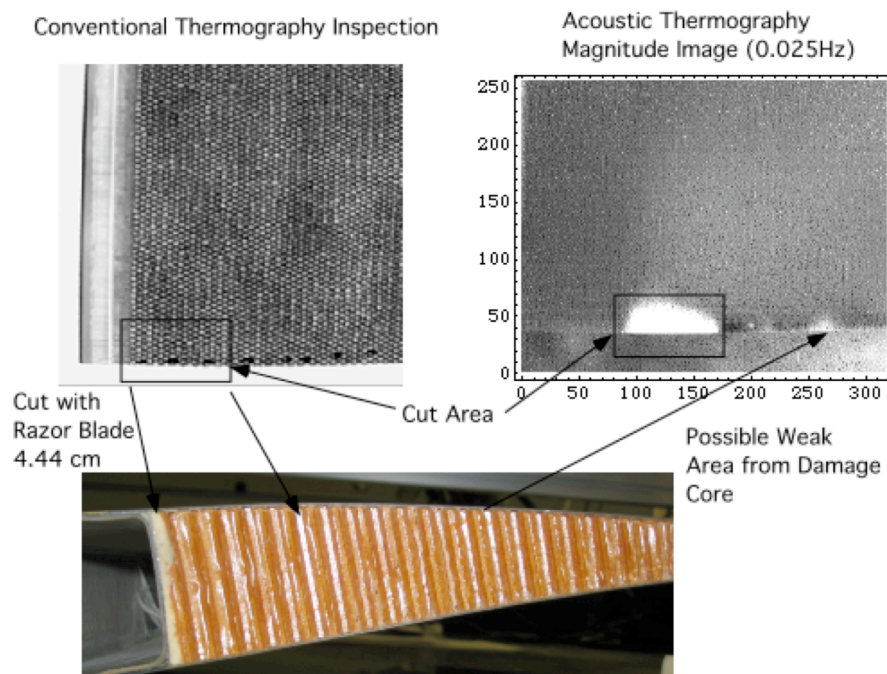
The air coupled acoustic source is a viable heating technique for thermal NDE and has good repeatability. This acousto-thermal technique has application for large area inspection of core damage in composite honeycomb structures. A circular plate model was used to verify the acoustic coupling of the sound energy using the ACAT system. It has been shown that conversion of acoustically induced vibrations into heat can provide good defect detection potential for composite structures. The mechanism of heat generation is likely due to internal friction, however further tests would be required to verify this.

## ACKNOWLEDGEMENTS

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**FIGURE 8.** Acoustic thermography processed magnitude inspection images.



**FIGURE 9.** Side view of blade section with flash thermography and ACAT inspection results on cut core.

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