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Abstract

Low-Power Vibrothermography for Detecting and Quantifying Defects on CFRP Composites †

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Abstract

Detecting and quantifying barely visible impact damage (BVID) in carbon fiber-reinforced polymer (CFRP) materials is a key challenge in maintaining the safety and reliability of composite structures. This study presents the application of low-power vibrothermography to identify and quantify such defects. Using a long-wave infrared (LWIR) camera, thermal data were captured from the CFRP specimens that inhibit BVID. How image processing, specifically principal component analysis (PCA) and sparse principal component analysis (SPCA), can enhance thermal contrast and improve the accuracy of defect size is also explored. By combining low-energy excitation with advanced data analysis, this research aims to develop a more accessible and reliable approach to non-destructive testing (NDT) for composite materials.

Keywords: thermography; low-power vibrothermography; barely visible impact damage; composite; carbon fiber-reinforced polymer

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1. Introduction

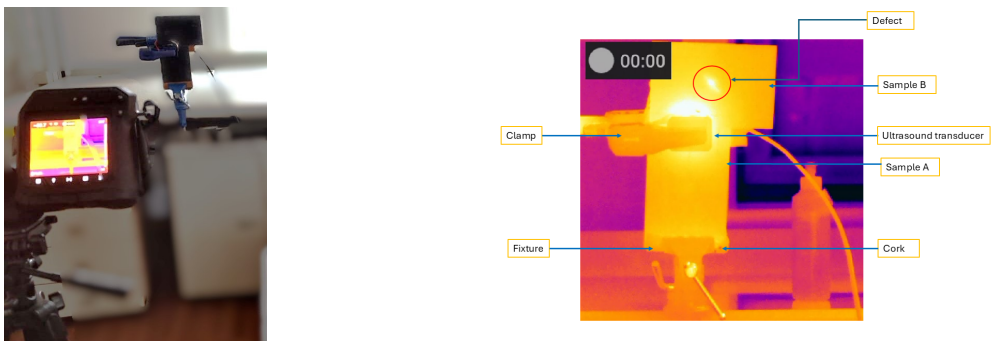
CFRP composites are widely employed in the aviation industry because of their strength, low weight, and corrosion resistance [1,2]. Despite these advantages, CFRPs are vulnerable to damage during the manufacturing process and the service process [3]. One of the most critical and difficult-to-detect types of damage is BVID, which may not leave clear surface markings but can lead to serious structural issues over time [4]. This makes the development of effective and accessible NDT techniques critical for ensuring safety and performance [5]. To monitor the health of CFRP samples and prevent unexpected failures, NDT methods are essential [5]. Among these NDT techniques, infrared thermography has gained popularity due to its non-contact nature, full field coverage, and relatively fast inspection process [6]. Two common types of active thermography are optical thermography, which uses an external heat source like flash lamps, and vibrothermography, which generates heat internally through ultrasonic excitation [7]. While optical thermography, particularly pulsed thermography, has made substantial advances in image processing and defect quantification using the variants of the PCA, low-power vibrothermography has yet

to adopt these tools [8]. A current study using low-power vibrothermography combined with the conventional image processing such as traditional PCA, partial least squares regression (PLSR), and fast Fourier transform (FFT) [9]. SPCA has been shown to enhance defect contrast in pulsed thermography applications, as demonstrated by Yousefi et al. [10], but its application to vibrothermography data, especially in low-power scenarios, remains largely unexamined and is the focus of this study. This preliminary study investigates how low-power vibrothermography, when combined with image processing methods such as PCA and SPCA, can enhance the detection of BVID in CFRP samples. We use two CFRP samples subjected to different impact energy levels and analyze the resulting thermal data captured with the thermal camera. The goal is to evaluate whether post-processing can improve defect visibility in cases where the raw thermal signal alone may not be sufficient, offering a more accessible and effective approach to the NDT of the composite material.

2. Materials and Methods

This study makes use of two CFRP specimens that were previously prepared in the work of Alhammad et al. [11]. These samples were manufactured using unidirectional (UD) IMS-977-2 pre-preg material and consist of 18 plies with fibers aligned along the longer dimension of the panel. Each specimen measures 100 mm × 150 mm, with an average cured thickness of approximately 3.8 mm. BVID was introduced using a 13 mm diameter hemispherical steel impactor at different impact energy levels, following ASTM D7136 guidelines [12]. Although the original study involved a larger batch of samples, this work focuses on two representative samples to explore post-processing techniques in low-power vibrothermography, which are the samples that received 8 joule impact energy (sample A) and the samples that received 12 joule impact energy (sample B). The front surface of each specimen was painted, and the back surface remained unpainted.

The experimental setup was designed to investigate BVID in CFRP specimens using a low-power vibrothermography technique. Mechanical excitation was delivered using a narrowband piezoelectric transducer with a center frequency of 28 kHz. A function generator produced a sinusoidal signal at 30.13 kHz and 20 V peak to peak (Vpp), which was then amplified using a voltage amplifier set to its maximum gain of 20 times. To ensure good transmission of ultrasonic energy into the specimen, a thin layer of couplant (Cytolax ultrasound gel) was applied between the transducer and the CFRP surface. The transducer was held firmly in place using a clamp. The amplifier is rated for a maximum peak output power of 40 watts. Thermal responses were captured using a FLIR T560 LWIR camera, featuring a resolution of 640 × 480 pixels and a frame rate of 30 frames per second. The camera records thermal image sequences before, during, and after excitation. All experiments were performed under stable ambient conditions to minimize environmental thermal noise. Figure 1a shows the setup of the vibrothermography experiment.



(**a**) (**b**)

Figure 1. (**a**) Experimental setup of low-power vibrothermography; (**b**) Raw thermal image at 6 s.

3. Results

Thermal responses from two CFRP specimens, each with a thickness of 3.8 mm and subjected to 8 J (sample A) and 12 J impact energy (sample B), respectively, were recorded using a low-power vibrothermography setup. Figure 1b is the raw image extracted from the video data at 6 s. In this experiment, both CFRP specimens were excited simultaneously using a single piezoelectric transducer. The transducer was positioned so that half of its surface was in contact with sample A (impacted at 8 joules) and the other half with sample B (impacted at 12 joules). This shared setup ensured that both samples received the same excitation conditions, enabling a fair comparison of their thermal responses. Under low-power excitation, sample B, which had experienced the higher impact energy, exhibited a clearly visible thermal signature at the damage site. The defect was detectable directly from the raw thermal frames, suggesting sufficient signal frequency to trigger localized heating through the low-power ultrasonic excitation. For sample A, the thermal response at the impact site was much less pronounced. While there was a slight temperature variation near the expected defect location, the thermal contrast was low, and the defect was not clearly visible in the raw thermal frames. To address this limitation, further image processing was applied to the thermal sequence from sample A using PCA and SPCA.

Figure 2 shows the first five principal components extracted from the thermal sequence by PCA and SPCA. In both methods, principal component 2 (PC2) and principal component 3 (PC3) clearly isolate the impact site. The defect signal is essentially absent or much weaker in principal component 1 (PC1), principal component 4 (PC4), and principal component 5 (PC5). The defect area on PC2 is larger than the defect area on PC3. Moreover, the SPCA PC2 image exhibits noticeably higher contrast at the damage location than the standard PCA PC2, easing visual detection of the BVID.

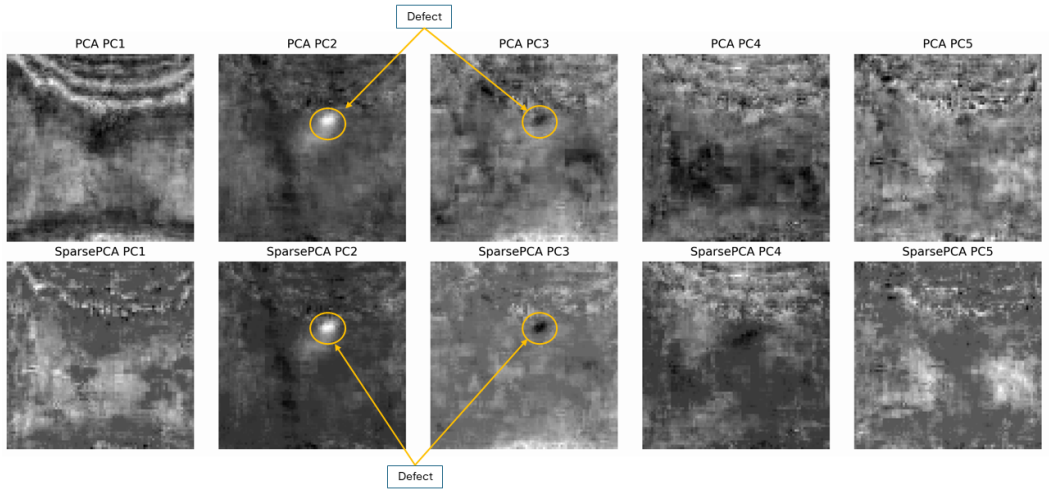


Figure 2. Defect identification on region of interest of sample A using PCA and SPCA (PC1 to PC5).

4. Discussion

In this work, low-power vibrothermography was used to record thermal responses from two CFRP samples impacted at 8J (sample A) and 12J (sample B). The higher-energy sample (12J) showed a clear hot spot in the raw thermal frames, while the lower-energy sample (8J) required further processing to make the defect visible.

For sample A, we applied both standard PCA and SPCA to the sequenced image. In both cases, the second and third principal components (PC2 and PC3) clearly isolated the damage site, whereas the other components contained mostly background variation. PC2, in particular, captured the main defect related signal over a larger area than PC3, indicating it is the most informative component for identifying the BVID.

Comparing PCA and SPCA, we found that SPCA PC2 produces a slightly higher-contrast image of the defect. This improvement possibly comes from the sparsity constraint built into SPCA. The result is an eigen image in which the damage could be seen more distinctly against a background. The main trade-off is that SPCA is more computationally intensive than standard PCA. However, in situations where defect visibility is important, the extra processing time can be worthwhile.

5. Conclusions

In this preliminary study, low-power vibrothermography combined with image processing (PCA and SPCA) was shown to effectively reveal BVID in CFRP specimens. While the 12 J sample exhibited a clear thermal signature in raw frames, the 8 J sample required further enhancement via PCA and SPCA. Both methods isolated the defect in PC2 and PC3, but SPCA PC2 provided a marginally higher contrast, causing the damage to stand out more distinctly against the background.

In future work, we will test additional CFRP specimens across a wider range of impact energies to confirm robustness. We also plan to investigates the other PCA variant, such as robust PCA, to capture the hidden defect in the CFRP material and conduct the area of the defect on the composite material.

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