Enhancing Low-Energy Impact Damage Detection in Carbon Composites Using Sweep-Excited Vibrothermography and Machine Learning

by Sreedhar Unnikrishnakurup[*], Keefe Wee[*], Santhakumar Sampath[*], Andrew Ngo[*,**]

[*] Institute of Materials Research and Engineering (IMRE), Agency for Science, Technology and Research (A*STAR), 2 Fusionopolis Way, Innovis #08-03, Singapore 138634
[**] Corresponding author: ngocya@imre.a-star.edu.sg

Abstract

Vibrothermography (VT) is an effective non-destructive technique for detecting barely visible impact damage (BVID) in composite materials. This study applies sweep-excited VT to carbon fibre-reinforced polymer (CFRP) specimens with low-energy impact damage (5–20 J). Narrowband frequency sweeps across the local defect resonance (LDR) band (45–55 kHz) yielded up to 16 K thermal contrast on the impacted face, outperforming fixed-frequency and broadband excitation. A frequency-activation mapping method links the sweep temporal axis to excitation frequency, enabling physics-informed feature extraction for machine learning-based damage segmentation. Flash thermography provides complementary ground-truth references, and SVD decomposition confirms LDR-driven defect activation independently of excitation frequency knowledge.

1. Introduction

Barely visible impact damage (BVID) in CFRP aerospace structures reduces residual compressive strength without visible surface evidence. Vibrothermography (VT) heats defects via friction at local defect resonance (LDR) frequencies governed by defect geometry [1]. Fixed-frequency VT requires prior knowledge of the LDR; frequency sweep excitation overcomes this by scanning the resonance band [2, 3]. Liu et al. [4] demonstrated enhanced BVID contrast with narrowband sweeps on CFRP. This work extends the approach with frequency-activation mapping for physics-informed ML feature extraction, validated against laser Doppler vibrometer (LDV) measurements across multiple impact energies (5–20 J).

2. Experimental Setup and Methods

Four CFRP quasi-isotropic laminates (0 J, 5 J, 10 J, 20 J drop-weight impact per ASTM D7136) were excited by a PZT wafer transducer bonded to the impacted face (0.7 V_{pp}, 100$\times$ amplified). A FLIR A655sc camera (640$\times$480 px, 50 Hz, NETD $<$ 30 mK) recorded thermal sequences of $\approx$1000 frames in *front-side* (co-located) and *back-side* (through-transmission) configurations. Flash thermography provided ground-truth damage references for ML label generation. An LDV confirmed LDR frequencies at 41–50 kHz for the 10 J and 20 J specimens.

Nine sweep bands from 20 kHz to 75 kHz were tested at 5, 10, and 15 s durations. Thermal contrast $\Delta T(x, y, t) = T(x, y, t) - T_{\mathrm{ref}}(x, y)$ was computed against 175 pre-excitation baseline frames. The temporal axis was remapped to instantaneous excitation frequency via the known linear sweep law, yielding a frequency-activation map $A(x, y, f)$. Per-pixel features — peak amplitude $A_{\max}$, peak frequency f_{peak}, integrated energy — combined with Singular Value Decomposition (SVD) spatial modes form a seven-channel physics-informed feature stack for a U-Net segmentation model.

3. Results and Discussion

3.1 Sweep band comparison and LDR identification

Figure 1 shows peak thermal contrast for all bands on the 20 J back face (5 s). Narrowband sweeps at 45–50 kHz ($\Delta T_{\max} = 4.9$ K) and 50–55 kHz ($\Delta T_{\max} = 4.4$ K) outperform broadband sweeps ($<$1.2 K). The front-side configuration achieves 16.0 K at 50–55 kHz due to direct co-location with the damage. Fixed-frequency 50 kHz back-side contrast (12.5 K) remains the highest single-waveform result, as continuous excitation sustains LDR with 3.0 μm displacement versus 1.9 μm for the sweep. The f_{peak} maps from the 20–50 kHz sweep show a coherent LDR cluster at 41–44 kHz, consistent with LDV measurements across all three durations.

3.2 Flash thermography comparison

Figure 2 shows flash and sweep VT results on the 20 J back face. Flash PPT detects damage at 10 J (SNR = 14.6 dB) and 20 J (SNR = 13.3 dB), providing reliable ground-truth labels for ML training. Sweep VT at 45–50 kHz reveals

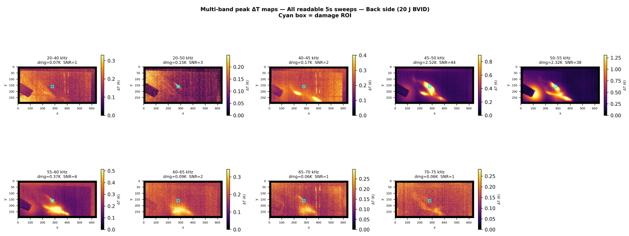

Fig. 1. *Peak ΔT maps for all sweep bands (20 J, back face, 5 s). Narrowband bands at 45–55 kHz produce the highest LDR-driven contrast; broadband and high-frequency bands show minimal activation.*

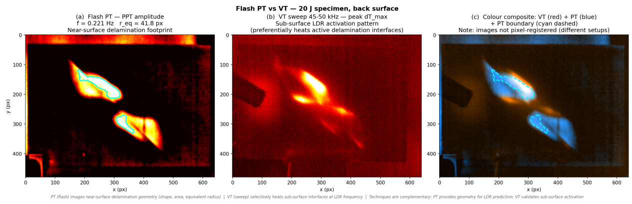

Fig. 2. *Flash thermography and sweep VT (45–50 kHz, 5 s) on the 20 J back face. SVD mode 2 isolates LDR-driven defect heating with a spatially distinct pattern complementary to the flash PPT amplitude image.*

LDR-driven friction heating with a spatially distinct thermal pattern. SVD mode 2 isolates the defect with a temporal peak at 42–44 kHz, providing independent data-driven LDR confirmation for the ML feature stack.

4. Conclusions

Narrowband sweep VT at 45–55 kHz outperforms broadband excitation for BVID detection in CFRP, with front-side measurement yielding the highest contrast (16 K at 20 J). Flash thermography provides reliable ground-truth references (SNR up to 14.6 dB at 10 J) used alongside VT for complementary characterisation. The frequency-activation mapping framework delivers physics-grounded ML features, validated independently by LDV and SVD decomposition. A U-Net segmentation model trained on the seven-channel feature stack is under development for automated, quantitative damage assessment across all impact energies.

References

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