



Performance of Time- and Frequency-Domain Analysis Techniques in Flash Thermographic Inspection of Monolithic and Sandwich Composite Parts

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Abstract

In flash thermography, the diffusive and damped characteristics of thermal waves complicate the detection of small and deep defects. To enhance the defect detectability of the recorded thermographic data, many researchers have developed a large range of advanced post-processing techniques. Most of these techniques either analyse the data in time domain or in frequency domain, however, there is no clear consensus about the optimal processing approach. In this contribution, an experimental comparison between several time- and frequency-domain analysis techniques is presented for the thermographic inspection of composite parts. In addition to laboratory coupon samples, also industrial composite components are investigated.

Keywords: Non-destructive testing (NDT), flash thermography, data processing, time domain, frequency domain, composites

1. Introduction

Due to the layered structure of composite materials, they are susceptible to internal damage features which could lead to catastrophic failure if they remain unnoticed. Therefore, a lot of effort has been dedicated over the past decades towards the development of reliable non-destructive testing (NDT) techniques [1, 2].

Flash thermography (FT) provides a fast, safe, full-field, non-contact NDT approach, where a defect may be distinguished from the sound material through the mismatch of their thermal properties [3-5]. First, an intense optical flash is aimed at the inspected sample, which causes its surface temperature to rise rapidly. The induced thermal imbalance causes thermal waves to diffuse into the depth of the specimen. Meanwhile, the surface temperature is recorded using a high-precision infrared (IR) camera. At a hidden defect, the heat diffusion is hindered, which causes heat to accumulate above the defect. As such, defects can be identified as localized hotspots in the recorded thermographic sequence. However, due to the diffusive and highly damped nature of thermal waves, the reliable detection of small and deep defects is very challenging.

In order to obtain an improved defect detectability, the thermographic dataset is typically enhanced with image processing [6, 7] and/or data processing algorithms [5, 8-14]. Many of the data processing techniques operate either in temporal domain or in frequency domain (after applying a fast Fourier transform (FFT)). In this contribution, the defect detectability of several time- and frequency-domain processing techniques is evaluated. Several (industrial) carbon fiber reinforced polymer (CFRP) components, with a range of defect types, are inspected. The remainder of the paper is organized as follows: section 2 highlights the inspected samples and



the experimental procedure. The considered post-processing techniques are briefly described in section 3, after which the results are discussed in section 4. Finally, section 5 concludes the paper.

2. Materials and Methods

The first CFRP component, depicted in Figure 1(a), is a 5.5 mm thick cross-ply $[(-45/0/45/90)_3]_s$ sample with five flat bottom holes (FBH) of diameter 20 mm at different depths, and is called CFRP_{FBH} hereafter. Secondly, a sandwich part with woven CFRP skins and a Nomex honeycomb core is inspected (see Figure 1(b)). During production, a 30×30 mm² disbond was created between the skin and the core, while after curing, also a barely visible impact damage (BVID) was created on the same side. As a reference, the inspection result of vibrational testing is shown. The third inspected part is a component of the vertical stabilizer in an Airbus A320 (see Figure 1(c)), which has stiffeners at the back side. Three BVID damages were created by impacting the component with a 7.1 kg drop weight from three different drop heights (20 cm, 35 cm and 30 cm for BVID_A, BVID_B and BVID_C, respectively). The vibrational NDT inspection results are shown as a reference.



Figure 1: Inspected CFRP samples: (a) $CFRP_{FBH}$ with a schematic illustration of a flat bottom hole (FBH); (b) schematic illustration of $CFRP_{Sandw}$ and the result of a vibrometric NDT inspection; and (c) $CFRP_{Airbus}$ and the result of a vibrometric NDT inspection.

All samples are inspected with flash thermography in reflection mode, where a Hensel linear flash lamp (6 kJ, 5 ms flash) provided the optical excitation energy. A cooled FLIR A6750sc was used to record the surface temperature: 100 s at 20 Hz for the CFRP_{FBH}, 20 s at 30 Hz for





the CFRP_{Sandw}, and 40 s at 30 Hz for the CFRP_{Airbus}. The IR camera has a focal plane array of 640×512 cryo-cooled InSb detectors, a noise-equivalent differential temperature difference (NEDT) of ≤ 20 mK and a bit depth of 14 bit. The camera is used in the calibration range of 10–90 °C, and is sensitive within the 3–5 µm mid- infrared range. The offset between the flash lamp and the inspected samples was ~300 mm for CFRP_{FBH} and CFRP_{Sandw}, and ~500 mm for CFRP_{Airbus}. The distance between the IR camera and the CFRP_{FBH} and CFRP_{Sandw} samples was ~500 mm, and ~1000 mm for the CFRP_{Airbus} component. Hard- and software modules from edevis GmbH guaranteed the accurate synchronization between the excitation and data acquisition. The obtained thermographic sequences are analysed in Matlab.

3. Post-processing Techniques

The data first undergoes a temporal standardization in order to suppress influences of non-uniform heating and other undesired effects [12, 14], after which it is further post-processed by several time- and frequency-domain processing algorithms.

In time domain, Dynamic Thermal Tomography (DTT) searches the value of the maximum thermal contrast and its associated moment in time, for every pixel. Therefore, we classify this here as a *single-bin evaluation* technique. The combination of these pixel values into images results in a maxigram^T and a timegram, respectively [10, 14, 15]. On the other hand, Thermal Signal Area (TSA) integrates the thermal signal within a user-defined time interval [9], and is therefore categorized as an *integrated-bin evaluation* technique. It is preferential to integrate the temperature signal around the time at which a defect shows its maximum thermal contrast (which can be found with DTT) [9, 14]. However, since the same integration domain is considered for all pixels, this approach is not optimal if multiple defects at different depths are present (since they all have different moments of maximum thermal contrast).

The temporal data can also be transformed to frequency-domain data by applying a fast Fourier transform, after which the phase data is used since it has emissivity-normalized properties. The counterpart of DTT in frequency domain can be obtained by evaluating each pixel's maximum phase contrast and its corresponding frequency, and is called Frequency-Domain Tomography (FDT) [14]. These pixel values then combine to a maxigram^F and a frequencygram. In frequency-phase domain, Adaptive Spectral Band Integration (ASBI) integrates the most-relevant spectral information (individually determined for each pixel without user input) in order to obtain a single damage index map [8]. ASBI is thus a frequency-domain *integrated-bin evaluation* technique.

4. Results and discussion

In this section, the defect detectability obtained with the post-processing techniques of section 3 is discussed for the three CFRP parts of section 2.

4.1. Coupon with flat bottom holes (CFRP_{FBH})

The results of the different post-processing techniques on the CFRP_{FBH} coupon sample are presented in Figure 2, with the true sizes and locations of the FBHs marked on the figures. Firstly, Figure 2(a,b) presents DTT's maxigram^T and timegram. In the maxigram^T, only the three shallowest FBHs (0.85 mm, 1.64 mm and 2.47 mm depth) are detected. Additionally, there are clear





effects of the fibre orientations which distort the background uniformity. The timegram in Figure 2(b) additionally hints the presence of the two deepest FBHs. The timegram is noisy since the values for sound pixels represent random fluctuations in the thermal contrast. Furthermore, the effect of lateral heat diffusion can be observed for the shallower defects, where the values in the timegram increase with the distance away from the FBH's centre. The defects therefore do not have a sharp outline in the timegram.

Several integration limits were carefully checked for TSA, and an integration over the first 50 s was found to provide a good detectability of the defects (see Figure 2(c)). This is a sensible integration range since it ranges over the timegram values of all FBHs (i.e. it encapsulates the times of maximum thermal contrast). In the TSA output, the three shallowest FBHs (0.85 mm, 1.64 mm and 2.47 mm depth) are clearly detected, while the presence of the fourth FBH (3.68 mm depth) is hinted. The background is significantly more uniform and less noisy than in DTT's maxigram^T and timegram. Of course, due to the integration procedure over a relatively long temporal range, the effects of lateral heat diffusion blur the edges of the shallow defects. In order to obtain better defect sizing, it would be beneficial to make the integration procedure adaptive in a pixel-wise manner. In that way, shallow defects will be associated with a shorter integration time which would limit lateral diffusion effects. Deep defects, on the other hand, will have longer integration times in order to increase their contrast.

The processed results of FDT are presented in Figure 2(d,e). The maxigram^F provides a good indication of the four shallowest FBHs (0.85 mm, 1.64 mm, 2.47 mm and 3.68 mm depth), and hints the presence of the deepest FBH (4.51 mm depth). Additionally, a highly uniform back-ground is retrieved, which provides a significant improvement over DTT's maxigram^T. The frequencygram provides an even better indication of the deepest FBHs, but with a noisier back-ground than the maxigram^F. Note that the frequencygram has the same values for the deepest defects due to the limited frequency resolution, which complicates the identification of their relative depth location. However, all defects have a very sharp outline in the frequencygram, as can be clearly observed in Figure 2 (e).

Lastly, ASBI's damage index map is shown in Figure 2 (f). It can be seen that all FBHs (depth up to 4.51 mm) are detectable with an almost uniform background and low noise level (note the logarithmic colour scale).

While DTT's maxigram^T and FDT's maxigram^F mainly serve for defect detection, DTT's timegram and FDT's frequencygram can be used for quantitative depth inversion. The main limitation for the timegram lies in its limited detectability of deep defects (FBHs detected clearly up to 2.47 mm depth, see Figure 2 (b)), however, quite uniform values are obtained over a defect's signature. On the other hand, the frequencygram can detect significantly deeper defects (detected up to 4.51 mm, see Figure 2 (e)), but the limited frequency resolution makes it practically very difficult to perform depth inversion for deep defects (deep defects have the same frequency values). With ASBI, only one single damage map is obtained, which serves for both defect detection and quantitative defect depth inversion (based on calibration curves from simulation) [8].







Figure 2: Processing results of the CFRP_{FBH} sample: (a,b) DTT maxigram^T and timegram; (c) TSA (0-50 s); (d,e) FDT maxigram^F and frequencygram; and (f) ASBI damage index map.

4.2. Sandwich sample with disbond and BVID (CFRP_{Sandw})

The post-processed results of the CFRP_{Sandw} sandwich part are displayed in Figure 3. With DTT's maxigram^T (Figure 3(a)), only the shallow BVID damage is detectable, while no trace of the skin-core disbond is observed. On the other hand, the woven structure of the CFRP skins is clearly visible in the result. In the timegram (Figure 3(b)), a hint of the disbond is observed, however, the background noise makes its detection non-trivial. The noise also covers a wide temporal range which appears to hide the BVID, however, a rescaling clearly indicates the BVID's presence (see inset). For TSA, it was found that integrating over the first 10 seconds after the flash excitation provided a good defect detectability of both the BVID and the skin-core disbond (see Figure 3(c)). TSA does not provide a uniform background, which is somewhat disturbing for defect detection. The disturbed region in the bottom right corner originates from lateral heat diffusion effects of the sample's clamping.

The maxigram^F obtained by applying FDT (Figure 3(d)) provides a very clear detection of both the impact damage and the disbonded region. The BVID and the disbond are both also identified in the frequencygram in Figure 3(e). As expected, a comparison of the dominant frequencies for both defects reveals that the disbond is located deeper than the BVID (defect depth is inversely proportional to the frequency of maximum phase contrast). Lastly, both defects are also straightforward to pinpoint in ASBI's damage index map (see Figure 3(f)). Besides providing a higher defect detection quality than TSA, ASBI additionally obtains a more uniform background than TSA.



The horizontal disturbance in the results are remnants of the non-uniform heating profile (linear flash bulb), which were not completely suppressed by temporal standardization (see Figure 3(c)) nor by phase calculations (see Figure 3(d-f)).



Figure 3: Processing results of the CFRP_{Sandw} sample: (a,b) DTT maxigram^T and timegram (with zoom of the BVID area); (c) TSA (0-10 s); (d,e) FDT maxigram^F and frequencygram; and (f) ASBI damage index map.

4.3. Aircraft component with 3 BVID damages (CFRP_{Airbus})

The post-processed results of the Airbus A320 component with three BVIDs are presented in Figure 4. Notice that in each of the subpanels, the clamp that was used to hold the sample is located between the two stiffeners on the right. At first sight, the background obtained with DTT's maxigram^T is very noisy (see Figure 4(a)). The vertical stiffeners at the back side are observed as locations of reduced maximum thermal contrast (due to the increased material thickness). The three impact damages can be detected, however, the strong background non-uniformity is a disturbing factor. DTT's timegram (Figure 4(b)) provides a comparable detectability as the maxigram^T, but with a less pronounced background non-uniformity. In this case,





the stiffened regions are highlighted as areas of increased time values (i.e. later maximum thermal contrast) in comparison to the skin plate. It is interesting to observe that the two left BVIDs (which are not located on top of a stiffener), are surrounded by a thin border of higher time values (and lower maximum thermal contrast values, see the maxigram^T in Figure 4(a)), which indicates an increased depth and lateral extent of the BVID delaminations. The integration range corresponding to the first 10 seconds of cooling provided a good defect detectability with TSA (see Figure 4(c)). All three BVID's are easily detected as regions of increased value. Also the backside stiffeners are sharply indicated.

In frequency domain, FDT's maxigram^F is presented in Figure 4(d). The three BVID's, as well as the stiffeners, are easily found. Furthermore, a highly uniform background is obtained in the non-defected areas. The frequencygram in Figure 4(e) may also be used for the inspection of the features of this component, but suffers from a more pronounced background non-uniformity. Lastly, ASBI's damage index map (Figure 4(f)) provides a clear detectability of the defects, and in lesser extent of the stiffeners.



Figure 4: Processing results of the CFRP_{Airbus} sample: (a,b) DTT maxigram^T and timegram; (c) TSA (0-10 s); (d,e) FDT maxigram^F and frequencygram; and (f) ASBI damage index map.

5. Conclusions

In this contribution, the performance of different post-processing techniques for flash thermography was evaluated in terms of their defect detectability. Both time- and frequency-domain, as





well as single-bin and integrated-bin, approaches are investigated. The study was performed on both monolithic and sandwich CFRP samples, and considered different defect types. In general, it could be observed that the frequency-domain analysis techniques had a superior depth probing range than the time-domain techniques. They also provided an improved suppression of background noise. Especially the integrated-bin technique (ASBI) showed a high performance for the different studied cases.

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