Method for quantitative 3D evaluation of defects in CFRP using active lock-in thermography

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Abstract

To guarantee an economic application of carbon fibre reinforced plastics (CFRP) throughout the entire product life cycle, the long term operational reliability and reparability of the products must be assured. The typical repair process starts with the defect detection and the defect evaluation. Based on the size and position of the defects the mechanical properties are evaluated and the most efficient repair process is selected. Therefore, the accuracy of the defect detection is essential for an economic repair process.

One approach to detect defects in CFRP is the active lock-in thermography, which is an imaging non-destructive testing method. The application of image processing algorithms on phase images enables automated defect detection in CFRP components. The determination of the depth position of defects is still a challenge since the phase images contain a superposition of different depth layers.

This paper introduces a method to quantitatively evaluate the 3D defect geometry from a stack of thermography images captured with different excitation frequencies. The phase images of blind bore holes are analysed. Digital evaluation criteria, e.g. area, enveloping circle and position, are defined. Algorithms for image correction, feature extraction and image analysis are implemented for automated defect detection. The stack of thermography images captured with different excitation frequencies is used to estimate the defect’s depth range. With the given thermal diffusivity and the excitation frequency the depth information is calculated. The results are visualized three-dimensionally. The method is validated by the comparison of the experimental results with calibrated coordinate measuring machine data.

Keywords: Thermography; CFRP; 3D damage detection

I. Introduction

The economic feasibility of carbon fibre reinforced plastics (CFRP) products must be assured throughout the whole product life cycle. In particular, long term operational reliability and economic repair processes must be assured. The established concepts from aerospace industry, where in general damaged parts are replaced, is not applicable for mass production of e.g. automobiles, since the effort and the amount of required resources are not economically feasible and ecologically justifiable. Impact damages are the most likely damages that occur to automobiles. In particular, impacts of small objects, such as stones or hail can cause severe damages that sometimes are optically invisible, but need to be repaired to assure the safety of the automobile.

The non-destructive detection of those invisible defects is a challenge. Therefore, non-destructive, reliable, efficient and automated measurement technology is required to fulfill the component (e.g. material, part size) and repair work shop specific demands (e.g. portability and price). One promising approach is the active lock-in thermography. Thermography systems are portable, safe, easy to use, and cover large components in a single image. Active thermography is non-tactile, reliable and capable to detect impact damages with their respective failure characteristics e.g. delaminations, debondings, air locks, porosity and fibre fractures [1]. The
disadvantage of thermography is, that it does not easily reveal the 3D defect geometry. This deficit is subject of this work.

2. Lock-in thermography for defect detection

Thermography is based on the detection of infrared radiation. External heat sources induce a heat-flow in the test object to disturb the component's thermal equilibrium. The heat propagates from the surface through the component and causes temperature peaks due to reflections at material inhomogeneities which can be captured at the component's surface with an infrared camera. For the optically excited lock-in thermography, halogen lamps are mainly used as a heat source. A sinus shaped temperature modulation on the object’s surface spreads in the inside as a damped and phase shifted thermal wave. The depth range for the optically excited lock-in thermography can be adjusted through the excitation frequency. The lower the frequency, the deeper the thermal waves penetrate the component.

To determine the severity of a damage and to take decisions about the repair options, the exact geometry (form and depth) has to be known. The state of the art provides some approaches to detect the geometry of damages using thermography. The thermographic phase images are able to reveal latent damages. Gleiter, Spießberger and Bai investigated the behaviour of thermal waves in test parts with defined damages [1–3]. Their investigations deliver information on the phase shift relating to the thickness of the part and material characteristics e.g. reflection coefficient. Dudzik investigated a method for thermal background approximation on a Plexiglas sample [4]. Zöcke investigated blind hole bores with varying diameters and residual wall thicknesses [5]. Artificial defects are captured using a global segmentation algorithm and the images are improved using a point spread function. The defect depth was calculated using the blind frequency. Defects that are not visible from the surface could be detected. The improvement worked under the conditions of a homogeneous fibre structure. Spießberger displays and analyses damage characteristics in the feature plane for defined inhomogeneities e.g. wedge-shaped geometries. Lahiri examines the impact of the lock-in frequency on the thermal and phase image. He determines the optimal lock-in frequency for different kinds of composites and rubber materials [6]. Schmutzler compares active thermography with optical and ultrasonic excitation considering the limits of depth resolution [7].

The aforementioned methods were applied on samples with a homogeneous fibre structure and artificial defects. An inhomogeneous defects and fibre structure makes the detection of defects much more difficult. A general approach to detect non-visible damages in inhomogeneous fibre structures is still in focus of research activities [8–10]. In particular impact damages are visible from the surface, and appear dot-shaped in the phase images. In this work, as a first approach, CFRP structures with blind bore holes are analysed frequency dependant to identify the 3D defect shape. Main goal is developing a procedure for automated defect detection and to quantify the depth resolution of the thermography system.

3. Method to evaluate 3D geometry of defects

The proposed method is based on the examination of using active lock-in thermography. It extracts the defect on each phase image and maps it in a three-dimensional defect model. For the 3D information the excitation frequency is varied from high to low frequency for each measurement. The method is structured into four main steps.

3.1. Preprocessing

The histogram of the phase images is illustrated in Fig. 1. Irregularities are represented by low grey scale values. The histogram shows overexposure due to suboptimal illumination indicated by the high frequency distribution of the grey scale value 255. This grey scale value is eliminated to remove areas with exceeded brightness.

![Fig. 1. Histogram of phase image with overexposure.](image)

3.2. Feature extraction

The image is segmented into areas of expected defects. A binary image is generated using the Otsu threshold method [11]. Defects are visualized in black. To eliminate structural irregularities on the binary image the erosion and dilatation operator are applied consecutively. The erosion operator is utilized to eliminate small irregularities caused by the CFRP-structure. The operator reduces the size of black spots. If the edge length of a spot falls below 5 px, the spot is filtered and eliminated. In a second step, the dilatation operator is applied to enlarge the black spot on its original size (Fig. 2). As a result of this process step the local position of defected areas is estimated and the defects’ centre of gravity is identified.
3.3. Image analysis

Preliminary studies show that the threshold varies depending on the excitation frequency. Therefore, contrary to the Otsu method, a dynamic threshold has to be determined to separate defected areas from defect free areas at the defects’ edge. A dynamic threshold is calculated using the sigmoid function as mathematical approach on the grey scale image. The sigmoid function is a s-shaped function and defined as in (1).

\[ f(x, a, c, m, n) = m + \frac{n - m}{1 + e^{-a(x-c)}} \]  

(1)

Nomenclature

- \( x \) control variable
- \( m \): lowest grey scale value
- \( n \): highest grey scale value
- \( a \) and \( c \) are approximated for each grey scale curve

The sigmoid function is fitted into the grey scale value distribution to approximate the edges of the defect. Therefore the grey scale value distribution is analysed perpendicular to the centre of gravity along the x- and y-axis (Fig. 3 down). The grey scale values are plotted and the sigmoid function is fitted into the measurement data.

The point of inflexion is calculated and equivalent to the local threshold (Fig. 3 up). The dynamic threshold for each defect is calculated in four positions to eliminate irregularities in the image acquisition. The average of the four values is utilized as dynamic threshold to retrieve a binary image out of the grey scale image.

The dynamic threshold is calculated for each phase image. Based on the local threshold the damaged areas are separated from the defect free areas. The phase imaged is converted into a binary image.

Impact damages that occur in service have damaged areas but also damage free regions right below the point of impact due to compression stress. The impact damage has white areas that are bounded by black edges on the phase image. To identify the entire impact damage, the defect is infilled. Main outcome of this process step is the calculation of the defect size.

3.4. Depth calculation

The thermal penetration depth \( \mu \) is calculated to retrieve the depth layer of each image from the stack,

\[ \mu = \sqrt{\frac{\alpha}{\pi \times f}} \]  

(2)

with the thermal diffusivity \( \alpha \) and the excitation frequency \( f \).

4. Experimental investigation on blind bore hole samples

4.1. Experimental procedure

CFRP samples were designed using 8 layers of BIAx HPT 300 C45 and milled 6 blind bore holes for each diameter (4 mm, 8 mm, 12 mm, 15 mm, 20 mm) (Fig. 4). The wall thickness to the top surface is 0.5 mm, 1 mm, 1.5 mm, 2 mm 2.5 mm and 3 mm. The artificial defects were designed based on the work of Zöcke [5] with the goal to investigate the resolution of the defect area in determined depth layers. The samples were geometrically calibrated on a ZEISS MICURA CMM.
The equipment is an Edevis OTVis 5000 lock-in thermography system with two 1,25 kW halogen light sources and a Flir Systems SC5650 infrared (IR) camera. The parameters were set to excitation frequencies \([0.5 0.4 0.3 0.2 0.15 0.125 0.1 0.09 0.08 0.07 0.06 0.05 0.045 0.04 0.035 0.03 0.0275 0.025 0.0225 0.02]\) Hz, three excitation and measurement periods, camera resolution \(512 \text{ px} \times 640 \text{ px}\), integration time \(0.0026 \text{ s}\).

An image stack consists of 20 phase images. The IR-camera and halogen light sources are placed on the same side of the CFRP part. Thus, the reflected IR-light is detected. The recorded video sequence is transformed pixel wise into a phase image using Fourier transformation.

4.2. Data analysis and results

The thermal diffusivity varies from each composite depending on fiber volume content and matrix material. Therefore, an experimental approach for the determination of the thermal diffusivity was chosen. It was experimentally determined by evaluating the phase images of the blind bore hole sample with different excitation frequencies. The first appearance of blind bore holes equals the depth penetration. With decreasing excitation frequencies, the thermal penetration depth \(\mu\) increases and the bore holes appear with increasing remaining wall thickness. With given thermal penetration depth \(\mu\) and excitation frequency \(f\), the thermal diffusivity \(\alpha\) is determined. The calculated thermal diffusivity is \(\alpha = 0.389 \times 10^{-6} \text{ m}^2/\text{s}\).

Blind bore holes with diameters of 20 mm, 15 mm and 12 mm and remaining wall thickness of 0.5 mm are evaluated in this paper (calibrated diameter and wall thickness: 19.897 mm/0.513 mm (20 mm), 15.905 mm/0.540 mm (15 mm), 11.954 mm/0.564 mm (12 mm)). Defects are detected on the phase image. The average blind bore hole diameter is calculated. The deviation in resolution of the defect’s depth and its respective area is determined by comparing the measured values with the calibrated values.

In a second step the aforementioned method is used for the frequency dependant analysis of the image stack for each blind bore hole. The detected defect of the 20 mm blind bore hole is illustrated in Fig. 6. The defect area is plotted against the calculated depth. The results illustrate the decrease of the detected defect area with increasing depth.

The thermography results of the 20 mm, 15 mm and 12 mm blind bore holes are compared. The maximum detectable depths for the blind bore hole (with diameter) are 2.226 mm (20 mm), 2.122 mm (15 mm) and 2.122 mm (12 mm). The area of the cylindrical blind bore holes (20 mm, 15 mm, 12 mm) with wall thickness of 0.5 mm is calculated and plotted against the calculated depth (Fig. 7). The regression is fitted into the measurement data with a coefficient of determination of \(R^2 = 0.893\) (20 mm), \(R^2 = 0.895\) (15 mm) and \(R^2 = 0.879\) (12 mm).
4.3. Discussion of results

As an example the 20 mm blind bore hole measurement is discussed. The calibrated area for the 20 mm blind bore is 310.923 mm$^2$. The calculated area from the phase image at 0.787 mm (0.200 Hz) is 261.536 mm$^2$ and slightly smaller compared to the CMM results. With decreasing excitation frequency, the detected area decreases. At an excitation frequency of 0.040 Hz (1.759 mm) the area decreases to 203.571 mm$^2$ (22.16%). At 0.030 Hz (2.032 mm) the detected area decreases to 170.532 mm$^2$ (34.80%).

The data illustrate a trend of decreasing areas and significant outliers at the top layer and the bottom layer. The bottom layer is the limit of the thermal penetration depth. The thermal diffusion length at the top is too short to reach the top layer of the blind bore holes. The defects are not sufficiently heated to create a sufficient contrast in the phase images.

The accuracy for area determination of the 15 mm decreases from 85.19 % (0.200 Hz/0.787 mm) to 37.23 % (0.025 Hz/2.225 mm) and for the 12 mm blind bore holes 94.3 % (0.200 Hz/0.787 mm) to 31.61 % (0.028 Hz/2.122 mm). The high reflectivity of the sample's surface decreases the energy absorption and leads to a smaller contrast in the phase image. This effect applies in particular to small features. This result is consistent to the work of Schmutzler [7].

5. Conclusion and outlook

In this work a method to reveal the 3D geometry of defects from thermography images is proposed. The correlation of excitation frequency, defect size on the thermal image and the real defect size is investigated. The experimental results of the blind bore hole sample showed a parameter setting dependent resolution, which needs to be further investigated and modelled in the next step. The information of depth resolution is considered to estimate the 3D defect geometry. Based on the analysis of the blind bore hole investigation, the method will be further developed for the detection of impact damages. The contour detection is the main challenge to enable the measurement of impact damages, since their geometry is not easily predictable. In particular, the algorithms for the damage area detection need to be further developed.

Acknowledgements

This work is supported by the Deutsche Forschungsgemeinschaft DFG within the scope of the German-Brazilian Research Initiative BRAGECRIM (reference SCHM1856/59-1).

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