A novel inspection method for locating and measuring structures embedded in CFRP

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Abstract
Active infrared thermography (AIT) has become an interesting method for NDT, being widely developed for aeronautical applications. In this paper, we focus on applications of lock-in thermography, where the surface to inspect is illuminated by halogen lamps following a sinusoidal period. Internal defects or structures act as a barrier for heat diffusion therefore producing changes in the surface response signal. Phase and amplitude images are retrieved from the Fourier transform of the acquired data series.

An inner structure at a given depth can be detected in the thermal image by adjusting the frequency and image parameters. The corresponding CAD model is superimposed in the thermal image by fitting the real edges through commercial computer vision algorithms.

Laboratory tests were performed on probes of CFRP with internal structures, and different dimensional values were computed and analysed for validation of the complete procedure. In summary, this solution allows dimensional measurements within the internal structure, obtaining a flexible NDT quantitative method based on infrared thermography.

Keywords: Active infrared thermography (AIT), Lock-in thermography (LT), Aerospace components, CFRP, Matching algorithms

1. Introduction

Infrared thermography has been successfully used as an NDT&E technique in many applications [1,2]. Following the advances for quantitative results based on active infrared thermography, a novel approach for internal dimensional measurements is established in this study, focused on aerospace materials. In particular, carbon fibre reinforced polymers (CFRP) parts, which are extensively used in large constructions as aircrafts. Efficient and automated non-destructive testing for large parts can be based on active infrared thermography (AIT) [3], which is based on generating a temperature difference between defective and non-defective areas in the specimen under examination [4,5]. Optical excitation - based on halogen lamps - stimulates the defects externally, delivering the energy to the surface of the specimen, where the light is transformed into heat. AIT techniques based on optical excitation are divided in two classical approaches: lock-in thermography (LT), and pulsed thermography (PT). Although both techniques allow to obtain quantitative results in terms of defects' characterization and depth location, lock-in thermography has been chosen for simplicity of characterization in the present work.

Location of internal structures, instead of defect detection, is the inspection goal of the AIT developed method. Location and dimensional characterization are obtained by mixing thermal images with the corresponding CAD models of the structures, as they are previously known from part design and production. A software tool from commercial computer vision libraries was developed for obtaining a matching between the model and the thermal image, based on shape-based localization. Further dimensional measurements can be performed directly on this matching results.

Laboratory tests were performed to validate the capabilities of this quantitative NDT method comprising internal structures, focused on aeronautical elements.
2. Method and materials

The interest in the matching of CAD models with thermal images is straightforward: this method allows to perform precise quantitative dimensional measurements on otherwise fuzzy images of structures showing blurry edges. Applying conventional edge enhancement algorithms leads to noisy borders without preserving the original shape of the structures, effects that can be avoided with the present technique.

2.1 Lock-in thermography

Lock-in thermography (LT), also known as modulated thermography [6,7], is an infrared NDT technique where the surface of the specimen is periodically illuminated by one or several modulated heating sources, as halogen lamps. The periodic wave produces heat by radiation at the specimen surface which is propagated inside the material. Internal defects, or internal structures, act as barriers for heat diffusion, thus producing changes in amplitude and phase of the thermal response at the surface.

The thermal response of the material at the surface is acquired with an infrared camera. Heat diffusion through a material is a complex 3D problem that can be described by Fourier's law of heat diffusion:

\[ \nabla^2 T - \frac{1}{\alpha} \cdot \frac{\partial T}{\partial t} = 0 \]  

where \( \alpha \) is the thermal diffusivity of the material to inspect, related with the thermal conductivity, density and specific heat of that material.

Commonly, sinusoidal waves are used for the illumination in lock-in applications: the frequency and shape of the wave are preserved, and only the amplitude and the phase delay of the wave may change (sinusoidal fidelity). For simplicity, the 1D Fourier's law solution for a periodic thermal wave propagating through a semi-infinite homogeneous material is considered:

\[ T(z,t) = T_0 \exp \left( -\frac{z}{\mu} \right) \cos \left( \frac{2\pi z}{\lambda} - \omega t \right) \]  

with \( T_0 \) the initial change in temperature, \( \omega \) the modulation frequency (\( \omega = 2\pi f \), with \( f \) the frequency in Hz), \( \lambda \) the wavelength and \( \mu \) the diffusion length:

\[ \mu = \sqrt{\frac{2\alpha}{\omega}} = \sqrt{\frac{\alpha}{\pi f}} \]  

From Eq. (3) it can be followed that thermal waves propagate deeper in more diffusive materials, but information about deeper features is available at lower frequencies. Therefore, for a known material with known \( \alpha \) the depth inversion is direct: it is possible to fix the inspection depth from the modulation (lock-in) frequency. This relationship will be employed to fix the lock-in frequency and the total inspection time for the proposed method.

2.1.1 Data processing

The processing of the acquired thermal image series requires the data transformation from the time domain to the frequency spectra by using the 1D discrete Fourier transform:
where \( j \) is the imaginary number \((j^2 = -1)\), \( n \) designates the frequency increment \((n=0,1,..., N)\), \( \Delta t \) the sampling interval, and \( \text{Re} \) and \( \text{Im} \) are the real and the imaginary parts of the Fourier transform, respectively. Both amplitude \( A_n \) and phase \( \phi_n \) images can be obtained:

\[
A_n = \sqrt{\text{Re}_n^2 + \text{Im}_n^2}; \quad \phi_n = \tan^{-1}\left(\frac{\text{Im}_n}{\text{Re}_n}\right)
\]

The phase image provides deeper probing capabilities, since it cancels part of the artifacts related to non-uniform heating, environmental reflections, emissivity and surface geometry variations. In this work, the structure detection is performed on the phase images, while amplitude images will be used to locate external landmarks.

### 2.2 Matching algorithms

A shape-based localization system was developed based on commercial algorithms, from HALCON software (www.halcon.com) for the CAD - image matching. The program extracts a region of interest (ROI) on the thermal base image, containing the internal structure of interest. Using the ROI, a correlation-based matching is employed for the alignment of the CAD model and the thermal image, based on the edges of the internal structure to measure. In detail [8], the thermal image is processed through an edge detector and a direction vector is extracted for each image point. Then, a similarity measure between the CAD model and the thermal image is obtained. Similarity, \( s \), is defined as the sum (for each image point) of normalized dot product of the direction vectors over all the points of the model, as follows:

\[
s = \frac{1}{n} \sum_{i=1}^{n} \frac{(d'_{i}, s_{q+p})}{||d'_{i}|| ||s_{q+p}||}
\]

Where \( d'_{i} \) denotes the direction vectors after an affine transformation of the CAD model, accounting for a translation to the \( q \) point and a linear transformation \( p'_{i} = A p_{i} \). This approach ensures robustness to both occlusion and clutter. Moreover, the maximum possible score of a detected object is roughly proportional to its visible area.

The search procedure is repeated up to five levels of an image pyramid and for a number of orientations, obtained through sub-sampling and rotation of the model image. Pyramid levels are represented by different image pixel resolution. The search proceeds through the pyramid from the top level for all possible poses of the model. Local maxima of \( s \) were taken as potential matches and were tracked through the subsequent pyramid levels from an initial value of 1 until they were found at the lowest level. Consequently, the search space is greatly reduced, since only small regions at finest scales (around previous matches in coarse scales) are evaluated. This gain in search efficiency is the major benefit of the adopted multi-resolution approach rather than others as scale invariance.

Once the model is found in the finest scale, the positioning of the CAD model is refined by fitting the similarity to a second order polynomial on the neighbourhood of the maximum scores. This final step endows the system with sub-pixel accuracy.
2.3 Experimental setup

The lock-in thermographic system employed is an own-developed laboratory solution with a Gobi 640 GigE Industrial camera from Xenics. The optical excitation system was implemented with a programmable power supply SM300-100D of 3000 W (from DELTA) and two halogen lights of 500 W each. The sinusoidal wave was programmed with a function generator HM8131-2 from HAMEG, where the frequency value can be initially adjusted.

Acquisition procedure is based on Ethernet connection with a trigger signal (programmed with an USB DAQ Labjack board). Frames (thermal images) for lock-in data are sequentially acquired, with 16 bits .png format. Different parameters must be fixed: the lock-in frequency (for depth location), total acquisition time, camera gain, integration time and minimum frame time. Framerate must be defined to limit image noise coming from aliasing, fixed from a combination between integration time and minimum frame time (up to the camera maximum, 50 fps - frames per second). The rule of thumb for better image quality is to maximize the image histogram, which depends on the indicated parameters. A previous heating of the surface is needed for obtaining a thermal stationary state, as it can also affect to the final image quality.

Total acquisition time will vary depending on the chosen frequency. Different tests were performed and finally a 4-period time for the corresponding frequency was chosen to minimize image noise and improve the matching process.
2.4 Materials and measuring of internal structures

Part probes of CFRP laminates were employed for the analysis of the developed inspection system. The probe definition consists on a honeycomb area with an interior resin piece covered totally by a CFRP panel (see Figure 2). The dimensions of interior pieces and the width of the CFRP panel are variable to check different depths for the detection. Therefore, the probes have variable dimensions and can simulate aerospace modular constructions, focusing of a further inspection in real production. Moreover, external landmarks have been included, as examples of real markers that are located for ensuring the quality control in the manufacturing of complex parts.

![Figure 2: Example of lateral section of the laboratory probes. Internal structures dimensions vary with CRFP width ranging from 1 to 4 mm, and different materials are chosen for the external markers. Drilled holes can have different depth within the internal part.](image1)

These markers are imaged as fiducial marks in the resulting thermal images. The markers are implemented of different materials, as lead, Teflon or even drilled holes, and are located over or inside the CFRP panel (Figure 3).

![Figure 3: Example of different markers: lead (left), Teflon inclusions (center), drilled holes (right).](image2)

2.4.1 Image scale

Dimensional measurements of internal structures are needed for quality control during manufacturing. Characterization of the image scale, i.e., pixel size in millimetres, is therefore needed, and can be performed from two points of view: an initial calibration or by measuring a known fact in the image. A calibration of the pixel size with the distance camera focus - probe's surface is useful for a measuring automatic system, where the distance will be known in consecutive measures. In other examples, the easiest approach is to characterize the scale from a known-real dimension, as the external marker size. This calculus has been implemented in the developed software.
3. Results

The inspection method for CFRP parts comprises two different steps: thermographic acquisition and matching correlation, to finally obtain the internal dimensions of interest (see Figure 4).

![Figure 4: Schematic view of the inspection process for internal dimensions.](image)

3.1 Internal measurements

The dimensional measurements that are needed in the manufacturing of these materials are usually included within a quality control protocol. Not only the dimensional facts (largest and smallest 2D dimensions for the internal structure) but also distances from external marks to the structure's edges should be characterized. These quantities can be calculated within the developed software tool, as shown in Figure 5:

- **Fiducial marks.** Detail of the external markers (marker or drilled holes) are extracted from the amplitude image. Markers are segmented from the grey levels gradient for a given threshold, and the corresponding centres are computed as the centroids of the segmented region.
- **Dimensional measurements.** The characterization of the structure is completed by measuring distances between the marker and the structure's edges, or other selected points in the image.
3.2 Lock-in parameters

Lock-in frequency was adjusted to the width of CFRP probes based on bibliographic data [3]. Considering a value of thermal diffusivity of $\alpha = 0.004 \text{ cm}^2/\text{s}$ (for CFRP with perpendicular fibre orientation), an initial frequency parameter for different diffusion lengths was calculated. It was later adjusted for better detection, since the specific CFRP laminate structure offered more resistance to heat flow than the reference material. Final parameters are shown in Table 1 along with the total acquisition time, established for 4 lock-in periods.

Table 1: Inspection depth and lock-in frequency ($\alpha = 0.004 \text{ cm}^2/\text{s}$) and total acquisition time.

<table>
<thead>
<tr>
<th>CFRP width (mm)</th>
<th>Lock-in frequency (Hz)</th>
<th>Acquisition time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.01</td>
<td>400</td>
</tr>
<tr>
<td>2</td>
<td>0.008</td>
<td>500</td>
</tr>
<tr>
<td>3</td>
<td>0.006</td>
<td>670</td>
</tr>
<tr>
<td>4, &gt;4</td>
<td>0.005 - 0.004</td>
<td>800-1000</td>
</tr>
</tbody>
</table>

3.3 Dimensional data analyses

Different analyses were performed for the dimensional results to evaluate the capability of the method for 28 probes, namely: comparison with real measures, repeatability and the scoring value from matching algorithms. The scale of the analyzed measures is in mm, from 0 to 50 mm.

3.3.1 Comparison with real measures

Thermal and real dimensional data were compared: its comparison was performed with 4 probes, by measuring the real structures after removing the CFRP laminate. Only 6 values for real data were computed by repeating series. The measures were performed on camera photographs of the structure using the developed software tool (see Figure 6).
Deviation (in percentage value) was calculated as the difference between thermal-CAD and real values, up to 5% maximum deviation. Direct comparison with real measures, with no repeatability series, was also analyzed, obtaining a maximum deviation up to 10% (on the 28 probes).

3.3.2 Repeatability and scoring
The repeatability of the thermal data was evaluated by acquiring consecutive lock-in periods in the same conditions. The uncertainty was extracted from the repeatability of 10 thermal data series, acquired for 7 probes with 16 internal structures. Relative uncertainty was calculated as the ratio of the standard deviation and mean value for each dimensional measure. Final uncertainty ranges from 2% to a maximum value of 7% for the thermal image - matching CAD method.

The general scoring of the matching process was also evaluated for all the probes. Minimum score for a correct matching is 0.7 for a maximum of 1 scoring, what ensures robustness in the final measure.

Different data were analysed to validate the feasibility of the presented method for dimensional measures from thermal images. A summary is shown in Table 2.

<table>
<thead>
<tr>
<th>Analyses</th>
<th>Computation</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative uncertainty</td>
<td>Std / mean (10 data series)</td>
<td>2 - 7 %</td>
</tr>
<tr>
<td>Maximum deviation</td>
<td>Real - thermo difference /real value</td>
<td>1 - 5%</td>
</tr>
<tr>
<td>(repeatability data)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum deviation (28 probes)</td>
<td>Real - thermo difference /real value</td>
<td>1-10%</td>
</tr>
<tr>
<td>Matching scoring</td>
<td>Eq. (6)</td>
<td>0.7-1</td>
</tr>
</tbody>
</table>

Table 2: Data analysis for the capabilities of the thermal image - CAD matching procedure.
4. Conclusions and future work

A non-destructive method is presented for dimensional measurements in internal structures from thermal images. The image - CAD model matching provides defined dimensions over a otherwise blurred image. This method is pretended to be a valuable tool for dimensioning and quality control of part production in aerospace applications, validated on the implemented laboratory tests with samples of CFRP laminates and internal structures.

The feasibility of the technique has been evaluated by repeatability measurements and its comparison with real data of the probes. The first results concluded a maximum deviation of 10%, a value that can assure accuracy within different applications.

Further work to develop will be oriented to a more complete study of the reproducibility of the thermal measurements. Specific analyses on the inspection time for its implementation in production conditions will be also of interest, along with its comparison with other quantitative NDT methods that are nowadays employed in aerospace production, as Ultrasound or X-ray applications.

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References