http://dx.doi.org/10.21611/qirt.2004.025

Development and trials of through skin sensing of aircraft fixtures using pulsed thermography

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Abstract

This work evaluates the potential of pulsed – transient thermography for locating fixtures beneath aircraft skins in order to facilitate accurate automated assembly operations. Representative aluminium and carbon fibre aircraft skin-fixture assemblies were modelled using ThermoCalc-3D. The assemblies were also experimentally investigated with the ThermoScope system and a custom built system incorporating a miniature un-cooled camera. Modelling showed that the presence of an air gap between skin and fixture significantly reduced the thermal contrast developed, especially in aluminium. Experimental results from the ThermoScope system show that fixtures can be located to accuracies of 0.5 mm. Preliminary images from the custom system are superior to the ThermoScope, and optimisation is expected to lead to further improvements.

1. Introduction

As aircraft are becoming larger there is an increasing desire to automate manufacturing processes. One such process, which forms the motivation of this research, is the automated wrapping, drilling and fixing of aircraft panels to structural ribs. Once the skin has been wrapped over the ribs a technique is required to located skin fixing points, known as feet. The technique must essentially 'see through' the skin to the underlying structure. Techniques of this type are necessary because the forces required during the skin wrapping stage can be strong enough to displace the ribs and feet from their initial position. The large forces exerted, and the associated rib and feet displacements, have important implications for the drilling and skin securing stages. Since these processes must adhere to tight tolerances it is vital that an automated robotic drilling system knows the precise location of the feet to which the skin is to be fixed.

Pulsed transient thermography is suggested as a means to detect the location of the feet [1]. In this technique the aircraft skin under investigation is pulse heated (time period of heating varying from ms to s) by flash lamps. In theory the feet will act as heat sinks, drawing thermal energy away from the surface of the skin, while the surrounding material remains at a higher temperature. If the resulting thermal transient at the skin surface is monitored using an infrared camera the location of the feet will become clearly visible as a low temperature region in the image. This research uses modelling and experimental evaluation of representative structures to investigate the ability of this technique to accurately locate fixture points in an automated assembly process. Results from a state of the art inspection system are compared to a custom built system incorporating a miniature un-cooled infrared camera.

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2. Experimental techniques

The pulsed transient thermography technique was evaluated by testing a representative structure. The structure consists of a skin and a strut, as shown in figure 1.

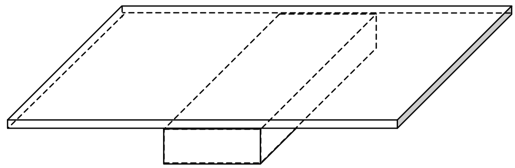

Fig. 1. *The representative test structure.*

The test structure was either comprised of a 1.6 mm thick aluminium skin (alloy 2024-T3) over a thick aluminium strut, or a 2.0 mm or 4.0 mm thick carbon fibre reinforced plastic (CRFP) skin over a thick carbon fibre strut. The carbon fibre lay-up was $[(\pm 45^{\circ}, 0_2, 90_2^{\circ})]_2$. The three material combinations were modelled, experimentally evaluated using a ThermoScope Pulsed Thermography system, and evaluated using a custom built thermography system incorporating a miniature un-cooled infrared camera.

2.1. Modelling evaluation

Finite difference modelling was performed on the three representative test structures. The structure was modelled using ThermoCalc-3D software Version 2.0 (Innovation Inc., 1998), which can tolerate very thin subsurface features in rather thick materials without loosing computational accuracy. The skin dimensions were 500 × 500 mm and the strut width was 100 mm. Additional parameters used for the modelling are presented in table 1.

Table 1. *Parameters used for finite difference modelling*

Material		k (W m^{-1} K^{-1})	c_p (J kg^{-1} K^{-1})	ρ (kg m^{-3})	Time step (s)	End time (s)
Aluminium 2024-T3		126	961	2768	0.003	0.5
CFRP	(⊥ fibre)	0.8	1200	1600	0.05	5
	(|| fibre)	7	1200	1600		
Air		0.026	1007	1.16	-----	-----

For both aluminium and CFRP structures the strut was modelled as being in perfect contact with the skin. Additionally, the effect of an air gap was investigated, with the skin-strut separation set to values of 1, 5, 10, 50 and 100 μm. Heat energy totalling 2 kJ was applied to the surface of the skin over a 3 ms time period to simulate the operational conditions of the ThermoScope. The skin temperature at positions above the strut and far from the strut was evaluated and used to construct contrast-time plots.

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2.2. ThermoScope evaluation

To perform an experimental evaluation the test skin (either 1.6 mm thick aluminium, 2.0 mm CFRP or 4.0 mm thick CFRP) was mounted on the test rig (figure 2). The aluminium skin was coated in water-soluble black paint to reduce reflections.

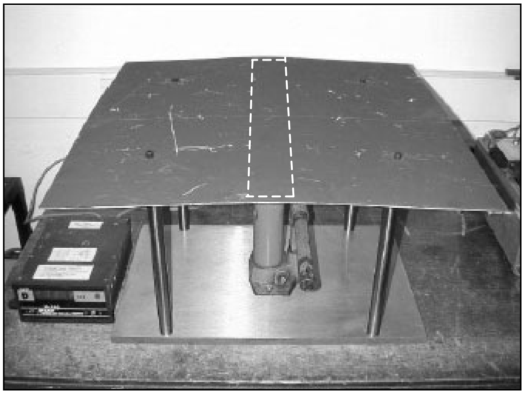

Fig. 2. *The experimental set-up for testing various skin-strut combinations.*

The testing rig consists of a base plate to which a jack and four supporting rods are attached. The skin material is fixed to the supporting rods and the strut material is positioned beneath the skin surface and forced into contact with the back face of the skin using the jack. A load cell is used to monitor the load applied to the strut, which in all cases was 50 N. For the aluminium skin the strut was 50.8 mm wide and 3.7 mm thick aluminium, while for both CFRP skins the strut was 62.4 mm wide and 5.0 mm thick CFPR. Transient thermography was performed using ThermoScope (Thermal Wave Imaging Inc.), a state of the art thermographic inspection system. The system combines integrated flash heating (2 kJ in 2-5 ms) with a Merlin 3-5 μm focal plane array (FPA) IR camera by Indigo. The FPA has 320 (H) $\times$ 256 (V) elements and the camera has a minimum detectable temperature difference of 0.02 K. Control of the system is achieved using the supplied software (EcoTherm V5.3) for setting image capture rates and storing, viewing and extracting data from the image sequences.

2.3. Custom system evaluation

In addition to the evaluation made using ThermoScope, the test structures were examined using a custom built thermography system. The system uses 2 $\times$ 500 Watt halogen lamps as the heating source in combination with an un-cooled miniature infrared camera (Indigo Omega) shown in figure 3.

Fig. 3. *The Indigo Omega camera*

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The camera consists of an un-cooled VOx FPA sensitive to radiation in the 7.5-13.5 μm spectral band. It has a minimum detectable temperature difference of 0.085 K (equivalent to 0.04 K at f/1.0). The lamps are positioned either side of the camera, and shutter plates positioned in front of the lamps. The shutters close as soon as the lamps switch off, thus preventing residual IR radiation from deteriorating the subsequent thermal images recorded. Heating times were typically ten seconds.

3. Results

Results from the finite difference modelling are presented in figure 4. This figure shows a graph of maximum contrast versus air gap for the three skin materials. From this graph it can be seen that at zero air gap aluminium develops a thermal contrast approximately three times that of the 2.0 mm CFRP, and approximately six times that of the 4.0 mm CFRP. A direct result of the very different thermal properties of the two materials is the significant reduction in thermal contrast seen in aluminium as the air gap between skin and strut increases. For CRFP the reduction in thermal contrast in significantly lower. These results show the criticality of achieving a good contact between the skin and the strut, especially in a high thermal conductivity material such as aluminium. The results also show that for thicker skins the contrast is reduced, as one would expect.

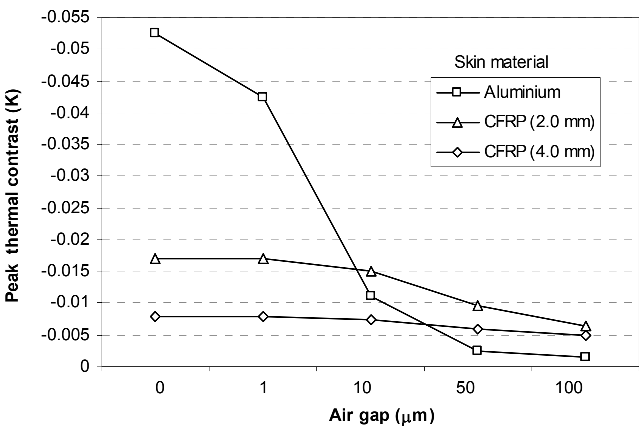

Fig. 4. *Thermal modeling results of peak contrast as a function of air gap for both the aluminium and CFRP models.*

Thermal contrast curves for aluminium and CFRP skins obtained using the ThermoScope system are presented in figure 5. This figure shows that maximum contrast between the strut and skin location occurs at early times for the aluminium skin compared to the two CFRP skins, confirming expected trends from the modelling. The magnitude of the contrast is significantly lower for the aluminium and 4.0 mm CFRP skins compared to the 2.0 mm CFRP skin suggesting that it will be more difficult to detect the strut position beneath these skins using simple algorithms. The low contrast developed in the aluminium case is attributed to the presence of an air gap between the skin and strut, while the low contrast developed in the 4.0 mm CFRP skin is attributed to the large skin thickness. Both these effects have been shown through modelling to have a significant effect on the thermal contrast developed.

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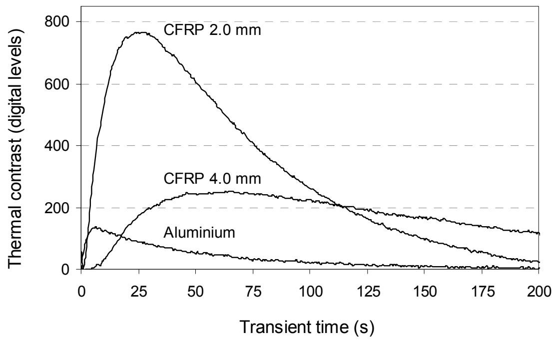
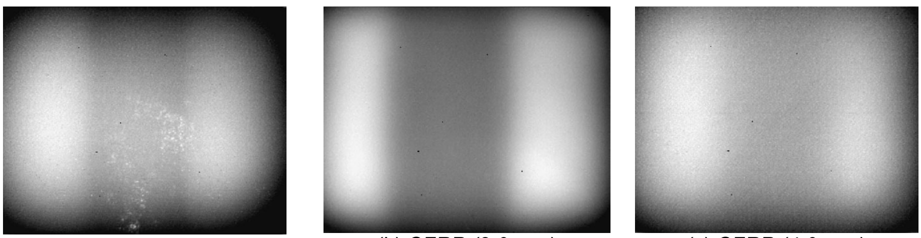


***Fig. 5.** Contrast-time plots for the aluminium and CFRP skins*

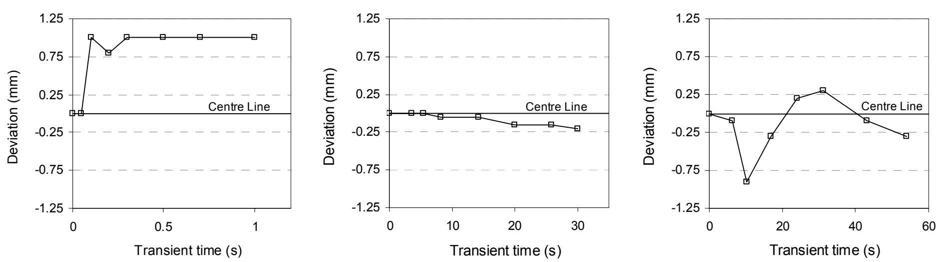
Thermal images taken at the time of maximum contrast for the three skin materials are presented in figure 6. In all the images the strut can be seen as a dark vertical band in the centre of the image.



(a) Aluminium *(b) CFRP (2.0 mm)* *(c) CFRP (4.0 mm)*

***Fig. 6.** Thermal images obtained using the ThermoScope system*

The ability to accurately determine the strut centre position is vital for the automated assembly applications. A simple full width at half maximum technique was applied to five evenly spaced horizontal grey-scale profiles taken from the images. The average of these five results was then compared to the struts true centre position, determined by markings on the skin surface. Graphs plotting the deviation from the true centre versus transient time for the three test cases are presented in figure 7.



(a) Aluminium *(b) CFRP (2.0 mm)* *(c) CFRP (4.0 mm)*

***Fig. 7.** Accuracy analysis of the centre line detection algorithm*

The results in figure 7 reveal that in all cases maximum accuracy is achieved at early times, with the predicted centre line deviating from the true value as time

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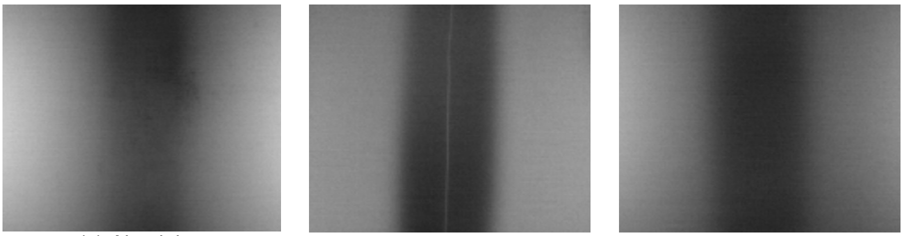
increases and thermal contrast diminishes. For the aluminium skin it is vital that early images are used for strut location because its high thermal conductivity leads to a fast image deterioration rate. In contrast, images up to 15 seconds from the 2.0 mm thick CFRP skin can be used to obtain accurate centre point information. The 4.0 mm CFRP skin suffers from a reduced accuracy because of the poor quality of the thermal images resulting from the larger skin thickness.

Typical images obtained using the custom system incorporating the miniature camera are presented in figure 8.



(a) Aluminium *(b) CFRP (2.0 mm)* *(c) CFRP (4.0 mm)*

Fig. 8. *Thermal images obtained from the miniature Omega camera system.*

By comparing these images to those presented in figure 6 it is apparent that the custom system produces superior results, even though the camera used is of lower sensitivity. This can be attributed to the increased thermal energy deposited on the skin (10 kJ cf. 2 kJ) due to the extended heating time used. This increases the thermal contrast developed, producing superior images. Optimisation of the heating and image acquisition timing is expected to increase the quality further.

4. Conclusions

This study has shown that images suitable for machine vision can be obtained using the principles of transient thermography. However, evaluations of test structures using the ThermoScope system have shown it is difficult to obtain good quality images with aluminium and thick (4.0 mm) CFRP skins. This can be attributed to the thickness of the skin in the CFRP case, and the presence of an air gap between the skin and strut in the aluminium case (confirmed by the modelling results). Applying a simple FWHM algorithm to the images enabled the centre line of the strut be located with high accuracies, differing from the true centre by no more than 1.0 mm (for the 4.0 mm CFRP skin). The high quality of the images obtained using a comparatively low sensitivity camera was attributed to the increased energy deposited on the skin surface. The size, weight, power and cost advantages offered by such a miniature camera system are attractive for machine vision applications.

5. Acknowledgements

This work was funded by the EU Growth Programme G1RD-CT-2001-00673 (AHEAD). The aluminium alloy and CFRP skins were kindly provided by Airbus.

REFERENCES

[1] Avdelidis, N. and Almond, D. Transient thermography as a through skin imaging technique for aircraft assembly: modelling and experimental results, *Journal of Infrared Physics & Technology*, **45**, 103-114, (2004)