Analysis of Pulsed Thermographic Sequences based on Radon Transform

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ABSTRACT

The automatic detection of subsurface defects has become a desired goal in the application of Non Destructive Techniques. In this paper, a new algorithm based on the Radon Transform is proposed to reduce human intervention to a minimum in the field of Thermography for defect detection and/or characterization. The analysis of a thermographic sequence for the detection of subsurface defects can be reduced to the identification of the -0.5 slope in the surface Temperature decay for each pixel within the image. Employing techniques commonly used in computer vision, an algorithm can be developed in order to look for the -0.5 slope in the temporal temperature decay profiles of each pixel. In our case, the Radon transform can be used to detect those -0.5 slope lines in the temporal temperature decay profiles. The final result provided by this algorithm is an image showing the different defects avoiding the necessity of evaluating parameters as relevant in other algorithms as the delayed time of the first image or any subjective point of view in the analysis. All the information is contained in only one image and leads to a quantitative estimation of the defect depths. The principal limitation is that the specimens under inspection should be semi-infinite homogeneous samples because this algorithm is supported on a 1-D Fourier diffusion equation approximation. Experimental works using a PlexiglasTM specimen were performed showing a good agreement with other semi-automated techniques.

Keywords: Pulsed Thermography, Image Processing, Radon Transform, defect detection.

1. INTRODUCTION

Nowadays, efforts are currently underway to create new innovative materials of superior properties to be employed in many different areas of manufacturing. In this context, material characterization and testing represents a key point for product standards and may be performed with both destructive and non-destructive tests. At the moment there are several techniques available in the Non Destructive Evaluation and Testing (NDT&E) scene, but only a few of them allow in situ analysis. Among the later ones, Infrared Thermography (IT) has been extensively used in recent years.

Various methods have been developed around the world to improve and widen the use of IT¹ but human intervention and subjectivity is still present when the thermographic sequences have to give quantitative results. Independency of the operator's point of view analysis of such sequences is one of the goals that authors, among others, have been trying to get recently as it can be extracted from some previous works^{2,3}. In order to do that, a priori knowledge of the specimen is fundamental. By simply knowing whether the sample can be modeled as a 1-D semi-infinite homogeneous body or not can help the analysis. It can be done, in an initial approximation⁴, relating linearly the logarithm of the temperature increase on sample surface to the logarithm of the time that the process of heat conduction takes⁵. In such case, and under Pulsed Thermography (PT) excitation, the heat transfer at the surface follows a linear decay, approximating a -0.5 slope, during all the inspection time for a non-defective or *sound* area, S , in a logarithmic space. On the contrary, thermal decay for a defective area diverges from this behaviour, as it is shown in Figure 1.

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Figure 1. Different temporal decays of superficial temperature for pixels belonging to defective and non-defective areas.

The analysis of a thermographic sequence for the detection of subsurface defects can be reduced to the identification of the -0.5 slope in the surface temperature decay for each pixel within the image. Using traditional techniques, coming from the field of computer vision, an algorithm can be developed in order to look for the -0.5 slope in the temporal temperature decay profiles of each pixel. Next sections summarize the features of the use of Radon Transform for our purposes.

2. RADON TRANSFORM ON THERMOGRAPHY

The Radon transform is an integral transform whose inverse is used to reconstruct images⁶. The Radon transform $g(\rho, \theta)$ of a function $f(x, y)$ is defined as the integral along a straight line defined by its slope and line offset. Several expressions of the Radon transform exists but its most very popular form uses the parametric representation of a line $\rho = x \cdot \cos \theta + y \cdot \sin \theta$, where θ is the angle and ρ the smallest distance to the origin of the coordinate system. In this way, it computes projections of an image matrix along specified directions as follows:

$$\begin{aligned} g(\rho, \theta) &= \iint f(x, y) \cdot \delta(\rho - x \cos \theta - y \sin \theta) dx dy \\ &= \int_{-\infty}^{\infty} f(\rho \cos \theta - s \sin \theta, \rho \sin \theta + s \cos \theta) ds \end{aligned} \quad \text{eq. 1}$$

The parametric representation of a line is also used by other common computer vision operation known as the Hough transform. Therefore, being closely related, the radon function can implement a form of the Hough transform used to detect straight lines⁷. The Radon transform is able to convert two dimensional images with lines into a domain of possible line parameters, where each line in the image will give a peak positioned at the corresponding line parameters. This has lead to many line detection applications within image processing, computer vision, and seismics.

Modeling a line with certain parameters (ρ^*, θ^*) with the Radon transform expression in eq. 1:

$$\begin{aligned} f(x, y) &= \delta(\rho^* - x \cos \theta^* - y \sin \theta^*) \Rightarrow \\ g(\rho, \theta) &= \int_{-\infty}^{\infty} \delta(\rho^* - (\rho \cos \theta - s \sin \theta) \cos \theta^* - (\rho \sin \theta + s \cos \theta) \sin \theta^*) ds \\ &= \int_{-\infty}^{\infty} \delta(\rho^* - \rho \cos(\theta - \theta^*) + s \sin(\theta - \theta^*)) ds = \frac{1}{|\sin(\theta - \theta^*)|} \end{aligned} \quad \text{eq. 2}$$

and if $\theta = \theta^*$, i.e., $\sin(\theta - \theta^*) = 0$, it is found that

$$g(\rho, \theta) = \int_{-\infty}^{\infty} \delta(\rho^* - \rho) ds = \begin{cases} 0, & \text{if } \rho^* \neq \rho \\ \int_{-\infty}^{\infty} \delta(0) ds, & \text{if } \rho^* = \rho \end{cases} \quad \text{eq. 3}$$

The result is that a peak is formed when $\rho^* = \rho$ and $\theta = \theta^*$.

Figure 2 represents an overview of the use of this transform for line detection. In the figure on the second column, the strongest peaks in R give the angle (actually it is the complementary angle) and location of the longest straight line segment on the first column. The different slope of the lines on the first column leads to different shapes in the transform domain.

Figure 2. Example of the use of the Radon Transform. The locations of strong peaks in the Radon transform matrix correspond to the locations of straight lines in the original image.

By applying the Radon transform to captured thermographic sequences, each pixel evolution (as those shown in Figure 1) can be transformed in the Radon domain. The various slopes of the temporal decay of pixels are associated to peaks located in the correspondent Radon transform matrix. However, the goal is not to identify a line which could be considered as a fitting or regression of data. The goal is to distinguish if a pixel belongs to a defective or a non-defective area. Therefore, assuming a semi-infinite homogeneous material, only the inspection of the -0.5 slope area is required to make the discrimination.

Translating that slope into angles, a -0.5 slope corresponds to -45 degrees. If all the points in the temporal decay agree with a line of -0.5 slope (-45 degrees), what should be seen in the Radon domain would be a strong peak just in a point at the column -45 degrees. In this case, this simplicity never happens because the temporal evolutions of the superficial temperature gradient can be considered highly noisy lines in the log space. Analyzing the distribution of the matches in the selected column for the Radon transform matrix, we can find different profiles. A correlation exists with the existence or not of a defect, as well as with its depth. Consequently, it is possible to identify pixels belonging to a non-defective area as they present a sharp distribution of matches at column -45 degrees. Otherwise, pixels belonging to a defective area show a broad distribution, broader for deeper defects, as it is shown in Figure 3.

Once the Radon transform is applied to each pixel-temperature temporal history, the algorithm evaluates the obtained distributions of matches and performs some statistics on them (mean and standard deviation). In order to classify a pixel in a defective or a non-defective area-pixel, it is enough to observe the results of those statistics. By mapping the values of the standard deviation, an image as the one depicted in Figure 4 is obtained, where it is possible to classify easily the pixels depending on the existence or not of the defects. When a defect is to be found, the depth can be also estimated in a relative way. Next section contains some of the results obtained using the algorithm.

Figure 3. Transformed domain for some defective area (Pt. 1) and free-defect area (Pt. 4) pixels on Figure 1. On second column, differences on sharpness of distributions are clear.

3. EXPERIMENTAL RESULTS

200 thermograms (from $t=0.1$ to $t=20$ s) were captured using a Santa Barbara focal plane infrared camera, model SBF125 in a typical Pulsed Thermography setup with two photographic flashes (Balcar FX60). The sample inspected is a 4 mm-thick PlexiglasTM plate of dimensions 15x15 cm which contains 6 10 mm-diameter flat-bottom circular holes located at different depths of 1, 1.5, 2, 2.5, 3, 3.5 mm (see Figure 1).

Processing the sequence with the Radon Transform Algorithm, it is possible to obtain results that agree with those obtained with other methodologies. A comparative can be done observing the Figure 4. This algorithm is still computationally expensive (authors are working on improving it) but provides good enough-quality contrast images. For example, while the deepest defect is visible with this algorithm, this is not possible by the IDAC method (previous automated algorithm presented by the authors³). Results as good as those obtained with other methods as the second derivatives⁸ or the PPT method⁹ can not be obtained. These last two methods get much better results according to the detection of the deepest defect. However, they depend on the delayed time of the first image and, therefore, they need the implication of a decisive human intervention.

Figure 4. Best contrast images for: a) Radon Transform algorithm, here presented b) IDAC algorithm c) First and second derivatives and d) PPT method. The full scale colorbar of all the images are set between [0,1] to compare.

According to depth, the color scale presents a good correlation with depth as can be seen in Figure 5.

Figure 5. Dimensionless value on the Radon Transform obtained image for each defect versus the depth of the defect. The presented algorithm exhibits a high linear behavior. The deviation from the linear fitting is always less than 2%.

In summary, this algorithm makes feasible the elimination of errors due to different operator's interventions and then, it offers a better performance in the inspection of specimens. All the information is contained in just one image and leads to a quantitative estimation of the defect depths. Besides, the selection of a sound area, necessary in most thermographic post processing techniques, is eluded due to being based in a 1-D model.

4. CONCLUSIONS

An algorithm based on the Radon Transform is proposed for the analysis of Pulsed Thermographic sequences. It provides contrast images free of human decisions and avoids the necessity of defining a sound area and establishing the initial time of acquisition. A whole thermographic sequence is concentrated in just one image and a relative estimation of the defect depths is provided. The principal limitation is that the specimens under inspection should be semi-infinite homogeneous samples because this algorithm is supported on a 1-D Fourier diffusion equation approximation. Good agreement with other techniques has been achieved using a PlexiglasTM specimen.

ACKNOWLEDGMENTS

The Spanish Science and Technology Minister under project SiRAS TEC2004-05936-C02-02 have supported this work. The authors also thank the Natural Sciences and Engineering Research Council of Canada for their support in the development of this paper.

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