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Technical Note

In-plane bulk material displacement and deformation measurements using digital image correlation of ultrasonic C-scan images

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1. Introduction

Image correlation of speckle patterns has been used extensively to measure surface displacements and deformations. The use of laser speckle can be found in many types of coherent imagery. The use of the two-dimensional correlation method to measure the local displacement with laser speckle patterns is well documented (Fraley *et al.* 1981). This approach has been applied in several special cases as a calculation procedure to determine the local displacement components due to uniform translation in pixel resolution (Peters and Ranson 1982). A novel approach that determined the local displacement and deformation gradients was later developed and used successfully (Chu *et al.* 1986). This made use of an applied speckle pattern on a surface, and was later improved upon in terms of speed (Sutton *et al*. 1986).

Uses of the image correlation method for engineering applications are numerous including the measurement of plastic deformation in cellular alloys and the use of scanning tunneling microscopy (STM) for three dimensional strain mapping with nano-scale resolution (Bastawros *et al.* 2000; Vendroux and Knauss 1998). Industrial applications of ultrasonic imaging technology have grown in recent years as a practical tool for research, development and health monitoring. Resolution improvements of ultrasonic images are typically achieved by increasing signal frequency and using focused beams. Frequencies from the kHz to GHz ranges are used to generate digital images of regions deep within a material, or at the surface. The use of ultrasonics to resolve defects of dimension smaller than an individual composite layer has also been demonstrated (Byrne 1995). The resulting C-scan digital images produced can contain a granular appearance similar to those produced by optical speckle methods. Some preliminary work using ultrasonic imaging to measure displacements of a solid has been performed (Shaeffel *et al.* 1980, Hong and Ohr 1998), but very little work has been done to extend the technique to measure bulk deformations. Genetic Algorithms (GAs) are random search techniques that work on grouped pieces of information called chromosomes. They have been shown to have the ability to get out of local mininas and converge

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on the global minimas. The feasibility of using genetic algorithms for the image correlation process has already been demonstrated (Pilch *et al.* 2004). The focus of this paper is to use GAs for extracting subsurface displacement and deformation from ultrasonic C-scan images.

2. Theoretical background

Two images are analyzed to estimate displacements and strains. The aim of the method is to find the displacements and deformations of small subsets from the second image relative to the first one. This is accomplished by comparing the intensity levels (0-255) of the subsets in the images (Kahn-Jetter and Chu 1990). Usually method for comparing two subsets is commonly given by the use of the cross-correlation coefficient, C

$$C\left(\xi\left(u,\frac{\partial u}{\partial x},\frac{\partial u}{\partial y}\right),\eta\left(v,\frac{\partial v}{\partial x},\frac{\partial v}{\partial y}\right)\right)=\frac{\int_{\Delta M^*} f(x,y)*(x+\xi,y+\eta)dA}{\left[\sqrt{\int_{\Delta M}[f(x,y)]^2dA\int_{\Delta M^*}[f*(x+\xi,y+\eta)]^2dA}\right]}$$

where ΔM is the subset in the undeformed image, ΔM^* is the subset in the deformed image, u and v are the displacement in X and Y directions.

$$\xi = u+\frac{\partial u}{\partial x}\Delta x+\frac{\partial u}{\partial y}\Delta y$$

$$\eta = v+\frac{\partial v}{\partial x}\Delta x+\frac{\partial v}{\partial y}\Delta y$$

The values of u, v, $\partial u/\partial x, \partial u/\partial y, \partial v/\partial x$ and $\partial v/\partial y$ which maximize C are the local deformation gradients for the selected subset, the best correlation value is defined as -1.

Preliminary work on using the GAs for finding only two variables (u, v displacements) shows the GA approach to have a very high likelihood of converging to the right solution after the system has been calibrated for the images being used. Chromosomes encoding only potential u and v displacements were developed. The subset size is 21×21 pixels; Initial population is 500 chromosomes; the kill off rate is 50%; the mutation rate is 5%.

3. Experimental setup

Ultrasonic scans can be used to obtain the intensity images of the front or back surface of an isotropic material (steel, aluminum, particulate composite, etc.). It can also be used for images at different depths for laminated composite materials. An ultrasonic C-scan system with 3-axis computer controlled motion was used to obtain C-scan images for all the specimens. Fig. 1 shows the scan system transmission and control configuration. The frequency and focal length of the acoustical wave receiver (transducer) used in the tests are 25 MHz and 25.4 mm (1 inches).

The specimen was placed under the water when the transducer received the acoustical signals; a pulser/receiver provides a voltage spike to excite the generating transducer and amplifies the low-level received signals. These signals are converted into C-Scan images and waveforms by the A/D

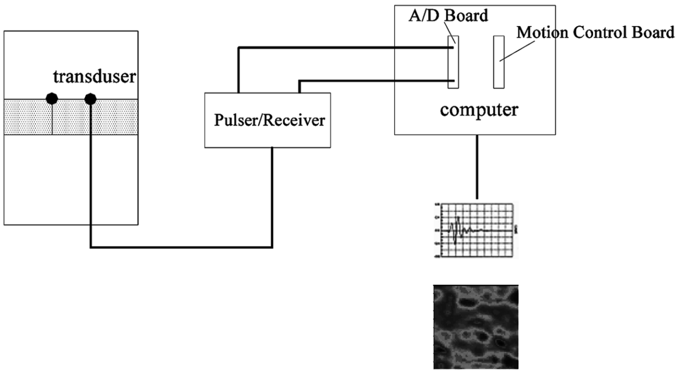

Fig. 1 Scan system transmission and control configuration

board (the analog to digital converter) in the computer. The transducer can move in X, Y, Z directions, which are controlled by the motion control system. In order to obtain digital images with a better resolution, the distance from transducer center to the scanning work-surface must match the focal length, and the data reorder speed is adjusted to the minimum value (0.254 mm/μs) of the C-scan system in both X and Y directions.

4. Results and discussion

Three experimental tests were designed. These tests include: 1) the uniform translation, 2) small angle rotation, and 3) the uniform deformation. Fig. 2 shows typical C-scan images taken before and after displacement, rotation and strain. The following sections present the results for the three cases.

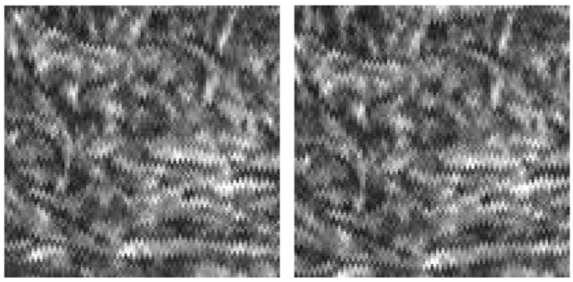

Fig. 2 Typical "before" and "after" C-scan images used to find displacement, rotation and strain

4.1 Uniform translation

A 305 × 305 × 8 mm laminated carbon/epoxy laminated composite panel was employed in this test. The C-scan images were obtained from the specimen's front surface. The image correlation program is used to calculate the displacements at various pixels intervals with various subset size. The image correlation program is used 10 times for each displacement test with varying pixel intervals and varying subset sizes. The average of the 10 is then taken for the displacement. A total of five scans were made in this test. The scanned area of interest (AOI) is 25.4 × 25.4 mm (100 × 100 pixels). This scan is made by moving the transducer at 2.54-mm (10 pixels) interval in the u-direction and at 2.54-mm (10 pixels) interval in the v-direction. The results are shown in Table 1.

Table 1 Uniform translation results

Displacement direction	Actual displacement (Pixels)	Average measured displacement (Pixels)
u	10	9.94
v	10	9.86

4.2 Small angle rotation

The composite material specimen that was used in the rotation test is the same as the uniform translation. The images were obtained by scanning the back surface, and the image area that was investigated is 17.78 × 17.78 mm

Table 2 Small angle rotation results

Actual angle of rotation (in degrees)	Measured angle of rotation (in degrees)
0.60	0.58
0.90	0.91
1.20	1.18
1.50	1.75

Table 3 Uniform deformation results

Actual measured strain (mm/mm)	Image correlation strain (mm/mm)
0.02075	0.02070
0.02588	0.03418
0.02836	0.03000
0.0310	0.03411
0.04718	0.04734

(260 × 260 pixels). The results are shown in Table 2.

4.3 Uniform deformation

This experiment was conducted to demonstrate the application of image correlation method with ultrasonic C-scan digital images in the determination of the normal strains. The surface of a rubber specimen that has randomly distributed tiny grooves was scanned to obtain the speckle pattern image. The AOI of the specimen is 25.4 × 25.4 mm (100 × 100 pixels). The image correlation program is used to calculate the strain fields at random pixel intervals and subset sizes. A total of five experiments were conducted varying ΔL in the Y-direction. The actual strains varied between with 0.02075 and 0.04718. The results are shown in Table 3.

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