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Real-time Measurement of Surface Deformation of Rotating Blades

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Abstract: This paper presents the results for the real-time measurement of surface deformation of rotating elements. A digital image correlation technique is used to estimate the surface displacements and strains. Speckle patterns are spray painted on the surface of interest and digital images taken before and during deformation caused by rotary motion. The digital image of the deformed blade is taken by freezing the speckled pattern with the help of a stroboscope. The technique provides several advantages over traditional methods in terms of obtaining whole-field deformation profiles, a non-invasive measurement scheme, and a simple and economical set-up. Results are presented for 1D uniform strain as well as 2D strain in a region next to a hole in a rubber specimen that is rotated at different speeds. The scheme presented in this paper can also be extended to measuring out-of-plane deformation by the use of an additional camera. The proposed technique can be used for measuring deformations in turbine blades, helicopter blades, or any other rotating elements.

Keywords: Image correlation, health monitoring, rotating blades, 1D in-plane strain, 2D in-plane strain

1. Introduction

Optical methods, such as holographic interferometry, shearography, laser speckle interferometry, and moiré were developed for measuring surface displacement and deformation. Some of these methods have been combined with the latest computer technology and imaging systems and developed into commercial scientific instruments. However, all of this equipment is still very expensive and requires a stable environment as well as laborious data reduction processes. Fraley, et al. [1] proposed the use of the two-dimensional correlation method to measure the local displacement with laser speckle patterns. This approach has been applied in several special cases to determine the local displacement components due to uniform translation in pixel resolution [2].

A more straightforward technique using digital image correlation method was developed in the early 1980's for measuring surface displacements and deformation. This method requires a digital imaging system to optically record images of the surfaces before and after deformation. The gray level functions of the images are then compared using advanced image correlation and processing algorithms in order to determine the displacements and deformation gradients. Unlike laser speckle techniques, which require an optically rough, reflective surface and minimal vibration, the only requirement for surface condition is a visually "speckled" surface. If not inherent to the material, this can be attained by application of a suitable random pattern such as with spray paints. This correlation method was later evolved into measuring both in-plane and out-of-plane displacements using two video cameras. A novel approach that determined the local displacement and deformation gradients was later developed by Chu et al. [3]. A much faster approach for image correlation was developed by Sutton, et al [4]. Instead of using the iterative approach such as coarse-fine method, a second order Newton-Raphson method was employed. This method improved the computation speed of the correlation. However, it presented some convergence difficulties.

Methods to determine three dimensional displacement have also been developed by combining digital image correlation, speckle metrology, and photogrammic or stereoscopic principles. These methods involve two cameras separated by a predetermined distance. The lines of sight from two cameras may either be parallel to each other [5,6] or form a pan angle between them [7]. As soon as two image points are matched by correlation methods, the three-dimensional coordinates of the physical point may be determined. A surface contour may be generated from one pair of stereo images, while deformation measurement requires the correlation of four images: a stereo pair before deformation and another after deformation.

Uses of the image correlation method for engineering applications are numerous. Recently, the measurement of plastic deformation in cellular alloys and the use of scanning tunneling microscopy (STM) for three dimensional strain mapping with nanoscale resolution has been reported [8-11]. The technology has been shown to be useful in studying the formation and evolution of plastic flow in alloys, and for high temperature measurements of surface deformations [12, 13]. Clearly, the correlation method has received considerable attention as a digital image analysis tool.

Various numerical techniques, such as the Newton-Raphson method, have been used for the image correlation process. This paper outlines the innovative use of Genetic Algorithms (GAs) for the search process. Genetic algorithms are random search techniques that operate on grouped pieces of information called chromosomes. The chromosomes contain all the information about the potential candidates for a minimization problem. At each iteration an objective function (cost function) is evaluated for all the existing chromosomes. The best chromosomes are kept and the worst discarded. The best chromosomes are then mated with each other to replenish the population, and the cost function evaluated again. Some of the chromosomes are then deliberately mutated to help in getting the search out of local minima [14]. Hence, the GAs provide the following strengths: Converge much faster, can cover a much wider search space, have the ability to get out of local minima due to the mutation effect, and can handle numerous variables at the same time without increasing the search time by the same proportion. In fact, there is some evidence regarding the benefits of using genetic algorithms for digital image correlation. Brooks, *et al.* [15] have reported some preliminary work where genetic algorithms are used to optimize correlation of gray-scale images. However, their focus was merely to minimize the effect of noisy sensors, and not to develop a versatile and robust method for the challenging task of extracting subsurface information.

Results on uniform 1D displacement and strain in rotating elements have been presented earlier [16] and are summarized in this paper too. The focus of this paper is to report preliminary results for the 2D case, i.e. strain measurements in a region next to a hole in a specimen that is under rotation.

2. Technique

The technique uses a spray painted speckle pattern on a specimen. The procedure entails the application of a random speckle pattern to a surface of interest, then capturing a digital image of the surface [3,16,17].

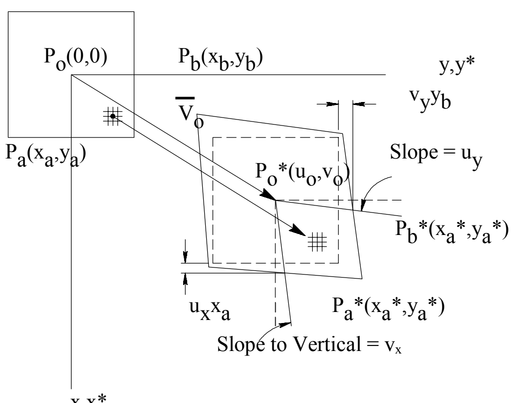

Figure 1: Local Deformation

This is followed by capturing an image after the surface has displaced or deformed, and then comparing the two images to compute the displacement and strain field for the surface. The location, shape and size of the shifted subset are determined by the state of strain and the mechanics of the material under investigation. Local deformation of a subimage, the corresponding displacement components and deformation gradients are shown in Figure 1.

The method for comparing two subsets is commonly given by the use of the cross-correlation coefficient, C,

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

where ΔM = subset in the undeformed image, ΔM^* = subset in the deformed image

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

The values of $u, v, \frac{\partial u}{\partial x}, \frac{\partial u}{\partial y}, \frac{\partial v}{\partial x}, and\ \frac{\partial v}{\partial y}$ which maximize C are the local deformation gradients for the selected subset. *The main objective of the image correlation process is to find these six values for the subset under investigation, and then repeat it for all subsets in a given region so as to find the whole-field deformation profile*.

3. Results on 1D Deformation in a Rotating Body

This section gives the results of deformation measurement for a body under loading due to the centrifugal forces caused by rotation at high speeds.

A motor was attached with a circular disk that had a slot machined in it. A flexible rubber sheet was pinned at the center and allowed to move within the slot. This was done to avoid out-of-plane movement. Weights were attached at the ends of the rubber sheet to allow for maximal expansion during rotation. A stroboscope was aimed at the rubber sheet with the camera placed near the disk. A CCD QuickCam is used to capture images, which are automatically downloaded to a computer. The QuickCam is calibrated for 14.016 pixels/mm or 1 pixel=0.071347 mm (356 pixels/inch). See Figure 2 for the experimental setup.

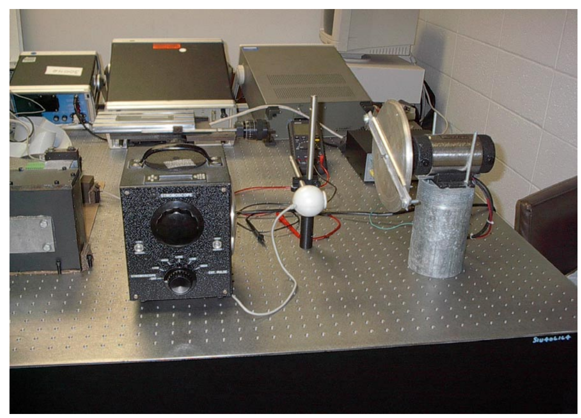

Figure 2: Experimental Setup

An image was taken of the rubber sheet before the disk was spun, and then another image was taken while the disk was rotated at 550 rpm. The stroboscope was used to freeze the image so that a good digital image could be taken. Figure 3 shows both the images.

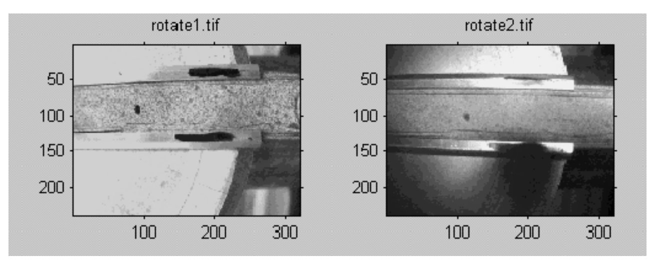

Figure 3: Images used for correlation (1D case)

A reference dot was used to make sure that the correct side was imaged under rotation. The actual strain in the radial direction was calculated by using the actual deflection due to the centrifugal forces caused by rotating at 550 rpm. The actual deflection was estimated by the following two methods:

- The centrifugal force was calculated at 550 rpm, and then an equivalent weight was hung at the bottom of the same length material. The actual deflection was then manually measured.
- A scale was placed at the back of the rotating weights, and the specimen rotated at 550 rpm. The change in the length of the specimen was then noted and the actual deflection extracted.

The average of the two methods gave an estimated deflection of 0.55 inches. The length of the specimen was 5 inches. This gave a 1D radial strain of 0.1100. Using a poisson's ratio of 0.45 [18] for a rubber specimen, the lateral strain was calculated to be -0.0495. The image correlation method gave a radial strain of 0.1250 and a lateral strain of -0.0385. The results are summarized in Table 2.

Table 2

	Strain (radial)	Strain (lateral)
Calculated Value	0.1100	-0.0495
Measured Value by using image correlation	0.1250	-0.0385
Actual Error	-0.0150	-0.0110
Percentage Error	13.60 %	22.22 %

Note, the results match well, though there is still a large percentage error. There can be various reasons for this such as error in calculating the actual deflection, poisson's ratio for the material, low resolution images, etc. Further investigation and improvement in these results remains as future work.

5. Results on 2D Deformation in a Rotating Body

This section presents results on 2D deformation on the surface of a body that is undergoing rotation. A higher resolution camera was used for this part of the experiment (32 pixels/mm or 1 pixel = 0.03125 mm).

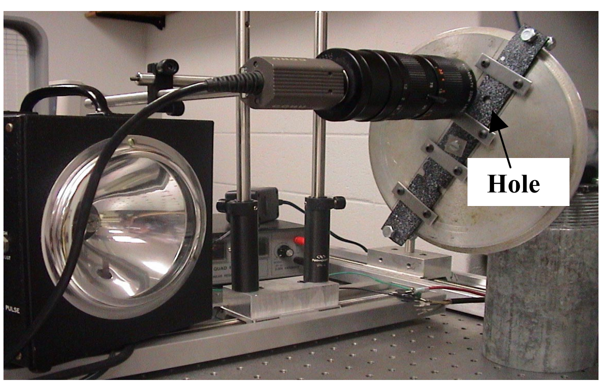

Figure 4: Experimental setup (specimen with hole)

The before and after (during rotation) images are shown in Figure 5. The hole is 5mm diameter.

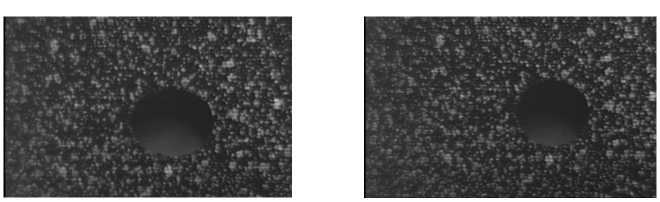

Figure 5: Images used for correlation (2D case)

A small region above the hole (70 x 140 pixels equivalent to 2.1875 x 4.375 mm) was isolated for strain measurement. Figure 6 shows the Exx strain in that region.

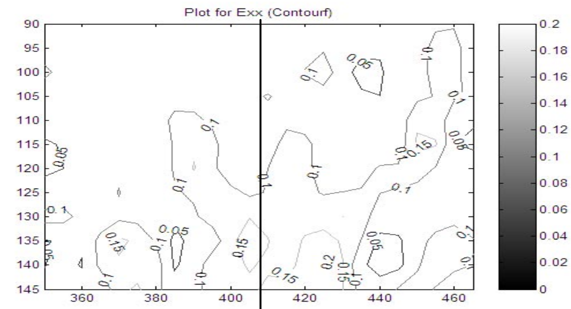

Figure 6: Exx strain contours near the edge of the hole

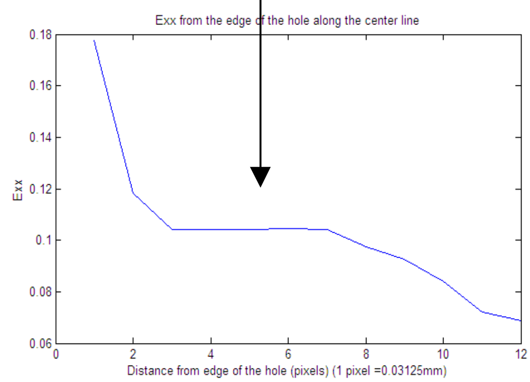

Figure 7: Exx strain profile along the center line

The edge of the hole is at pixel location 410 in the x-direction. The high strain contours are consistent with the strain contours of a similar specimen under static displacement.

For verification of the results, a similar analysis was done for the 2D case as presented for the 1D case. The specimen was statically loaded with a weight equivalent to the centrifugal force caused by the rotational speed of 1007 rpm. The static deflection was measured and the average strain was calculated to be 0.0700. The far-field strain estimated by the image correlation method was 0.0771. The percentage error was found to be 10.14%. As can be seen in Figure 7, the highest strain was measured to be 0.1775 which is approximately 2.3 times the far-field strain.

6. Conclusions and Additional Future Work

This paper presents a digital image correlation technique to estimate surface displacements and strains on rotating blades. Realtime estimation of blade deformation is possible due to the use of genetic algorithms. Speckle patterns are spray painted on the surface of interest and pictures taken before and during loading caused by rotary motion. Subpixel accuracy, required for measuring displacements and strains accurately, is obtained by using interpolation methods. The technique provides several advantages over traditional methods in terms of obtaining whole-field deformation profiles, a non-invasive measurement scheme, and a simple and economical set-up.

This paper reports on very preliminary results on the 1D and 2D strain profiles on a rubber element that is fixed to a disk which is under rotation. Future work entails the use of a higher resolution digital camera, more control on lighting conditions, and a thorough study on optimal conditions for speckle size, image subsize used for correlation, etc. The scheme presented in this paper will also be extended to measuring out of plane deformation by the use of an additional camera.

The proposed technique can be used for measuring deformations in turbine blades, helicopter blades, or any other rotating elements.

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