DETERMINATION OF HIGH TEMPERATURE STRAINS USING A PC BASED VISION SYSTEM

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INTRODUCTION

With the widespread availability of video digitizers and cheap personal computers, the use of computer vision as a experimental tool is becoming common place. Theses systems are being used to make a wide variety of measurements that range from simple surface characterization to velocity profiles. The Sub-Pixel Digital Image Correlation technique[1,2,3] has been developed to measure full field displacement and gradients of the surface of an object subjected to a driving force. The technique has shown its utility by measuring the deformation[4,5,6] and movement of objects that range from simple translation to fluid velocity profiles[7] to crack tip deformation of solid rocket fuel* . This technique has recently been improved and used to measure the surface displacement field of an object at high temperature.

DIGITAL IMAGE CORRELATION

Sub-Pixel Digital Image Correlation uses a digitized image of a random pattern attached to the surface on an object. The pattern may consist of the natural surface finish, if appropriate, or may be applied using any method which will produce a random "speckle" pattern. A representative pattern is shown in Figure 1. After the object is subject to a driving force a second image is acquired. The movement of the pattern on the surface can be determined by correlating the two image's intensity patterns. Sub-Pixel accuracy is obtained by interpolation between pixel gray levels. Typical accuracy for this technique is $\pm$ 0.02 pixels[8].

The correlation is performed by selecting from the undeformed image a set of neighboring pixels around the point of interest. The subset must be large enough to contain a unique portion of the surface's random pattern. A typical subset size is 20 pixels by 20 pixels. The subset chosen is then compared to subsets of the deformed image to find a match.

* Sutton, M.A., work in progress.

Because the corresponding subset in the deformed image will probably not only be translated but also be deformed, the comparison of the subsets is done by also deforming the original subset to find the match. The deformation across the subset is assumed to be linear. The deforming of the subset is performed using

$$x^* = x + u + \frac{\partial u}{\partial x}dx + \frac{\partial u}{\partial y}dy$$
$$y^* = y + v + \frac{\partial v}{\partial x}dx + \frac{\partial v}{\partial y}dy \qquad (1)$$

where x and y are the coordinates of a pixel in the subset before deformation, u and v are the displacement of the center of the subset, and dx and dy are the distances from the center of the subset to the pixel.

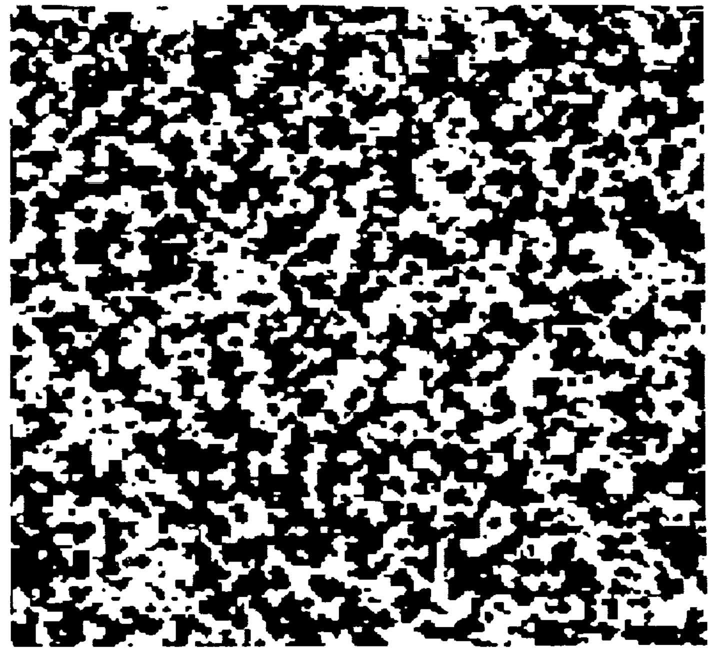

Figure 1. Representative speckle pattern.

The correlation function used is

$$C\left(x,y,u,v,\frac{\partial u}{\partial x},\frac{\partial u}{\partial y},\frac{\partial v}{\partial x},\frac{\partial v}{\partial y}\right) = 1 - \frac{\sum_{i,j=1}^{n} A(x_i,y_j) * B(x_i^*,y_j^*)}{\sqrt{\sum_{i,j=1}^{n} A(x_i,y_j)^2 \sum_{i,j=1}^{n} B(x_i^*,y_j^*)^2}} \qquad (2)$$

where $A(x_i,y_j)$ is the gray level at in the undeformed image at location (x_i,y_j), $B(x_i^*,y_j^*)$ is the gray level in the deformed image at location (x_i^*,y_j^*) which was determined by Equation 1, and n is the subset size.

When the image is digitized each pixel is assigned a single value representing the intensity over a finite area of the sensor. The correlation technique was designed assuming that the gray level value is at the center of the pixel. The mapping of Equation (1) usually maps integer pixel locations of the undeformed image to non-integer locations in the deformed image. To determine the gray level at these non-integer locations bi-linear interpolation is used. The formula for this interpolation is

$$B(x,y) = a_1 + fract(x) * a_2 + fract(y) * a_3 + fract(x) * fract(y) * a_4 \qquad (3)$$

where

$$a_1 = B(int(x),int(y))$$

$$a_2 = B(int(x+1),int(y)) - B(int(x),int(y))$$

$$a_3 = B(int(x),int(y+1)) - B(int(x),int(y))$$

$$a_4 = B(int(x+1),int(y+1)) + B(int(x),int(y))$$

$$fract(x) = fractional\ part\ of\ x$$

$$int(x) = integer\ part\ of\ x$$

The correlation used in the work presented here assumes that all motion of the object is parallel to the camera's image sensor. When this is true then the displacement of the subsets from the undeformed image to the deformed image is proportional to the displacement of the object's surface, and the gradient terms are equal to the gradients of the object's surface. When long focal length lenses are used small amounts of movement toward the camera can be tolerated without significant error being introduced. 3-D correlation methods are available[†,‡,§] which can handle large amount of out-of-plane motion.

PC IMAGE CORRELATION

The program required to perform sub-pixel correlation is memory and CPU intensive. In the past, the program was run on a VAX 11/780. By running on a machine such as this, there are a host of problems associated with the transferring of the images between the vision system and the computation system. Due to the increase in power and memory capabilities of personal computers, the correlation program has recently been implemented on a PC[‖]. By implementing the program on the PC, the system which acquires the images can now be used to correlated them. This allows for ease of implementation and quicker turnaround.

The PC based correlation program runs under Windows 3.0. It was written so that other applications can be run at the same time. It is user friendly with features which allow it to run automatically or on a point by point basis. Images from different sources and different formats can be used. It can display images on the PC monitor (requires a super-VGA monitor card with 1-Mbyte RAM). Two different correlation schemes are available and user selectable.

The processing times for PC based correlation are, of course, dependent on the machine configuration. When running a PC configuration of 486, 33Mhz, 8MegRam, 64K CPU cache, and

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[†] McNeill, S.R., Sutton, M.A., Miao, Z., Ma, J., "Automated Measurement of Surface Shape by Computer Vision: Part I", submitted for review to IEEE Transactions on Pattern Analysis and Machine Intelligence, 1992.

[‡] McNeill, S.R., Sutton, M.A., Miao, Z., Ma, J., "Automated Measurement of Surface Shape by Computer Vision: Part II", submitted for review to IEEE Transactions on Pattern Analysis and Machine Intelligence, 1992.

[§] McNeill, S.R., Sutton, M.A., Ma, J., Miao, Z., "Image Correlation for Determination of 3-D Displacements and Gradients", paper in preparation.

[‖] Work done on contract by S.R.McNeill Services, NAS8-39030.

64K Disk Cache the correlation time per point is the same as the program used on the VAX 11/780. In addition, due to the nature of the PC, when image correlation is being performed on a large number of points per image, results are obtained faster for the PC than for a multi-user VAX 11/780.

EXPERIENTIAL DETERMINATION OF HIGH TEMPERATURE STRAINS

One application of the systems described above is in the area of high temperature strain measurement. To test the viability of such a system, an extensive experimental program was initiated and recently completed to quantify thermal strains by computer vision for temperatures from 0 to 1200°F. The experimental setup, shown in Figure 2, included a Lindberg Furnace with radiative heating elements and a central open area 250mm X 250 mm X 200mm. The door of the furnace had a 100mm X 50mm viewing area. The viewing area contained two thin panes of high quality sapphire glass, with the panes separated by 38mm, to minimize optical distortion. All of the specimens were rectangular thin strips, approximately 25mm X 50mm X 3mm in size. Both aluminum and titanium alloys were used. The surface preparation prior to obtaining the digital images included spray painting each specimen with a random black and white pattern, using high temperature paint. The maximum temperature for the paint is approximately 1200°F. After painting, the specimen was heat cured in the oven to ensure stability of the paint during the tests. For the strain tests, each specimen was placed on a high temperature ceramic stand in the middle of the furnace open area. The stand was used to support the specimen during the test and to minimize out-of-plane motion of the specimen due to expansion of the oven interior. The specimen was illuminated by white light using a fiber optic lamp placed directly outside of the furnace door. A video camera was placed approximately 2.2 meters away with various Nikon lenses used to magnify the image. Typically, the image-camera resolution was 40 pixels per mm on the object surface. The images were obtained during the high temperature test and stored in the computer for detailed analysis after the test was completed.

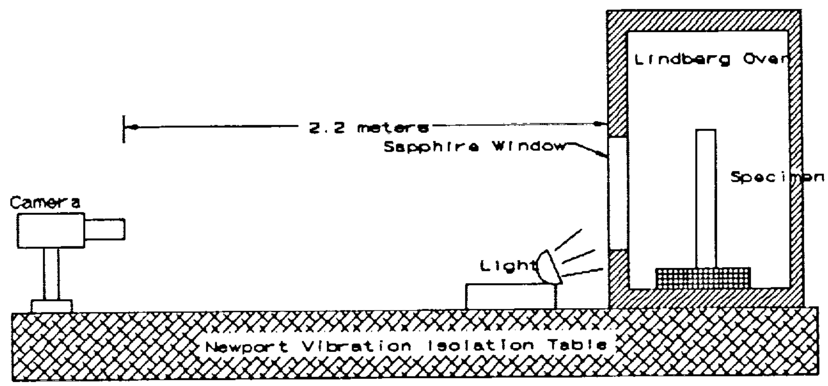

Figure 2 Experimental Setup

After several experiments were completed, it was determined that thermal oscillations in the air outside of the sapphire windows were the primary source of noise in the optical images. To reduce this noise, several approaches were tried. The most successful was the use of a steady flow of air over the surface of the sapphire windows. This was accomplished by using a small fan to blow room air over the windows. Images obtained using this procedure at temperatures of 0, 400, 800 and 1200°F were obtained. Results for the displacement field on the specimen surface were determined to be relatively free of large variations due to the thermal convective air currents.

To obtain the surface strain fields, the displacement fields at each temperature were first smoothed[9]. By averaging approximately 1000 derivatives of the smoothed displacement fields over the surface of the specimen, and using small strain-displacement gradient theory, the surface strains could be estimated. Results of several tests indicate that (a) the point to point variation in optically measured strain (this is important if the strain field is not uniform) is on the order of 300 microstrain, (b) the average strains, obtained by comparing several composite images obtained at one temperature, vary by 10-30 microstrain, (c) the thermal oscillations in the air outside the window are almost solely responsible for the errors in the strain data and (d) comparison of the optically estimated thermal coefficient of expansion to data obtained from the literature indicates that the optical values are within the scatter in available data.

EXPERIMENTAL RESULTS

A representative sample of the data obtained is shown in Figure 3 and Figure 4. The ±0.02 pixel error can be seen in the data.

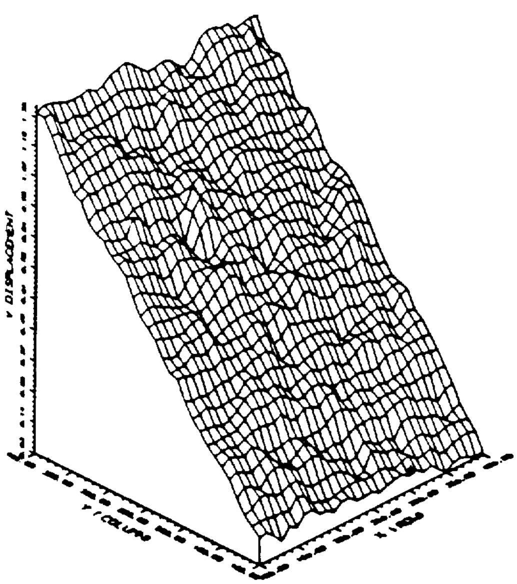

Figure 3 V-Displacement at 800°F

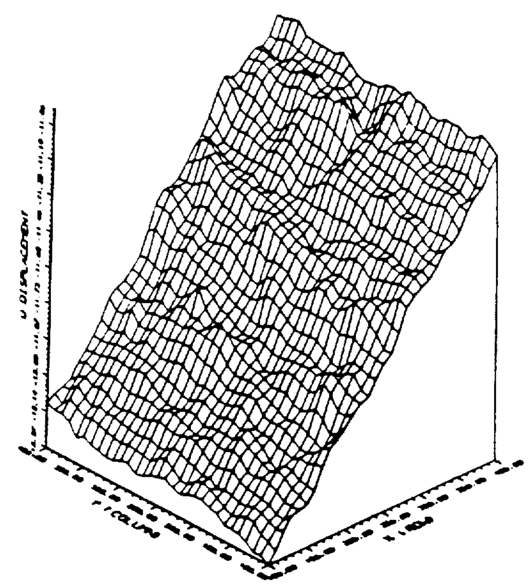

Figure 4 U-Displacement at 800°F

The data was smoothed and is shown in Figure 5 and Figure 6.

It is emphasized that the images shown in Figures 3 and 4 were obtained using the small fan to "randomize" the effect of the convective currents. If the fan is not used, the effects of these currents can be seen in Figures 7 and 8. Figs. 7 and 8 are correlation results from two images that were taken at the same temperature but different times. If a fan is used to circulate the air then the plots would have been essentially flat.

SUMMARY

In summary, the development of a PC based Sub-Pixel Digital Image Correlation system has yielded an accurate and easy to use system for the measuring surface displacements and gradients. Experiments have been performed to show the system is viable in use of measuring thermal strain.

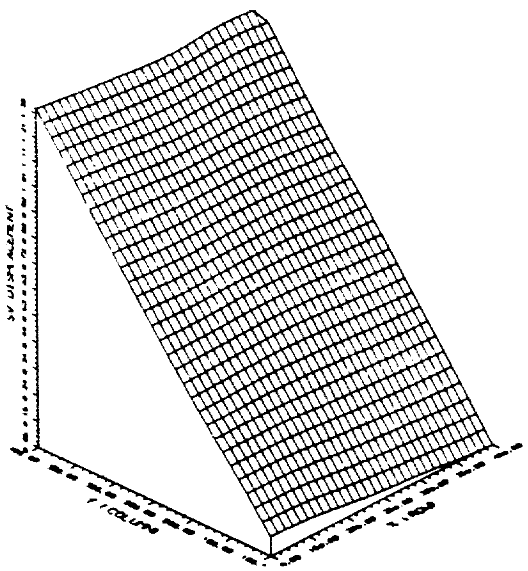

Figure 5 Smoothed V-Displacement at 800°F.

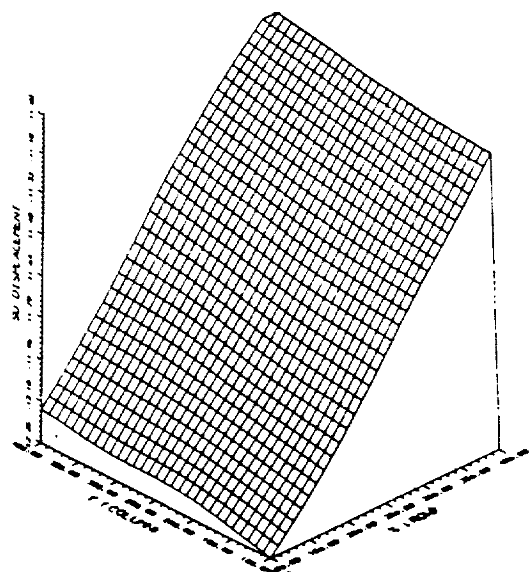

Figure 6 Smoothed U-Displacement at 800°F.

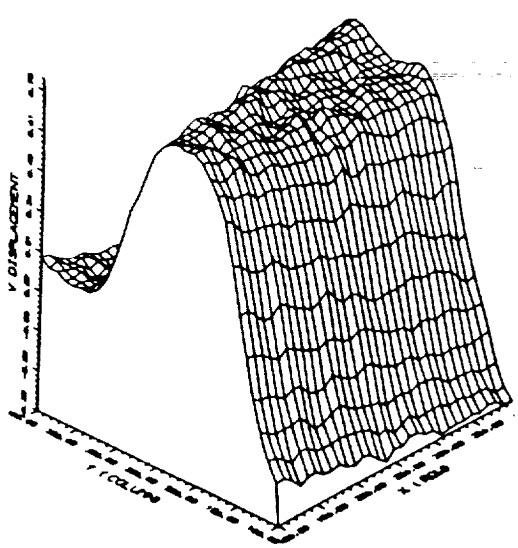

Figure 7 V-Displacements due to convective current.

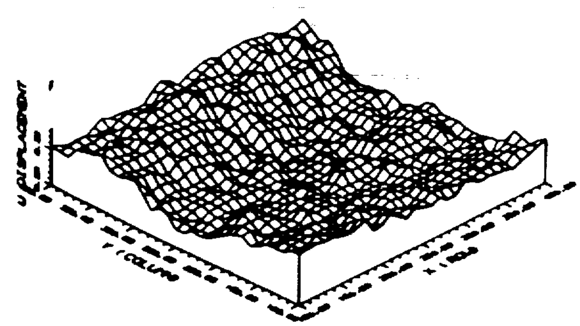

Figure 8 U-Displacements due to convective currents.

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