A NEW FOURIER-TRANSFORM SPECKLE INTERFEROMETRIC METHOD FOR MEASURING LARGE OBJECT DEFORMATION

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Abstract: In this paper we propose a new method to measure large object deformations using speckle interferometry. The principle of the method is that the object is deformed continuously and a large number of frames of the object motion are collected to be analyzed at a later time. The object deformation is then retrieved from the data by Fourier transformation. The method is capable of measuring deformations of over 200 microns that is not possible using conventional electronic speckle pattern interferometry. We discuss the underling principle of the method and results of the experiment. Some nondestructive testing results are also presented in this paper.

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1. Introduction:

Speckle methods have been used for different deformation measurements because of several advantages and especially for the simplicity of experimental arrangement as well as theory of fringe formation [1]. Electronic processing of the speckle interferometric pattern called Electronic Speckle Pattern Interferometry (ESPI) has enhanced the possibility of real-time and highly quantitative analysis [2-4]. However, the speckle interferometric methods suffer because of its high sensitivity that is of the order of half the wavelength of light. For larger deformations the number of fringes that can be observed is dependent on the size of the CCD array. With a 512 x 512 array one can observe about 20 fringes on the monitor with reasonable good quantitative analysis. Therefore, the upper limit on the object deformation is about 6 μm to 7 μm. Several methods to reduce the sensitivities have been reported of which two beam illumination with a small angle between them [5], oblique incidence and observation [6] and longer wavelength lasers [7].

The purpose of this paper is to report a new method that can be used to extract the object deformation using Fourier transformation of the speckle pattern recorded in a sequence as the object is being deformed. This technique can measure large object deformation ranging from few tens of microns to few hundreds of microns. The range of deformation measurement is dependent on the instrumentation and the correlation between the speckle patterns. The analysis of the obtained sequence of speckle pattern is the same as in the Fourier-transform technique for fringe pattern analysis [8]. This Fourier-transform technique has been combined with wavelength shift for measuring step height and object shapes called Fourier-transform speckle profilometry [9-11]. The technique we propose can measure changes in object shape unlike profilometry. First we describe the principle behind the method and then the experimental results. Some results with nondestructive testing and the limitations of this method are also discussed.

2. Theory of the method:

The schematics of the Fourier-Transform speckle interferometric method is shown in Fig. 1. The configuration is similar to that of the Michelson's interferometer, except that one of the mirror is replaced with the diffuse object. The mirror arm and the object arm are set to have arbitrary path length from the beam splitter. A telecentric system is used to focus the object onto the sensor of a high speed CCD camera. The telecentric system insures the propagation axis of the beam from the mirror and the object is collinear.

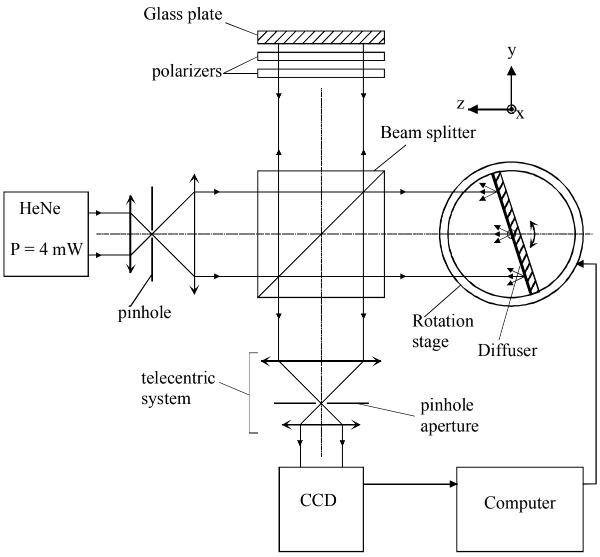


Fig.1: Schematic of the experimental arrangement of the Fourier-transform speckle interferometric method.

It is very well known that the angle between the object and the reference beam should be such that the fringes modulating the individual speckles must be resolved by the CCD camera. The beam from the mirror serves as the reference beam and therefore has to be reduced such that it is of the same intensity of the object beam. We have also used a reference scattering surface instead of the mirror. The object and the reference beam interfere forming a complex interference pattern. The intensity at an image point of the object can be expressed as

$$I(x, y, t) = I_0(x, y)\left\{1 + V\cos\left[\Phi_0(x, y) + \frac{4\pi Z(x, y, t)}{\lambda}\right]\right\} \qquad (1)$$

Where $I_o(x,y)$ is the bias intensity of the speckle pattern, V is the visibility of the speckle modulation, $\Phi_0(x,y)$ is the random phase, and Z(x,y,t) is the direction at which the object is deformed. The sensitivity of the speckle interferometric system in our arrangement because of the illumination lies along the Z-direction. Let us consider one point on the object and as the object is deformed the intensity fluctuation is recorded as a function of time. If the deformation is kept linear then the intensity fluctuation is sinusoidal with one frequency. Assuming that the object deformed $\Delta Z(x,y,t)$ distance in t seconds, then the temporal frequency of the signal observed at a given point of the object is

$$f(x, y) = \frac{2\ \Delta Z(x, y, t)}{\lambda\, t} \qquad (2)$$

This shows that the temporal frequency of the signal observed at different points on the object is different if the deformation is different. In our method a series of frames of the speckle pattern is recorded as the object is being displaced linearly. With the high speed digital CCD camera we can record as many as 800 frames per second. Each frame is then a record of the speckle and it intensity at that instant of time. Thereby a record of the time propagation of speckle is obtained as the object is deformed. One method of observing this change is to determine the difference in the temporal frequency at various points on the object. Alternately by taking the Fourier-transform of the signal then for a single temporal frequency two sharp spikes must be obtained at either side from the center in the frequency plane. The separation of the peak from the center can be used to determine the distance of displacement at the given point. It is well known that the accuracy of the Fourier-transform analysis increases if the temporal frequency is greater and sharper. This is usually obtained for large object deformations. However, to create large object deformations the correlation of the speckle pattern has to maintained. The speckles in the time domain are correlated if the following condition is met.

$$D = \frac{4\lambda}{\alpha} \qquad (3)$$

Where α is the half angle subtended by the aperture of the imaging system with the optic axis. The speckle correlation can be increased by reducing the half angle. Also in the speckle profilometry the temporal frequency is chosen such that the temporal variation of the bias term is small thereby three spectra can be separated. Finally using a band-pass filter one of the side order peaks is filtered and an inverse Fourier-transform is applied to the analytical signal to retrieve the phase information at that point from the imaginary part of the transform. This procedure is slightly different from the method proposed by Takeda [8]. The phase is then unwrapped as in phase shifting interferometry and thereby a 2-D map of the phase of the object deformation can be generated. The final phase can be expressed as

$$\Phi\,(x, y) = \Phi0(x, y) + \frac{4\,\pi \Delta Z(x, y)}{\lambda} \qquad (4)$$

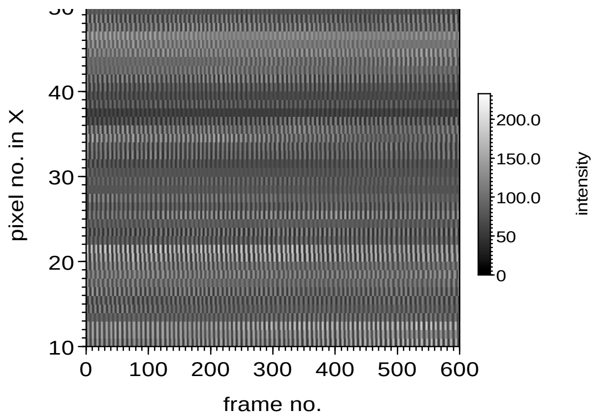
where Φ_0 is the initial phase which is usually a constant and can be disregarded. Essentially the instantaneous angular frequency or the linear velocity generated during deformation of the object point is determined. From these extrapolations the 3-D plot of the object deformation can be extracted.

3. Experimental Procedure and Results:

3.1 Object tilt:

A He-Ne laser with a power of 4 mW was used in our setup. To test the principle of the method an aluminum plate was taken and mounted on a computer controlled rotational stage. Tilting of the plate will produce linearly varying displacement along the Z axis from the center of rotation. The intensity of the image on the CCD camera was adjusted to lie within the dynamic range of the camera. The intensity of the reference beam was adjusted by the help of two polarizers so that the same polarization state was maintained between the reference and the object beam.

As the different specimens that were investigated were coated either with aluminum and retro-reflective paint for effective use of the laser power, the scattered light had the same polarization state as that of the incident beam. Finally the speckle size was adjusted to be of the order of the pixel size. The rate of rotation of the object was determined so that at least 120 cycles of the intensity fluctuations was observed.



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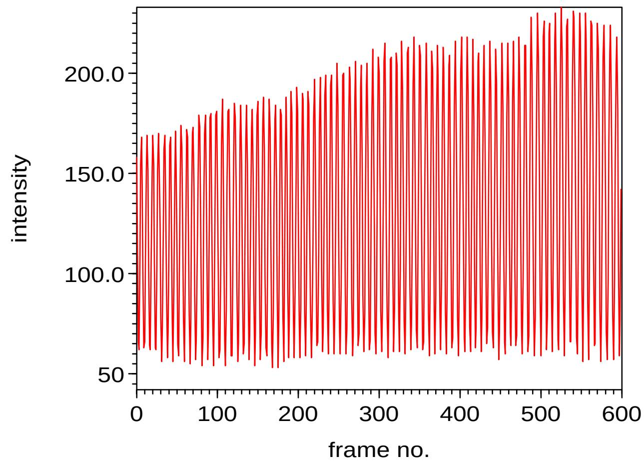

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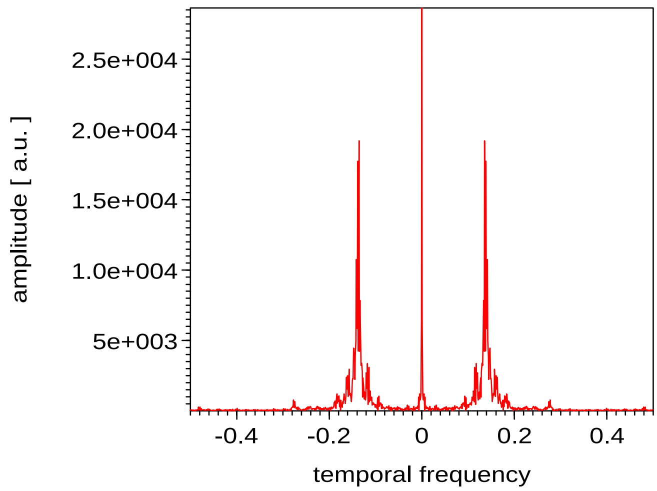
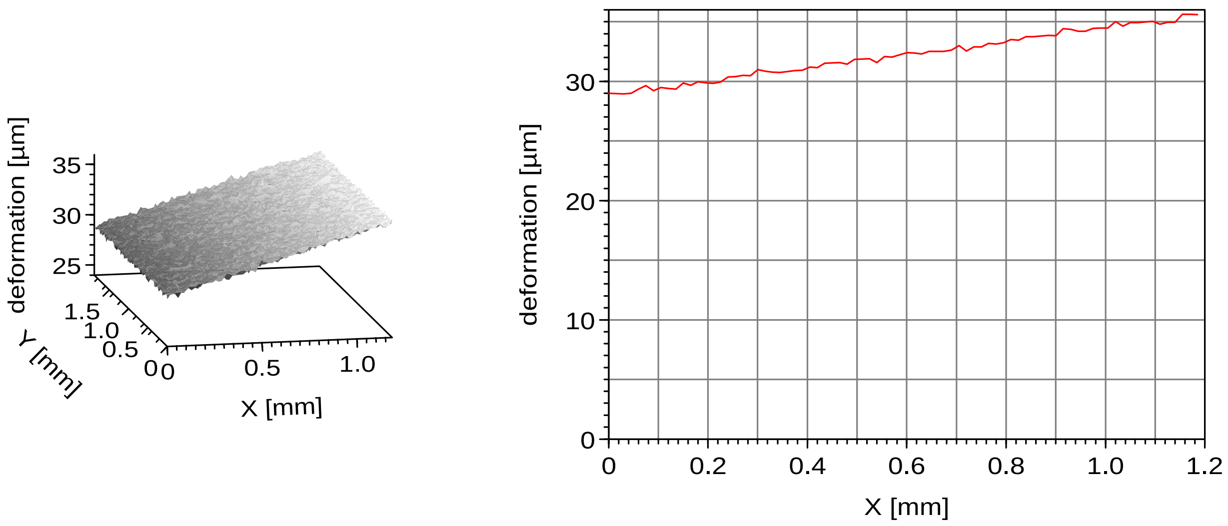


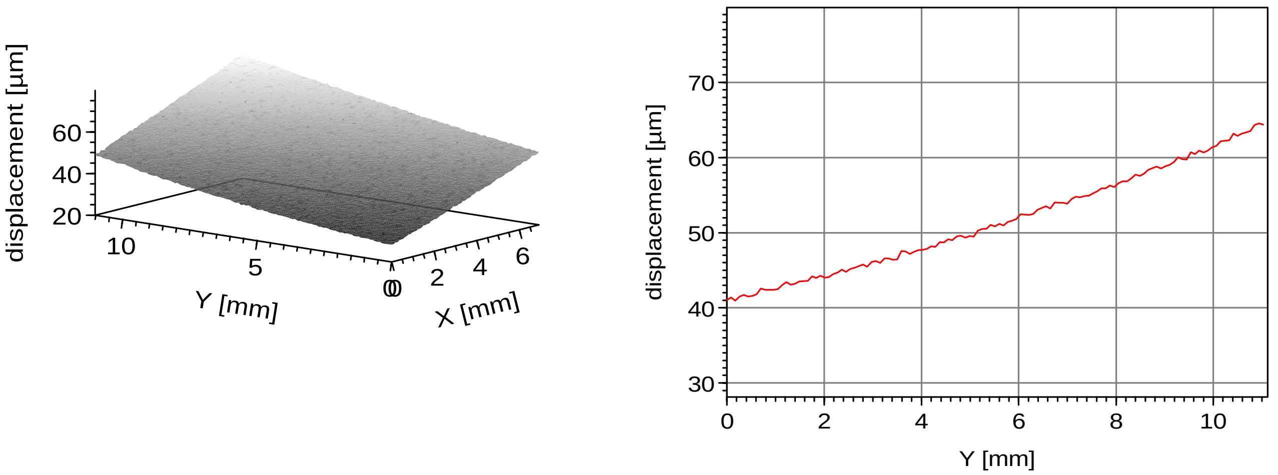
(c)

Fig. 2: Experimental results with tilting of a aluminum plate.
a) Shows the slice of one horizontal line of pixel from each frame stacked together. Only 600 of the 1024 frames are shown to clearly depict the speckle modulation. b) The intensity fluctuation of one speckle as a function of time. c) The Fourier-tranformation of the temporal signal shown in (b).



(a) (b)

Fig. 3: Shows the data processed using Fourier-transform techniques with no filter for smoothing of the speckle noise. a) The 3-D plot of a small section of the object that was tilted by 0.28 degrees. b) A slice along the 3-D plot to show the tilt. Displacement of the object at one end is 28 µm and at the other is 36 µm.



(a) (b)

Fig. 4: Shows the results with the bending of the plate of about 80 µm in the direction of observation. a) The 3-D plot of the deformation obtained with FFT process and no filter was used to smoothing the data. b) An arbitrary slice along the 3-D plot showing the bending of the plate.

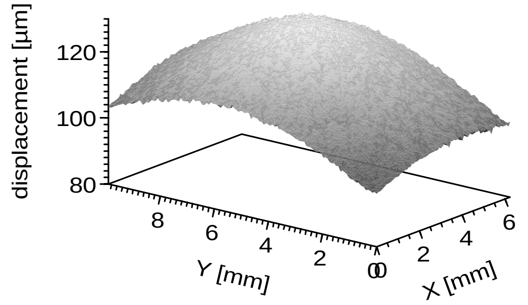
Acquisition of the 1024 frames as well the rotation of the stage was computer controlled. Figure 2a shows one horizontal slice from each frame stacked with the time along the vertical axis. In order to show the speckle intensity fluctuation with time not all the 1024 slices are shown in the figure. The fluctuations of the each individual speckle as the object is rotated can be observed. A plot of the signal at a pixel point is shown in Fig. 2 b and the corresponding FFT of the signal is shown in Fig. 2 c. The separation of the one of the peak of the spectra gives the angular frequency of the signal and thereby the displacement of the object. In our experiments on a 7 X 5 mm area of the object was observed. The displacement of object between 80 μm and 120 μm was measured and the 3-D plot of the tilt and a slice along one axis is shown in Fig. 3 a and b. The data presented in these figures were not smoothed to eliminate speckle noise. Calculations using the rate of rotation and the point of observation agrees quite well with our results from FFT.

3.2 Plate bending:

To study object with non-uniform displacement a rectangular plate 28mm x 18 mm was (Taken from a top of a damaged 3 ¼ floppy) used. The plate was clamped along its smaller side and point loaded at the other side. The direction of loading was along the sensitivity axis that is the Z-axis. The rotation stage was used for loading the object in this case by having a long rod attached to a point away from the center of rotation. Experimental results for the rectangular plate showed feasibility of this method to study non-uniform deformation. In order to determine the quality of the data for speckled reference beam, the glass plate generating the reference specular beam was replaced with a ground glass plate. The intensity of the speckle reference beam was adjusted with the help of a neutral density filter to match the object beam. A series of trails was carried out and Fig. 4 a shows the 3-D plot of the plate deformation. Figure 4 b shows a slice along the 3-D plot confirming the bending of the plate.

3.3 Circular diaphragm:

A plate clamped along its edges and loaded at the center was used as our object of study to test this method. The plastic sheet of 1.0 mm thickness was cut to a circular shape of around 65mm with a clear aperture of 60 mm and clamped uniformly along its edges. The object was then point loaded at the center with the tip of a dial gauge whose scale reading can be read to one μm accuracy. The dial gauge was then loaded with a step-up motor operated linear translation stage where the speed of translation and the distance translation was controlled by the computer to synchronize with the data acquisition. The distance of translation was determined so that not more than 512 cycles was obtained during data acquisition of three seconds. In order to obtain one constant frequency the data was usually acquired after two seconds of loading. A series of trials on this object was carried out. The technique was found to be robust and immune to external disturbances.



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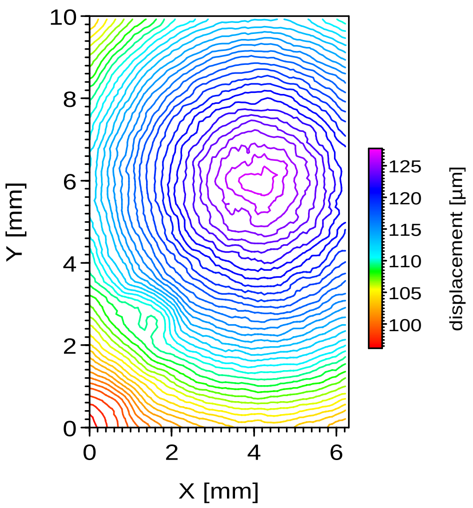
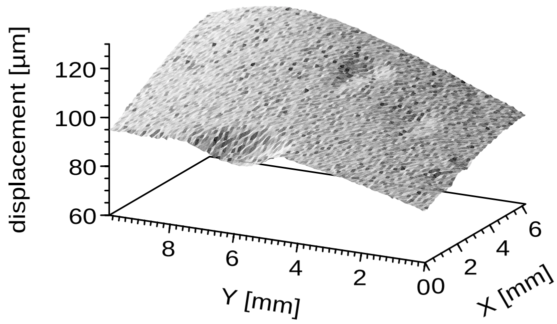


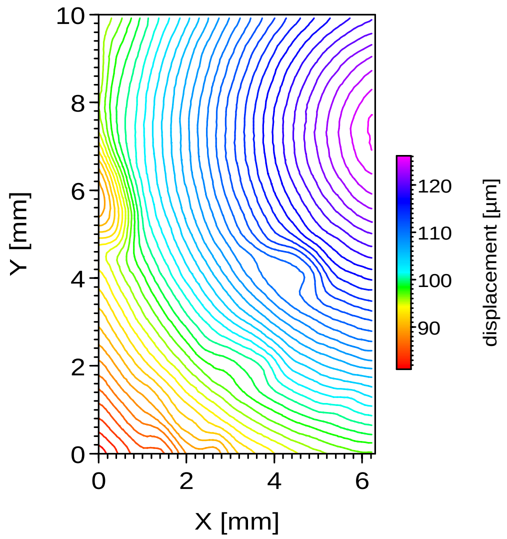
(b)

Fig. 5: Results for the circular diaphragm clamped along the edges and loaded at the center. The center of the diaphragm was loaded to 126 μm. a) Shows the 3-D plot of he deformation of the diaphragm. b) Contour plot of the deformation clearly showing the presence of a defect at one edge. The defect was later determined to be the air gap between the retro-reflective tape and the diaphragm.

Figure 5 a shows the 3-D plot of the deformation of the object in a 11 x 7 mm area of the center of the object. The contour plot of the deformation is shown in Fig. 5 b. From the contour slices as well the 3-D plot small deviations are observed which is due to the air gap between the retro-reflective tape and the diaphragm. The center of the object was loaded to 120 µm. This experiment suggests the use of this technique for non-destructive testing (NDT) since large object deformations can be determined. Therefore a test was carried over a region where prevalent air gaps between the retro-reflective tape and the diaphragm was observed. Figure 6 a shows one such result at an object area away from the center of loading. The contour plot of the deformation is shown in Fig. 6 b.



(a)



(b)

Fig. 6: A different section of the diaphragm with many air gaps was studied. The object was again deformed to 126 µm. a) Shows the 3-D plot of the deformation b) The contour plots showing the deviation caused by the defect.

Further to enhance the NDT capability of the method the diaphragm was changed to a 1.5 mm thick rubber cut from a tube mounted in the same unit and pressure loaded. The air pressure was uniformly increased by a piston arrangement where the compression was controlled by the linear translation stage. One such result of the NDT is shown in Fig. 7 where the ridge (is harder than the other regions) generated during the manufacturing process has deformed less than the other regions.

4. Discussions:

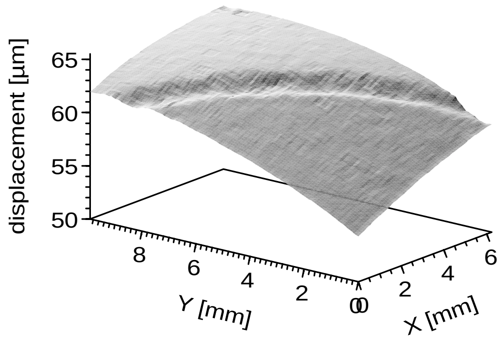
Speckle decorrelation reduces the modulation that is observed and the modulation reappears if the object is further deformed or displaced. The narrow band of the band-pass filter gives us the possibility to measure large speckle displacements while changes in frequency are automatically eliminated during the filtering process. On the other hand, the separation of the spectra is related to the displacement of the object thereby points on the object with no displacement cannot be resolved. Also points where the displacement is not large enough to get a resolvable separation of the spectra then the displacement cannot be resolved. This resolution is dependent on the band-pass filter used to separate one of the side order peaks. However if the frequency scanning method is used then one needs at least one period within 1024 frames. Therefore, displacement up to a wavelength of light can be resolved. Therefore, lower limit on the deformation that can be measured is about one wavelength of light.

To overcome this problem the mirror can be displaced such that a reference frequency signal is produced which modifies equation 1 to

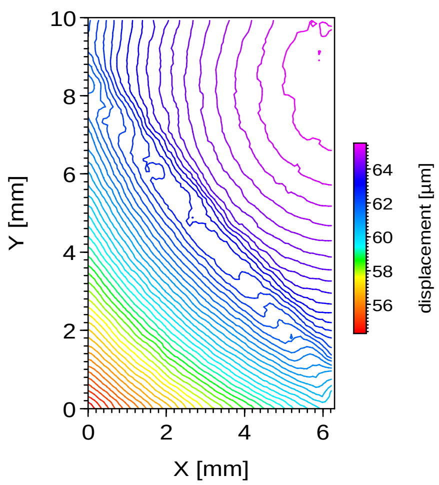
$$I = I_0 \left\{ 1 + V \cos\left[\varphi(x, y) + \frac{4\pi Z0}{\lambda} + \frac{4\pi Z(x, y, t)}{\lambda} \right] \right\} \quad (4)$$

Where Z_0 is the displacement of the reference mirror. Consequently with no object displacement there is a reference frequency. The mirror displacement can be so chosen such that for object points with no displacement three resolvable spectra are produced. Then the displacement of the object at every point can be obtained.

However this will reduce the number of frames that can be used to measure very large displacement.



(a)



(b)

Fig. 7: The results with a rubber diaphragm uniformly pressure loaded. The object was loaded to 70 µm at the center. The data was filtered with a spike removing filter of 5 x 5 which eliminated 0.1% of the pixels. Finally a low-pass filter with a kernel of 5x5 was used; a) Shows the 3-D plot is shown in the figure. b) Shows the contour plot of the slices showing the deviation of the lines around the defect.

If the deformation is not linear then the process of extracting the data using Fourier-transform method is not possible because numerous side peaks are obtained. A simple method of extracting the displacement would be to count the number of cycles thereby determining the total displacement or even the intermediate displacement of the object. Further since the data is available the process can be carried our for small displacements also.

4. Conclusions:

We have proposed a new speckle interferometric method where object displacements in excess of 200 µm have been recorded. A high speed CCD camera was used to acquire a large number of frames of the object that is being deformed linearly. In principle one can use a standard CCD camera to collect the data. The linear deformation results in generating a sinusoidal signal if the large number of frames is placed along a time axis. This data was then analyzed by Fourier-transform techniques where the side peaks were then isolated by a band-pass filter. Various experiments were carried out to test the principle proposed in this paper. The results suggest the high usability of this method for NDT analysis. Finally some discussions on the limitation as well as some solutions have also been proposed.

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