Fundamentals of Holographic Interferometry, Electronic Speckle Pattern Interferometry (ESPI) and Shearography

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Abstract

Optical Non-Destructive Evaluation methods, using lasers as the object illumination source, include holographic interferometry, electronic speckle pattern interferometry and shearography. The techniques use coherent polarized light beams so that surface strain and deformation can be measured from the behaviour of the rays reflected from the test surface. Although the techniques are relatively new their application in a wide range of areas of strain and vibration analysis has yielded a notable large volume of works of fundamental and applied research nature. In the area of non–destructive evaluation these techniques have proven invaluable in that they reveal defects and flaws readily with the advantages of being full view, non invasive and mostly performed in real time or video rates. This paper attempts to provide an introduction to the subject's fundamentals in the hope of assisting NDT practitioners who wish to become familiar with the techniques and apply them to real problems.

Introduction

Holographic and speckle interferometry have been used to extend the methods of classical interferometry to investigate a much wider range of situations. Through these techniques we are able to make static and dynamic measurements of displacement and shape of any optically "rough" surface. These measurements are effected at sensitivities roughly of the order magnitude of the wavelength of light of the lasers, normally used as the source of illumination of the device or system designed for the purpose.

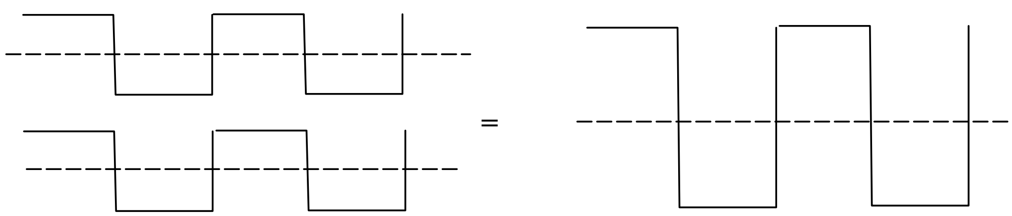
Holographic interferometry was "fortuitously" discovered and developed in the mid 1960's as it has been anecdotically reported when Powell and Stetson [1] were attempting to make a hologram. The technique is based on the interference resulting from the reconstruction of holographic wavefronts.

Speckle interferometry has its origin partly on holographic interferometry and partly on the "speckle effect" that is usually seen when a surface is illuminated with a single wavelength coherent light source such as a laser.

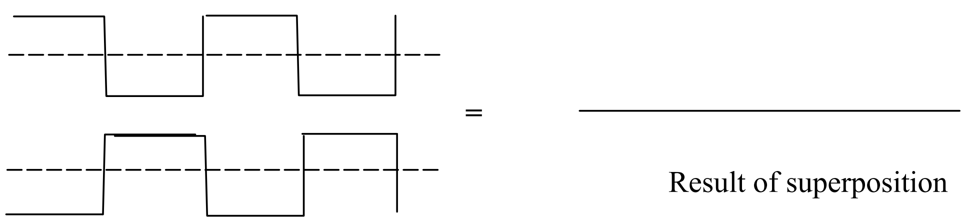
Both holographic and speckle interferometry, are relatively new because they only became reality due to the development of lasers as coherent and intense sources of illumination. However their application in a much wide range of areas of strain and vibration analysis has yielded a notable large volume of work of fundamental and

applied research nature. The results of this work has now become of importance to engineers working in the areas of stress analysis, vibrations, flow visualization, metrology and Non – Destructive Testing.
This paper is attempting to provide a brief introduction to the fundamentals of the subject in the hope of being of use to NDT practitioners who wish to become familiar with the techniques and apply them to real problems. To this end we will begin with a brief introduction to holography and the speckle effect.

HOLOGRAPHY
Comes from the Greek words meaning “whole record” and is based on the reconstruction of light wavefronts, therefore it is important to understand the principle of superposition and interference of waves.
If two light wavefronts are traveling and pass a given point the total intensity is given by the algebraic sum of the intensities of the individual wavefronts.
Thus when the phases of the two wavefronts are the same the intensity is the sum of the incident intensities, but when the phase of the two wavefronts is 180 degrees apart the intensity is zero.



(a) wavefronts in phase   Result of superposition



Result of superposition

(b) wavefronts 180 degrees out of phase

Figure1. Addition of wavefronts

This effect is known as interference which is the most important element or basis of optical measurement techniques. Thus when two plane wavefronts of Intensities I_1 and I_2 are superimposed the intensity varies periodically between the maximum value ($I_1 + I_2 + 2\sqrt{I_1 I_2}$) and the minimum value ($I_1 + I_2 - 2\sqrt{I_1 I_2}$). This intensity variation is known as a fringe pattern and is in the form of a series of planes of uniform intensity which are parallel to the plane that bisects the angle between the two wavefronts or beams of light.

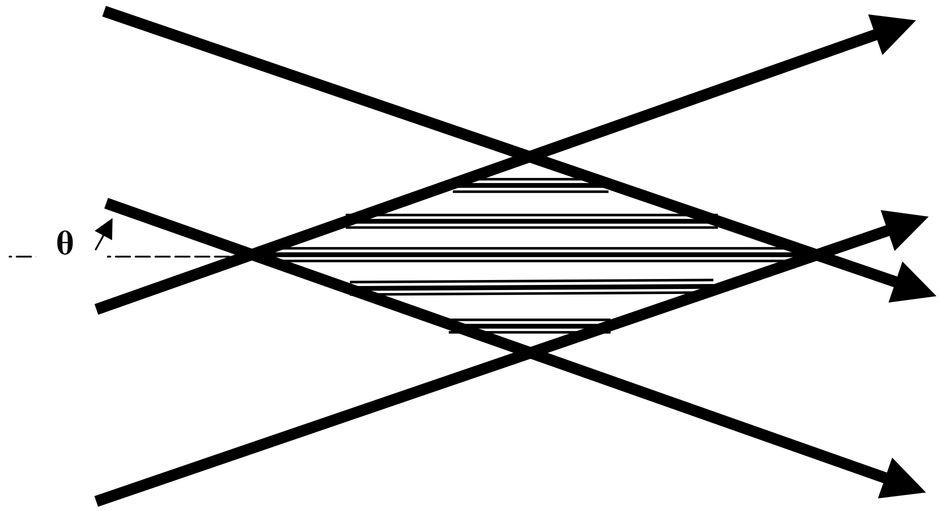


Figure 2. Formation of a fringe pattern

In summary any pair of light wavefronts of the same single frequency (monochromatic light) which are added together will give rise to a fringe pattern. The shape and spacing of the fringe pattern will depend on the nature of the wavefronts.
In the discussion of waves the Fourier transform theory is a very important mathematical tool, however it is fairly complex. A number of investigators of light phenomena have opted to describe light energy manifestations by using the ray theory of light propagation which is the method adopted here as well.

INTERFEROMETERS

Many methods of combining two wavefronts have been devised, because as we mentioned previously interferometers are very important measuring tools, which enable accuracy of the order of the wavelength of the light they use.
One important method of combining wavefronts which has a particular application to NDT, as we will see later, is the Michelson interferometer shown in the schematic below.

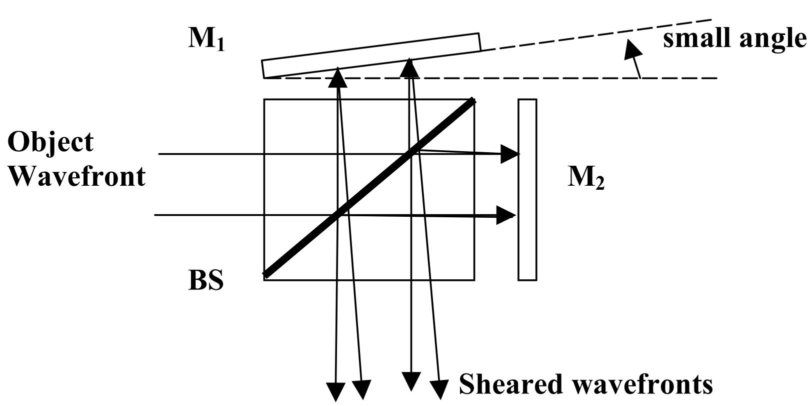


Figure 3. Michelson Interferometer

A beam of light is partially reflected to M_1 by the beam splitter (BS) and partially transmitted to M_2. The reflection from M_1 and M_2 recombine producing interference or a sheared image depending on the extend of the angle of M_1.

HOLOGRAPHY

It is a technique where one wavefront can be recorded and subsequently reconstructed without the presence of the original wavefront. When reconstructing the original wavefront a three dimensional image is observed.
It is a fairly recent technique which although was originally suggested by Gabor [2] in 1949, it only became practical with the availability of lasers which as we know produce coherent monochromatic light.

Holographic interferometry is an extension of holography which has its usage in the scientific and engineering fields. There are two distinct techniques of holographic interferometry which enable very accurate surface displacements to be accomplished.

The "**frozen fringe**" or "double exposure" holographic interferometry involves the recording of the image of an object (in the same manner as attempting to make a hologram) and subsequently making a second recording of the object after it has been stressed minutely. Thus the recording medium (usually an emulsion film) contains two almost identical images of the object. After reconstructing the images an interference between the images is noted, in the form of a fringe pattern superimposed on the object's image. This fringe pattern, in the form of zebra markings (contours) is the measure of the dimensional changes of the object between its stressed and unstressed condition.

An alternate techniques allows "real time" or "**live fringe**" patterns to be observed. This technique is accomplished by recording a single image of the object (i.e. making a hologram of it), and after processing the film is relocated in the exact position where it was during the recording. I f one views the reconstructed image of the hologram it is superimposed on the real object and thus any perturbation on the object will create interference of the two images and as such a fringe pattern will appear. It should be noted that such a technique is very demanding on stability, in that requires exact relocation of the processed hologram in its original position and compensation for the emulsion shrinkage that takes place during the chemical processing. With care these conditions can be satisfied resulting in the highly desired "real time" examination of the objects behaviour under stress.
Practical arrangements for holographic interferometry make use of the offset reference beam principle, suggested by Leith and Upatnieks [3] as shown in the schematic below.

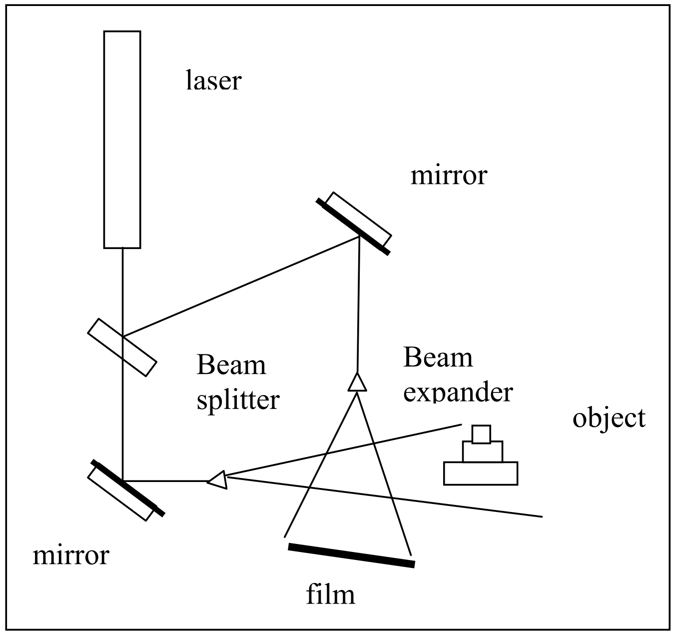


Figure 4. Holographic set-up

THE SPECKLE EFFECT

Anyone observing a surface illuminated by a laser will have seen the curious "granular" appearance of such a surface. This granular appearance, known as the speckle effect, occurs when the surface is optically rough (any real ordinary surface) where height variations of the surface roughness are of the order or greater than the wavelength of the illuminating laser light. It is the result of random interference resulting from the numerous reflections occurring within the rough surface.

This effect plays a vital role to the production of a fringe pattern which is derived from any real surface as it is observed in its original and stressed condition. Depending on the method employed in recording and observing the fringe patterns, local surface displacements or displacement gradients can be made sensitive to desired planes of observation. Added to the above, since the recording medium need not be of a high spatial resolution, speckle pattern interferometry is a more flexible technique then holographic interferometry not withstanding the poorer fringe definition.

Electronic Speckle Pattern Interferometry (ESPI) is a technique that was first demonstrated by Butters and Leendertz [4] in 1971. Since it is only necessary to resolve the speckle pattern and not the very fine fringes required by holography, standard video cameras may be used to record the pattern (speckle size varies from 5 to 100 micrometres). The video camera signal corresponding to the object's un-displaced position is stored electronically in the memory of a personal computer. The object is subsequently displaced and the live video signal is subtracted or added to the previously electronically stored image. The result is displayed on the video monitor where the correlation fringes are displayed "live".

ESPI can be used in arrangements where fringes will represent lines of either in plane or out-of-plane displacement. (see figures 5 and 6).

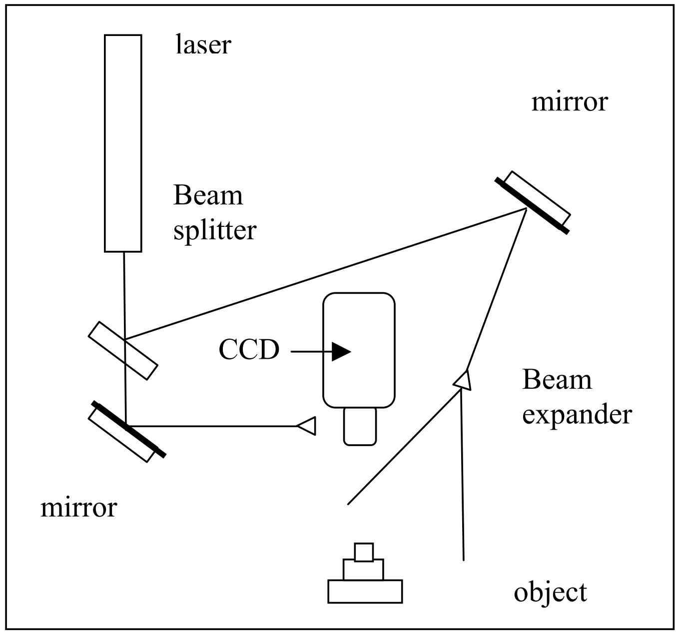


Figure 5. ESPI set-up (out of plane sensitive)

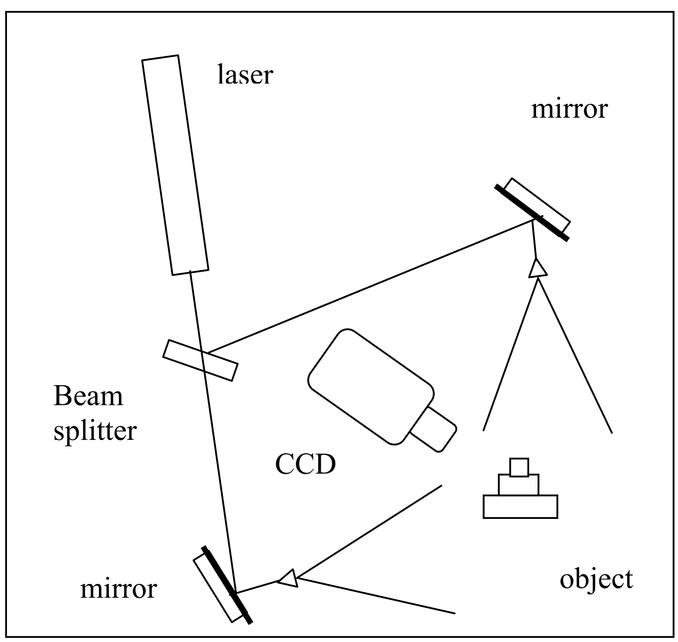


Figure 6. ESPI set-up (in-plane sensitive)

The fringe sensitivity of out-of-plane displacements may give fringe spacing of the order of $\lambda/2$.
The fringe sensitivity of in-plane displacements is of the order of $\lambda / (2\sin\theta)$ where λ is the wavelength of the light used and θ is the angle of incidence of the illuminating beams. The fringe sensitivity for in-plane and out-of-plane displacements can be arrived at with simple ray theory as demonstrated below in figure 7.

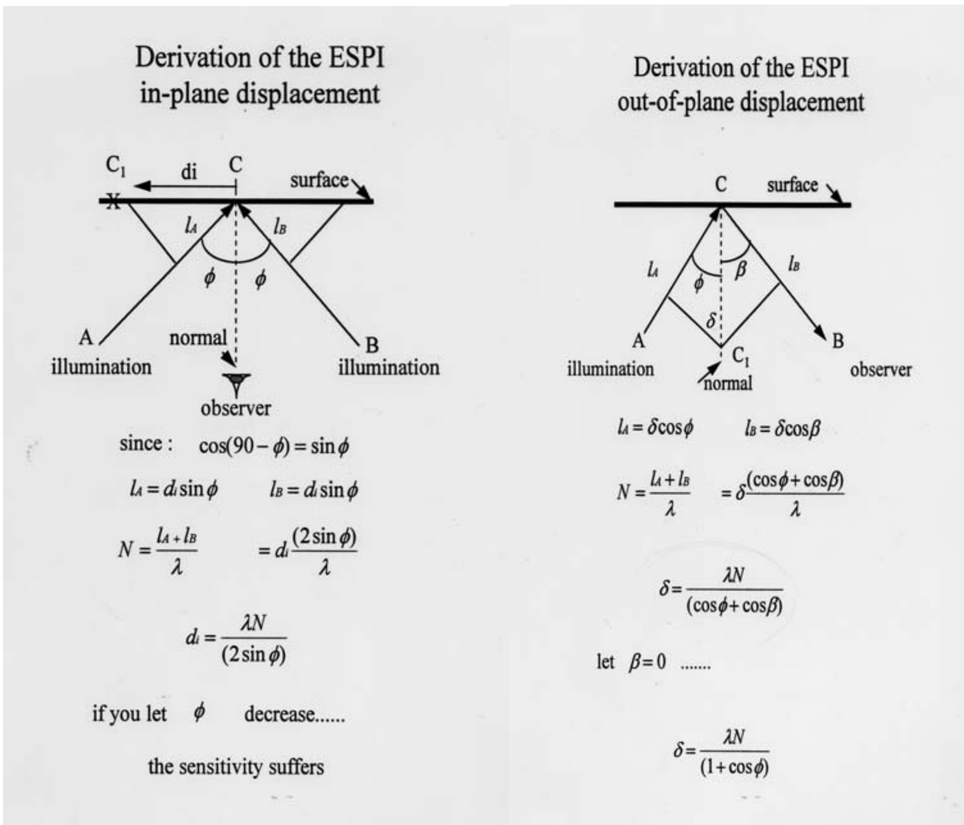


Figure 7. In-plane and Out-of-plane displacements (ESPI)

SHEAROGRAPHY
Shearography is another form of speckle pattern correlation interferometer which relies on beams that are both derived from the illuminated rough surface and in addition incorporates an image shearing device. This type or speckle interferometer can be made sensitive to out-of-plane **displacement gradients**.
Shearography was not widely used in the 1980's and early1990's because of the reluctance to use film as the recording medium. However since Hung's [5] work in 1989 the use of a video camera to record the speckle pattern has given rise to what is now known as **electronic shearography** or **digital shearography.**

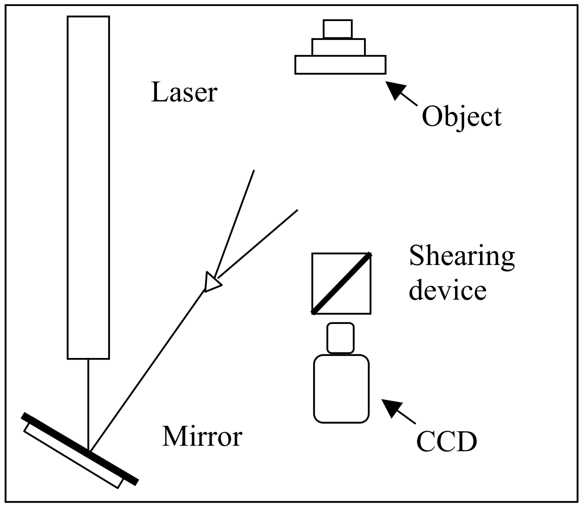


Figure 8. Digital Shearography set-up

The object is illuminated by a single beam inclined at a small angle to the surface normal and is viewed through an image shearing device as for example the Michelson interferometer as was shown in figure 3. As a result of the shearing action of the viewing arrangement two images of the object are formed at the plane of observation.
The effect of shearing is to map a point on the object into two points in the image. This is equivalent of taking two separate points on the surface of the test piece and bringing them together to meet at the image plane. The distance separating two points on the surface can be controlled by the tilting of the Mirror M_1 and may be considered as a gauge length.
There are several ways of producing a sheared image. The principle of the discussion above may be easier to grasp in discussion around a very simple method of shearing.
Introducing a glass wedge in front of the camera lens will have the effect of shifting the rays emanating from a point on the object away from the normal focal point of the lens and thus a pair of laterally sheared images of the point are formed on the camera image plane. (Figure 8a)

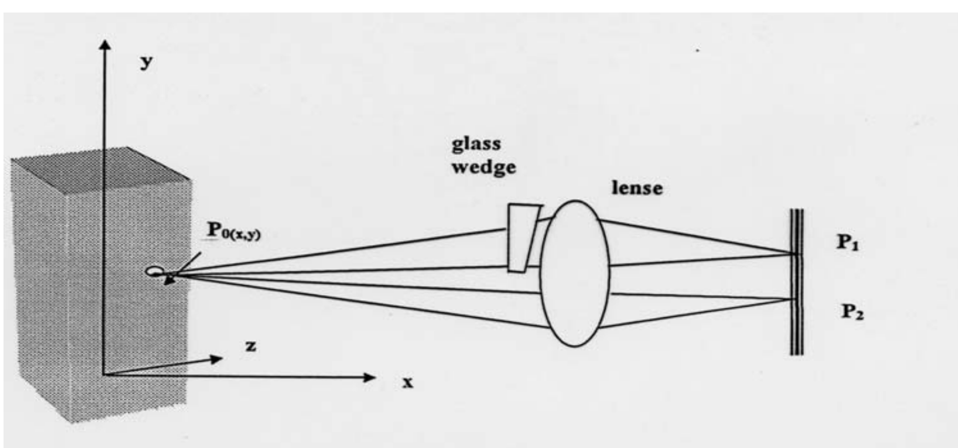


Figure 8a. Creating a pair of lateral sheared points.

Because the rays passing through the prism are deviated the image produced by the upper half of the lens is shifted upward. Conversely because rays are reversible the image shearing camera brings two neighboring points on the object $P_{(z,y)}$ and $P_{(z+dz,y)}$ to meet at the image plane. (figure 8b)

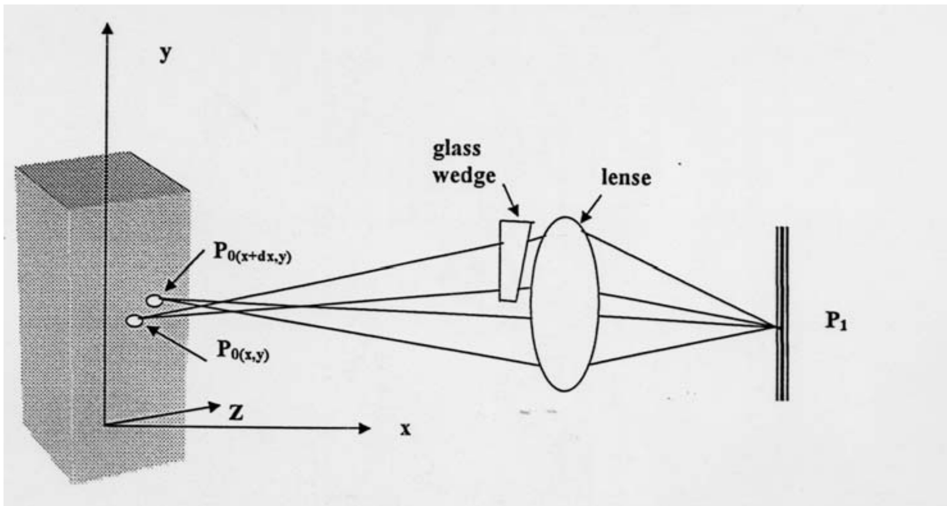


Figure 8b. Bringing two neighboring points together.

The two overlapped portions of the sheared images interfere with each other producing a random interference known as speckle, superimposed on the common portion of the sheared images.

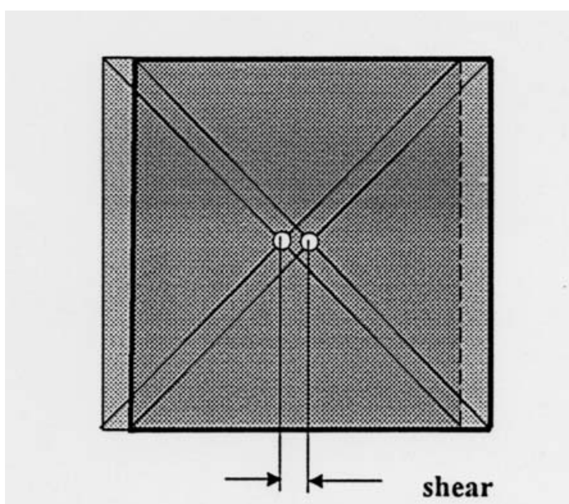


Figure 9. Common portion of sheared images.

Subsequent to deformation of the object the speckle is modified and comparing the two patterns produces a "**beat fringe pattern**" representing the derivative of displacement with respect to the direction of separation i.e. the shearing direction.

The direction of shearing can be controlled by for example rotating the wedge in front of the camera lens (as shown in figure 8a) or by tilting the mirror in a different plane (as shown in figure 3.)

Shearography is more readily accepted by industry in the identification of discontinuities such as defects rather then strain measurements. The reason for this is that it is very difficult or ambiguous to identify the fringe order as required for strain measurement. In inspection for defects the fringe order is not necessary and simply one looks for the fringe anomalies which result from the presence of a defect.

The size and location of the defect is simply determined by the size and location of the fringe anomaly. Furthermore experience is teaching us that the nature of the defect can also be determined by the shape or signature of the fringe anomaly.

Although Shearography has gained rapid acceptance since the 1990's the full capacity of the technique awaits further exploration.

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2. D. Gabor (1949), Proc. Roy. Soc., A197, 454-87
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