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Certificate

This is to certify that **Mr. Ragansu Chakkappai**, student of St. Xavier's College, Mumbai (Autonomous) has completed his summer internship (3/04/2019 to 3/06/2019) from the **Indian Institute of Space Science and Technology, Trivandrum**. He has worked under the guidance of Dr. Dinesh N. Naik Dept. of Physics on the topic "**Temporal and Spatial Phase Shifting Digital Shearography**".

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Comparative study of temporal and spatial phase-shifting Digital shearography

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I. Abstract

Digital shearography [1] has found its way as one of the primary methods in non-destructive testing (NDT). NDT has many applications when it comes to aerospace and automotive industries, there are many methods of Digital shearography here I am discussing 3 types of shearography done using temporal or spatial phase shifting, and comparing one with the other to see their advantages and disadvantages . When one may excel at quality other excels at speed and suggesting methods to get better results.

II. Introduction

Composite materials due to its complex structure, makes defect analysis and testing really hard, But due its wide range of application, aerospace and automotive industries have found many uses for these materials. Thus proper testing and defect analysis for different materials is very important, Thus new methods of non-destructive testing are developed and one of them is Digital Shearoghaphy, Digital Shearography can be done using many different ways and one of them is phase shifting Shearography. In this Project I have worked on single-shot Shearography, 2 + 2 Shots Phase shifting shearography and 4+4 Shots phase shifting Shearography. By first performing Simulations and later achieving those results experimentally I have being able to find the pros and cons of different testing methods. To begin with I stared with single shot shearography , which has been experimented and presented by Xin Xie, Lianxiang Yang,* Nan Xu, and Xu Chen[2] in their paper where they used Michelson interferometer. My primary work was to find effect of aperture size and shearing amount on quality of the result. For the experimental study I have used a Sagnac Interferometer, which has few advantages over Michelson interferometer when it comes to control of carrier frequencies and shear. Sagnac interferometer can be adjusted such that we can change the shear keeping the carrier constant which is difficult to achieve in Michelson Interferometer. But unlike Michelson interferometer Sagnac interferometer is a common path interferometer thus getting temporal phase-shift would require a geometric phase-shifting after the Sagnac interferometer. This paper demonstrates what are advantages or single-shot and 4+4 shots Shearograph and how we can reach a middle ground such that we could get the advantages of both the setups.

III. Principle

For digital shearography, a shearing device must be placed in front of the camera, which introduced a shear between two copies of the object imaged at the camera plane. Let us suppose a complex object field o is imaged at the camera plane using a shearography setup. o_1 and o_2 are the two copies of this object, sheared by some arbitrary amount in along x direction. These two copies interfere at the camera plane and produce an intensity pattern I_1 which can be written as

$$I_1 = |o_1|^2 + |o_2|^2 + o_1 o_2^* + o_2 o_1^* \quad (1)$$

Where $*$ denotes the complex conjugate. Applying a Fourier transform (F.T.) to the above equation

$$F.T.(I) = F_1 \otimes F_1^* + F_2 \otimes F_2^* + F_1 \otimes F_2^* + F_2 \otimes F_1^* \quad (2)$$

Where $F_i(i = 1,2)$ denote the Fourier transform of the respective copies $o_i(i = 1,2)$ and $\otimes$ denotes the convolution. For a cut-off frequency of the object spectrum is f_c, each term in the above equation has a cut-off frequency $2f_c$. In order to separate the terms, carrier frequency f_o must be chosen to at least $2f_c$, this is how we do with single shot method, After we get the 3 terms separated we would perform a windowed inverse Fourier transform(WIFT) thus eliminating the unwanted part. Since at least $2f_c$ is required in the carrier frequency f_o will finally leads to low resolution in SPS-DS. in order to improve the resolution we suggest a method to remove the first two terms in Eq. (1) before applying the F.T., which can be achieved by recording an additional interference pattern I_2 with an additional constant phase ϕ_1 in one of the copies. In this case, the second image recorded at the camera is expressed as

$$I_2 = |o_1|^2 + |o_2|^2 + o_1 o_2^* e^{-2\pi i \varphi_1} + o_2 o_1^* e^{2\pi i \varphi_1} \quad (3)$$

By subtracting Eq. (1) from (3) one can get rid of the first two terms, and subsequently applying the F.T. results in

$$F.T.(I_2 - I_1) = F_1 \otimes F_2^* (e^{-2\pi i \phi_1} - 1) + F_2 \otimes F_1^* (e^{2\pi i \phi_1} - 1) \quad (4)$$

Since in frequency domain only two terms are present, therefore, in this case carrier frequency can be reduced to half. This leads to two-fold improvement in the spatial resolution. By applying a windowed inverse Fourier transformation (WIFT) on the 3rd term, phase distribution can be measured. Similar procedure can be followed in deformed case as well. The gradient of the phase distribution can be obtained by comparing the distributions of two phases, with and without the deformation. We can skip the entire process of (WIFT) where we use 4 copies with 0, 90,180& 270 degrees phase difference between the 2 sheared copies. Hence the name 4+4 method, here we directly remove both the dc and the conjugate term by carefully subtracting and dividing using the 4 images we captured thus

$$I = (I_1 - I_3) - i(I_2 - I_4) \quad (5)$$

WhereI_1,I_2,I_3 and I_4 are respectively images with 0,90,180 & 270 phase between the the 2 sheared copies. And angle of I will give the required result.

IV. Simulations and Experiments

A. Simulation

For the purpose of simulating what will actually happen in an experiment we first create a Gaussian beam using an exponent function. Next we use a 'rand' function to generate a random matrix which will act like the surface of our object. Then we will multiply the FFTs of both of these terms and then the inverse Fourier transform of the product will give us the required image of the object. Next step is to propagate the image that is to convert the image from intensity domain to phase domain. [Fig 1(a)]. Now that we have the image in phase domain, we can generate another image which will act as the copy of the image from the same surface which has been deformed. There can be different types of deformation, here we are having a 'fixed end centre loaded circular plate' as our object. Theoretically such a system would have a cubic equation as its profile. After applying the conditions and solve for the coefficients of that cubic equation, we would achieve the equation for its surface,

$$y = Y\left\{\left(\frac{r}{R}\right)^3 - 2\left(\frac{r}{R}\right)^2 + 1\right\}$$

Where *'r'* is the radial distance and y is the vertical distance, *R* is radius of the plate, and *Y* is the amount of deformation. See [Fig 1(b)]. Using the polynomial just derived. We can now find the phase change occurred by deforming the surface [Fig 1(c)]. After multiplying the deformation with the original image we could get the deformed copy.

In the process of shearography we would require the get both shear and carrier in the setup, for single-shot and 2+2 shot method we will have to set a cut-off frequency since we would need the carrier to be at least 2 times the cut-off frequency for single-shot and same as the cut-off frequency for 2+2 shot method. So for this, both the set up will have aperture kept at the Fourier domain. So for simulation we will need an aperture places in the Fourier domain. That is by Fourier transforming the respective image and masking the image with circle. While masking the image, we must note that the 2 sheared copies inherently will have a carrier frequency. To simulate this effect we will makes 2 copies of the image and in the Fourier domain mask them separately with different masks, both are circles with center slightly shifted, where the amount of shift will directly be the carrier frequency. Now the two copies have the required carrier frequency. After Inverse Fourier Transform we will get the two copies back to the image domain, now we will give shear to the system. For giving shear we will have to shift one of the images with respect to other, and then add them with the other to get the interference pattern at the camera plain. For shifting we would first need to pad both the image. After padding, with the help of some simple image shift algorithm we will be able to shift one image with respect to the other and after which we will add both the images. Finally by multiplying the added sum with its complex conjugate we will get the final intensity at the camera plain [Fig 1(d)].

$$I = (O_1 + O_2).(O_1 + O_2)^*$$

Where I is the intensity at the camera plain and O_1& O_2 are the 2 sheared images and '*' indicates the complex conjugate. This is case with single shot Shearograph. But for 2+2 method we would require to take 2 shots each for deformed and undeformed. Here an extra phase will be added to one of the sheared copies. So for simulation after the shear and carrier is set O_2 thus the intensities I_1 & I_2 will become which is the image at the camera plain. [Fig 2(b)].

$$I_1 = (O_1 + O_2).(O_1 + O_2)^*$$

$$I_2 = (O_1 + O_2 . e^{i\theta}) . (O_1 + O_2 e^{i\theta})^*$$

For 4+4 method we will have 4 images per deformations namely $I_1, I_2, I_3, \& I_4$ each will have $0, \frac{\pi}{2}, \pi \; \& \; \frac{3\pi}{2}$ phase difference between the two sheared copies respectively, Thus we get in the camera plain. [Fig. 3 (b)].

$$I_1 = (O_1 + O_2) . (O_1 + O_2)^*$$

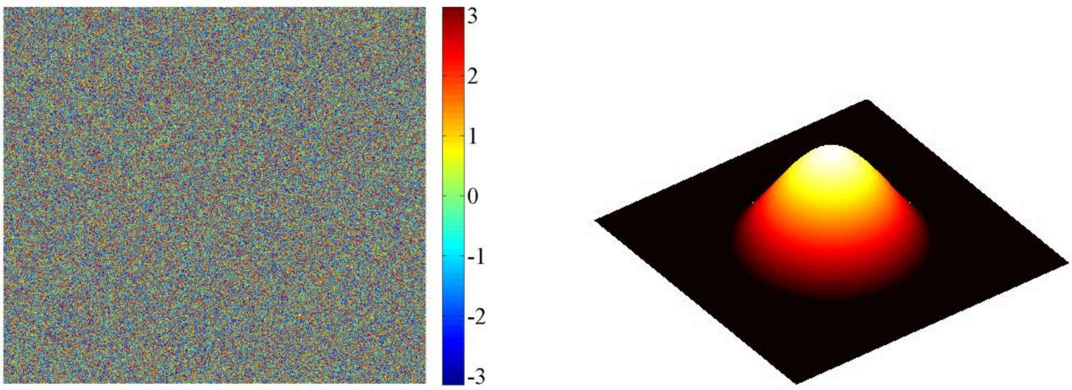
$$I_2 = (O_1 + O_2 e^{i\pi/2}) . (O_1 + O_2 e^{i\pi/2})^*$$

$$I_3 = (O_1 + O_2 e^{i\pi}) . (O_1 + O_2 e^{i\pi})^*$$

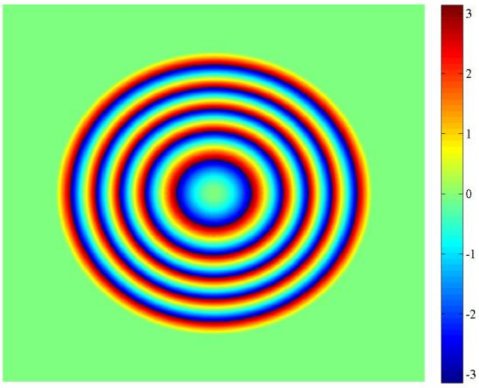
$$I_4 = (O_1 + O_2 e^{i3\pi/2}) . (O_1 + O_2 e^{i3\pi/2})^*$$

Technically with this the simulation is complete since we simulated the shearogram we generate in an actual experiment. Now all that remains is getting the Shearograph. For the shearoghaphy result, we have to separate out the 3rd term out of equation 1, for which we would require to perform a WIFT. So first we will Fourier transform the image. Thus we see 3 lobes formed due since we kept carrier frequency equals to 2 times cut-off frequency.

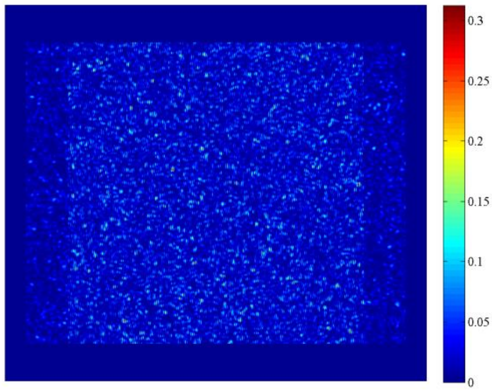
[Fig 1(e)]. Since we know that the first 2 terms in equation (1) is having no carrier frequency hence it forms the central lobe. The next two terms, since it has carrier frequency with different signs it will form the two adjacent lobes. The phase information which we need is there both these lobes but we only need one of them. So we will perform a WIFT such that we get either one of the side lobes. Here I took right side which was personal preference. After the WIFT we will get a image of the surface which has the required phase information. By doing the same for the deformed copy we will get an image of the deformed copy having the phase information. And by multiplying one with the complex conjugate of another we will get a term whose angle will give the required shearography. [Fig 1 (f)].



(a) (b)



(c)



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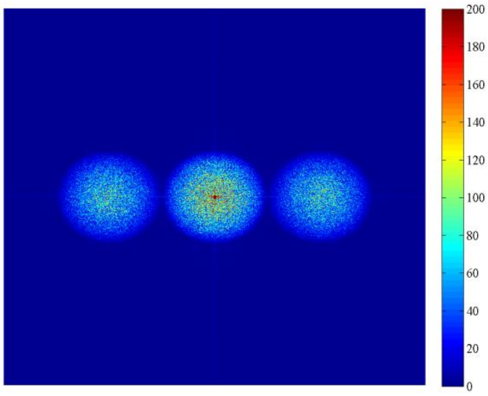

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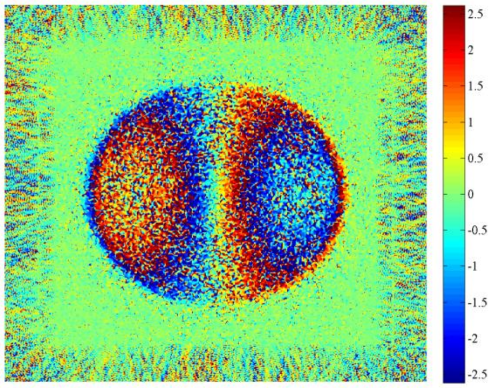
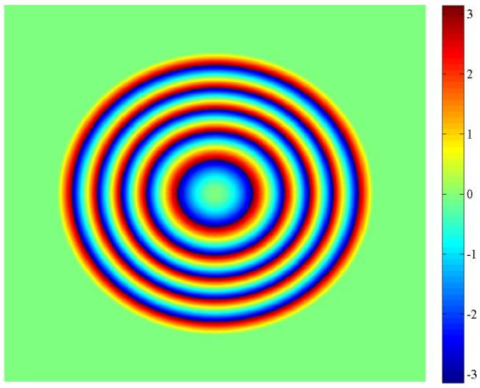


(f)

Fig 1 shows the simulated results obtained with single-shot techniques, Fig1.(a) display the random initial phase and Fig.1 (b) shows the added deformation. Fig.1(c), shows the phase of the deformation added to the initial phase. Fig.1 (d) shows the Shearogram recorded at the camera plain. Fig.1 (e) shows the absolute of its Fourier spectrum In its spectra, first two terms mentioned in Eq. (1) are still there and are located at the center. Fig.1 (f).presents the final Shearograph obtained by applying a window Fourier transformation to the right spectra and comparing the result with deformed case.

For the case the process of 2+2 the process is similar, but before doing the Fourier transform, we will first eliminate the central dc term. This is done by subtracting the first shot from the second, since we don't have the dc term anymore we can decrease f_0 to $f_c$and also use larger aperture. So after we do the subtraction, we will end up with one image of deformed and one undeformed. Now it's similar to single shot. The Fourier transform will now have only 2 terms and can choose either one of them for WIFT. [Fig 2 (c)] and by multiplying the image formed from the deformed case with the conjugate of the undeformed case we will get an image who's angle will give the required Shearograph. [Fig 2 (d)].



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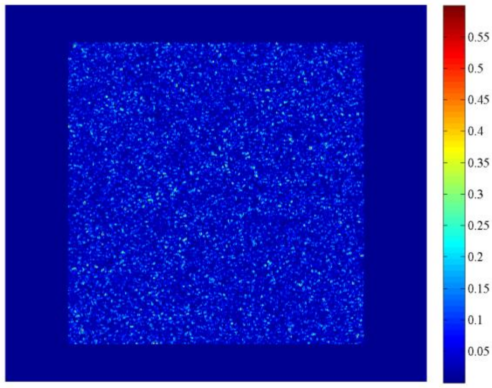

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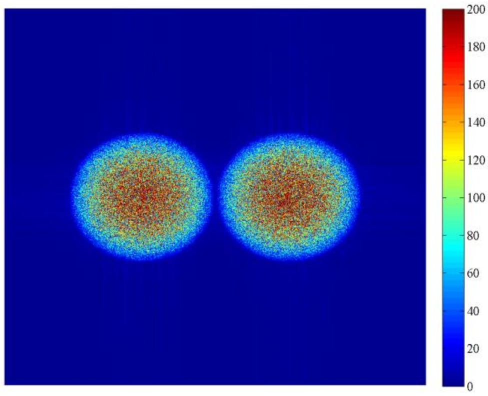

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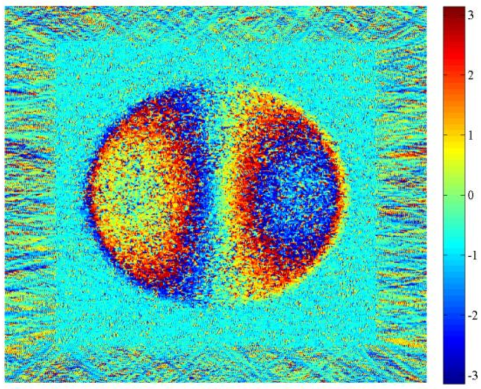
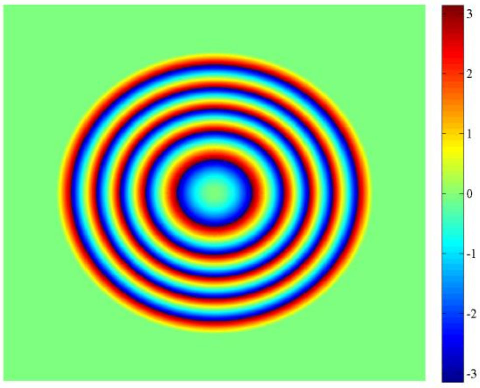


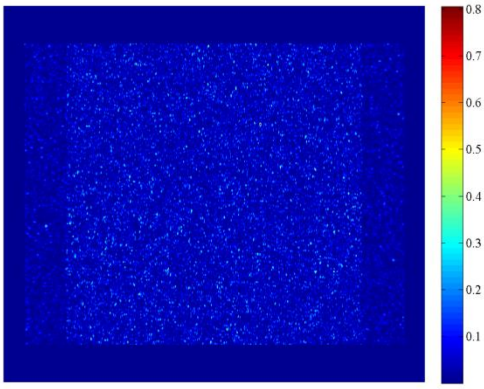
(d)

. Fig 2 shows the simulated results obtained with our 2+2 techniques for the same deformation and shear, Fig.2 (a), shows the phase of the deformation added to the initial phase. Fig.2 (b) shows the Shearogram recorded at the camera plain. Fig.2 (c) shows the absolute of its Fourier spectrum In its spectra, first two terms mentioned in Eq.(1) now removed using the second image as mentioned before Fig.2 (d).presents the final Shearograph obtained by applying a window Fourier transformation to the right spectra and comparing the result with deformed case.

In the case of 4+4 method we have 4 shots each for deformed and undeformed object. By using equation (5) on both deformed and undeformed case we will get the phase information directly multiplying one with the conjugate of the other will get the image whose angle is the required Shearograph. [Fig 3 (c)].



(a)



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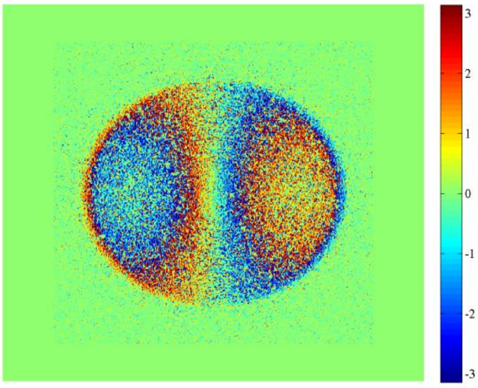


(c)

Fig 3 shows the simulated results obtained with the 4+4 techniques for the same deformation and shear, Fig.3 (a) shows the Shearogram recorded at the camera plain. Fig.3 (c).presents the final Shearograph obtained by using the 4 shots and getting only the required part. Then comparing it with the deformed case will give the result.

B. Experiment.

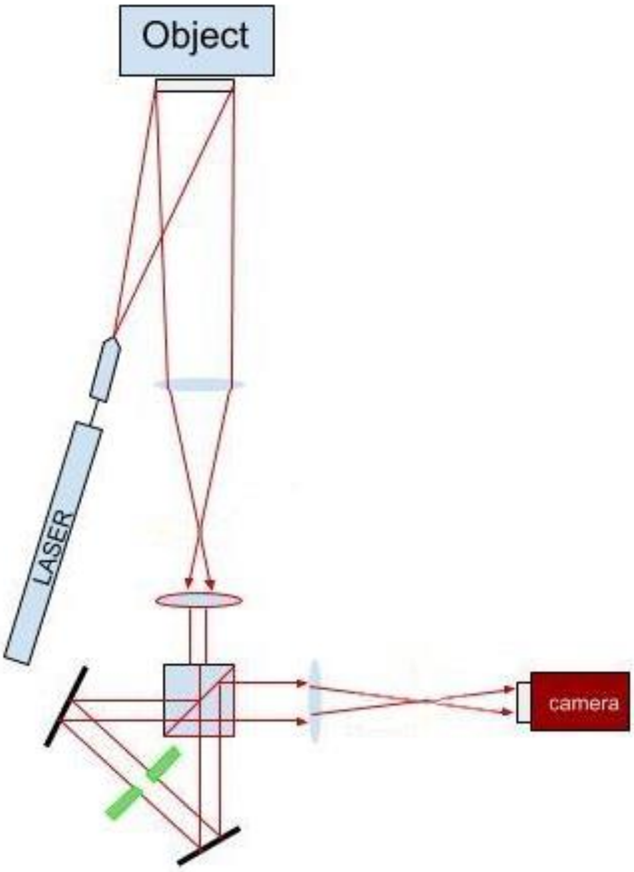


Fig 4 shows the setup for single-shot Shearography.

Figure 4 shows the setup for single-shot Shearography. The object is illuminated with a 633 nm Laser. An MO is used to diverge the beam so it illuminates the entire area of interest. The imaging lens places, and then images the object such that the image is formed exactly at *f* distance from the lens L1. This will ensure that the image is collimated before entering that Sagnac. The Sagnac interferometer is first set such that both the beams travel the same path. After the Sagnac we place another lens L2 such that the optical distance from the lens L1 is exactly *2f* where L1 and L2 have the same focal length *f*. Once the light passes through the second lens it will focus at a point which is *f* distance from the lens L2. This is this is where the camera will be places and thus making the *4f* geometry. As of now that 2 copies formed by the interferometer will not have any carrier in them. Once we align the interferometer for zero path difference, we will translate one of the 2 mirrors which will bring a shift in the two beams in the X-axis. [Fig 4]. Since we are using 4f geometry, the inside of the interferometer is in the Fourier plain. Thus a shift in the X axis will mean introducing a carrier frequency of $+f_0$ and $-f_0$ respectively for the two copies. Next step is to create a shear. There are multiple methods of creating a shear. One them is tilting a mirror. This is generally done in Michelson interferon meter. But such assembly would affect both shear and carrier which is not a recommended setting for such experiment. Thus we are using different method here we would shift the camera in the Z-axis and thus get a shear. Thus the amount of carrier is now independent of the shear, but it would need us to sacrifice in clarity due to it going out of focus. To avoid this we would also shift the imaging lens such that the focus would come back to the camera plain. Thus the set up will give us both control over shear and carrier. Now from above we know that the cut off frequency f_c should be equal to f_0 /2. To control the cut-off frequency f_c we would need to put an aperture in the Fourier plain. As in figure 4, we would use an aperture inside the interferometer such that it is f distance from both the lenses L1 and L2. This completes the set-up and would result in giving the required shearogram in the camera plain. The rest of the processing required to generate the shearography is the same as in simulation.

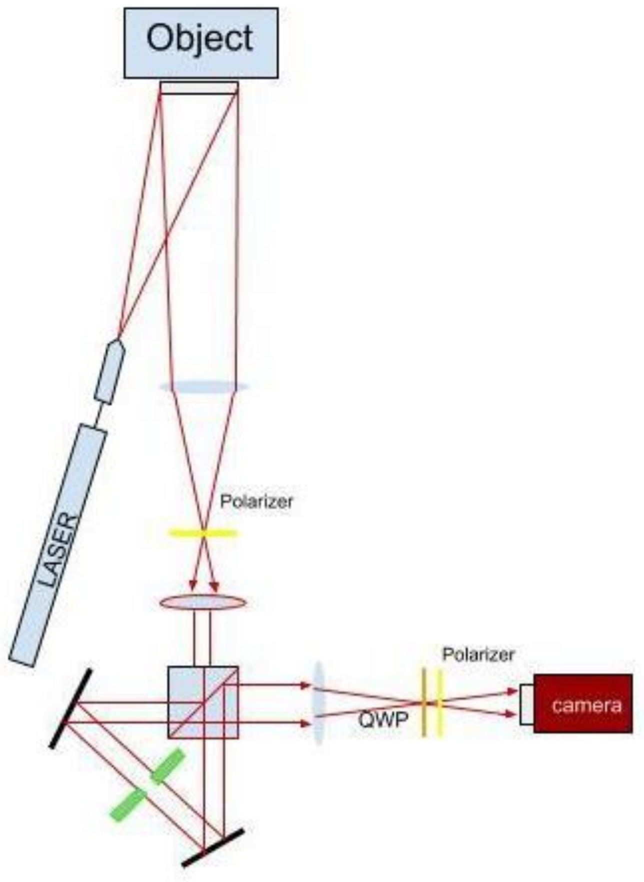


Fig 5 shows the setup for 2+2 -shot Shearography.

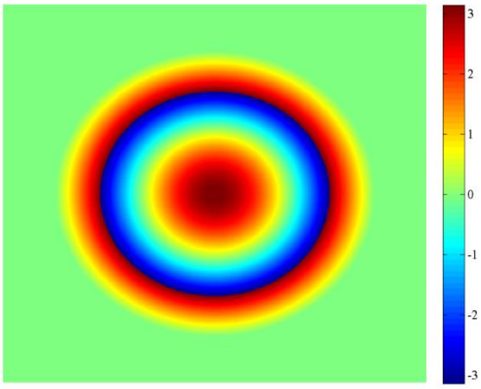
The set up for 2+2 shots shearography is very similar. But unlike Michelson base shearography we cannot create extra phase for one path in a Sagnac. We would need a geometric phase shifting method. Thus we will be using a PBS instead of a BS in the setup, an extra polariser is kept to ensure that the light entering the PBS has equal components of both X and Y polariser light. In other words we are keeping the polariser at $45^{0.}$ After the Sagnac we will have the same 2 sheared images but in 2 different polarisation (X and Y). Thus we can use a geometric phase shifter. Since for 2 +2 method we can use any phase between the two shots, I did not use the conventional geometric phase shifter but instead I fixed the polariser and rotated Quarter Wave-Plate (QWP) such that in one shot we will have the X-polarised retarded by $\frac{\pi}{2}$ and in the other shot retarded the Y-polarised by $\frac{\pi}{2}$. Thus we would end up with 2 shots with the sheared images having π phase difference between them. Since mentioned before the 2+2 method can use larger aperture thus we can increase the aperture for better spatial resolution.

V. Results and Discussion

A. Simulation Results

With single shot shearography we simulated results with varying shear and deformation.

Deformation | Shearograph



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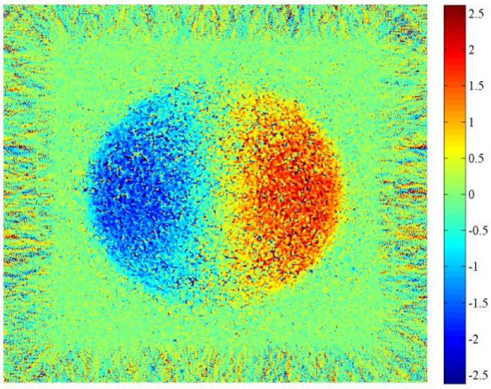

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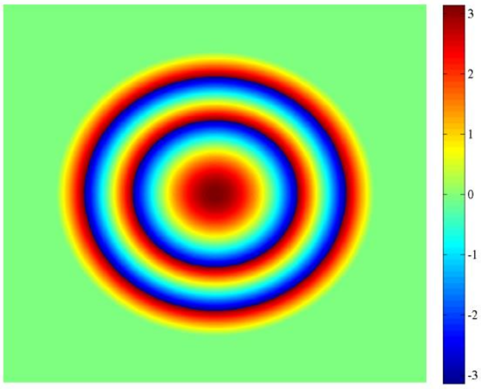

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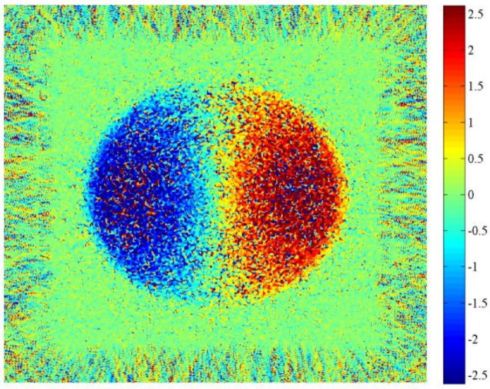
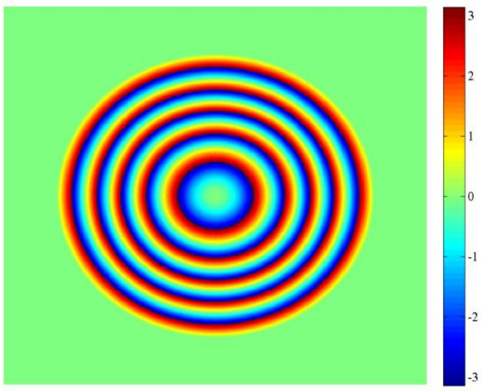


(d)



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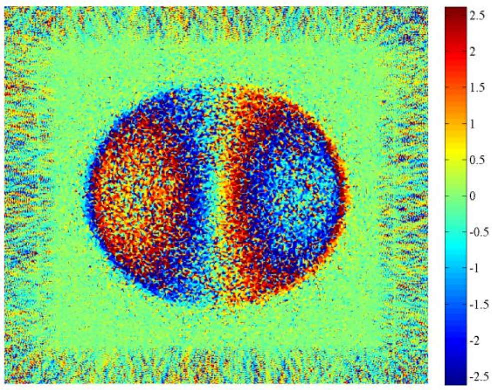
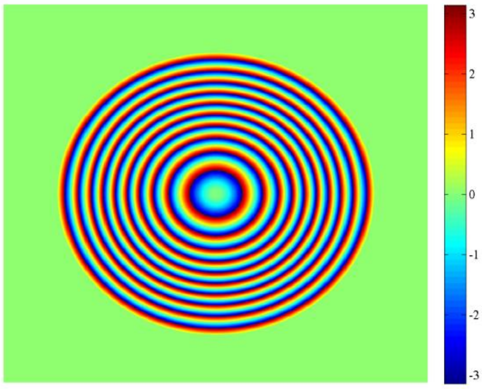
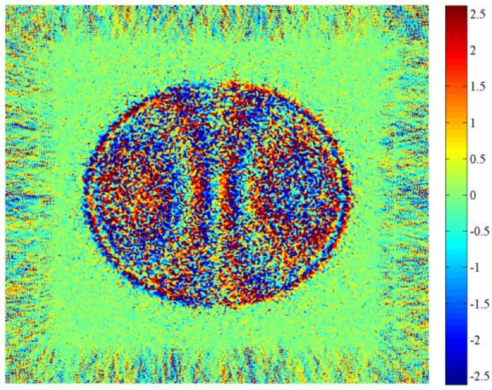


(f)



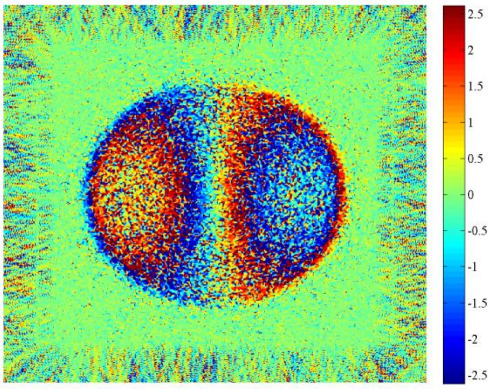
(g)



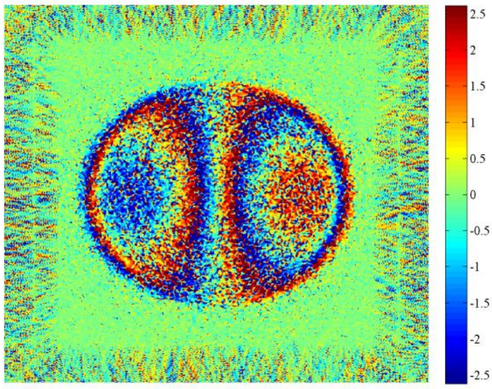
(h)

Fig 6 depicts different deformation. With their respective Shearograph

Figure 6 (b) shows that Shearograph formed by small deformation. Here we can clearly see that the phase is first starting from negative and then going to zero and then to positive while going from left to right this is evident since a shearography is takes the first derivative along the direction in which it is sheared. And since the linear profile of the deformation is a cubic polynomial we can expect a quadratic equation as its Shearograph. For larger deformation, the path difference excides λ and thus the curve start to resemble more and more to the butterfly pattern. See Figure 6 (d), (f), (h). For the same deformation the phase in the Shearograph changes faster with increasing shear. See figure 7 (a), (b), (c), (d).



(a)



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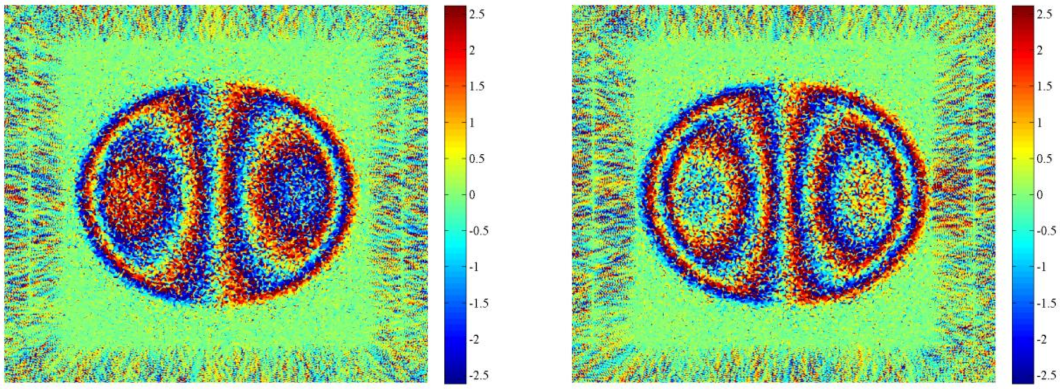
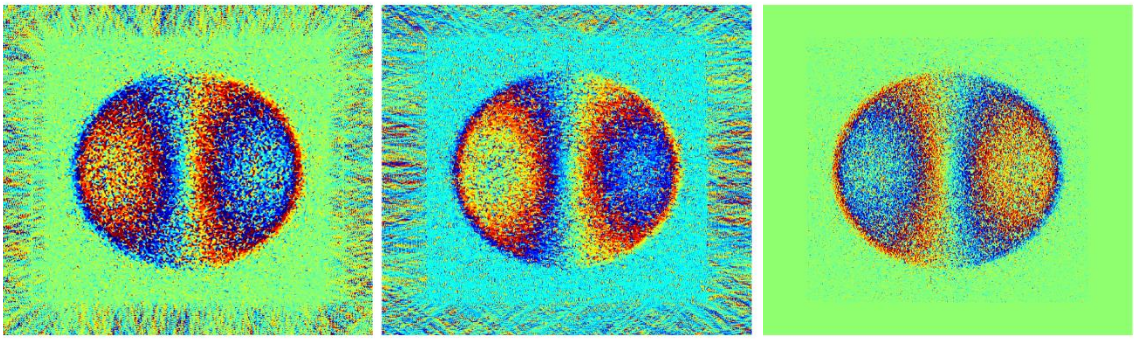


(c) (d)

Fig 7 represents simulation of shearograph with increasing shear.

Note: similar results can also be achieved by other methods like 4+4 shots and 2+2 shots.

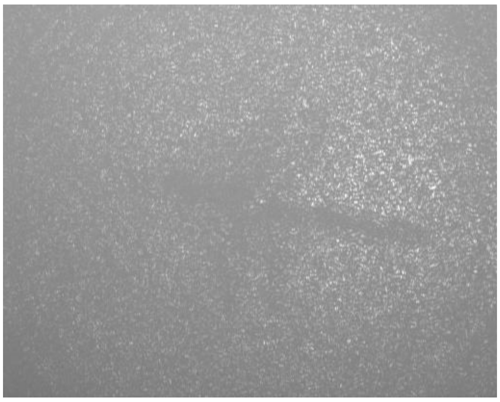


(a) (b) (c)

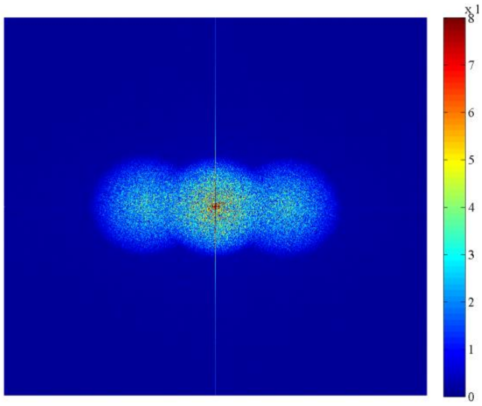
Fig 8 represents simulation of shearograph with different methods.(a) single shot method(b) 2+2 method (c) 4+4 method,

Compared to Single-shot and 2+2, 4+4 clearly has a better quality.[Fig 8 (a), (b), (c)]. This is because for both 2+2 and single-shot we need to fix a cut-off frequency. For which we will need to keep an aperture which will increase the speckle size thus decreasing the spatial resolution. To get a middle ground between 4+4 and Single-shot, 2+2 was proposed. As mentioned before we still need a aperture but the size can be double that of the case with single shot, hence significantly increasing spatial resolution.

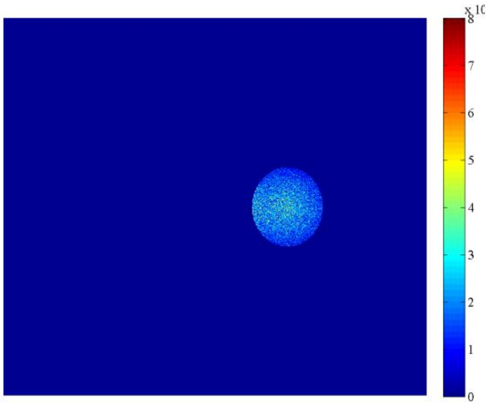
B. Experimental results and inference



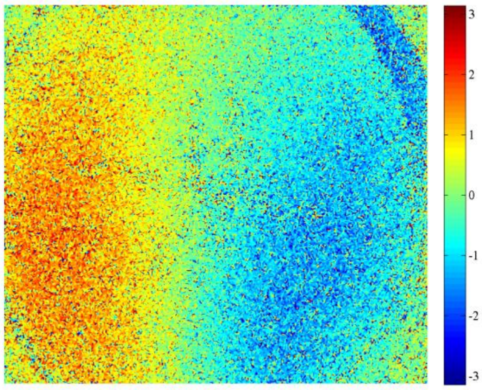
(a)



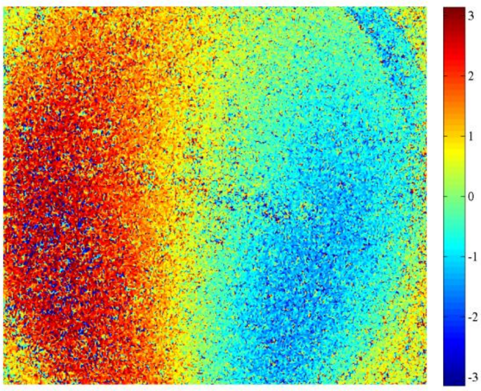
(b)



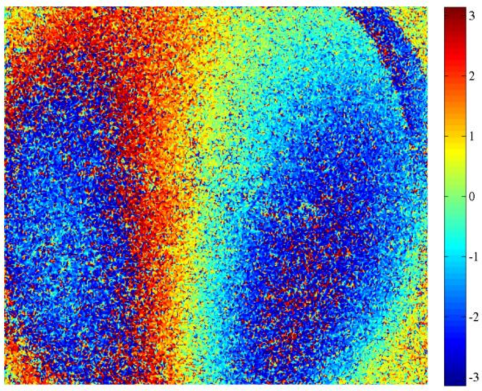
(c)



(d)



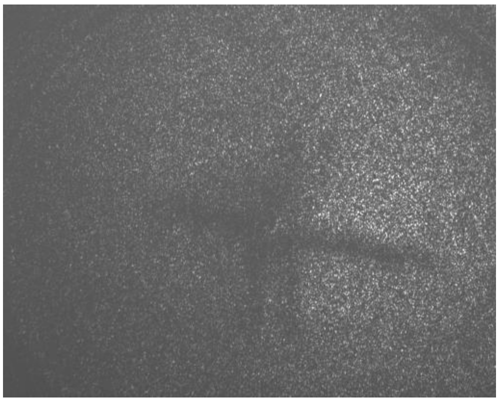
(e)



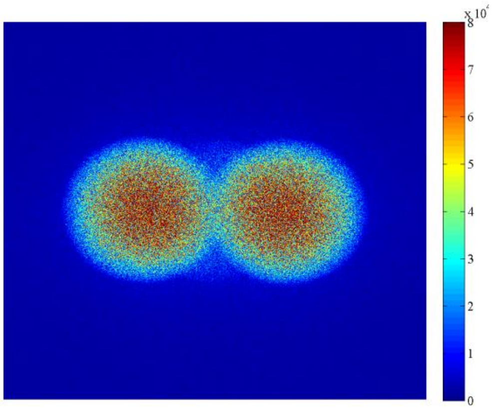
(f)

Fig 9. Different stages in processing a single-shot shearogram to get a shearograph. (a) the shearogram taken with certain value of shear and carrier. (b) The Fourier transform of the shearogram. (c) Making the Fourier domain with a circular mask. (d) Final shearograph with low deformation, (e) Final shearograph with medium deformation. (f) Final shearograph with high deformation.

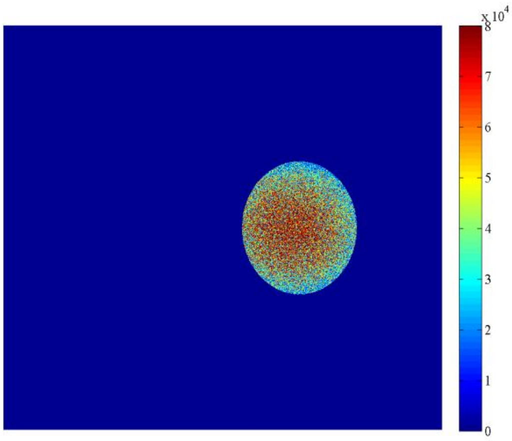
As mentioned before the Fourier transformed image has 3 lobes and in the single shot method. In which only a small part of the information is useful since we are performing a WIFT, instead we could use another image to delete the dc part hence increasing the area which we can use from the Fourier transform. That is nothing but 2+2 method.



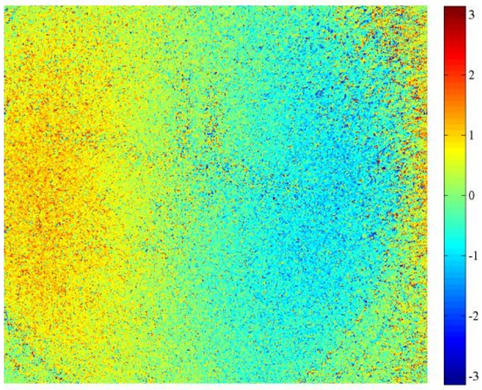
(a)



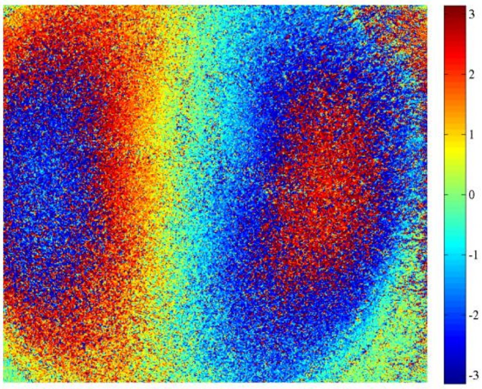
(b)



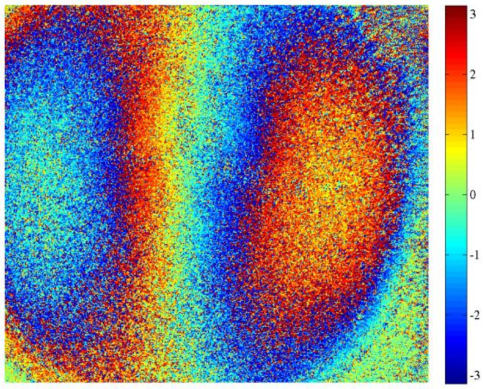
(c)



(d)



(e)



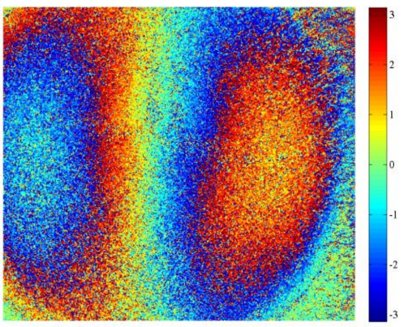
(f)

Fig 10. Different stages in processing a 2+2 shot shearogram to get a shearograph.(a) the shearogram taken with certain value of shear and carrier. (b) The Fourier transform of the shearogram. (c) Making the Fourier domain with a circular mask. (d) Final shearograph with low deformation, (e) Final shearograph with medium deformation. (f) Final shearograph with high deformation.

Here in fig 10 (b) we can see that the extra dc has been almost removed with the help of using the second image. We can only remove the dc to a certain limit because during the time we take the second shot the dc might have changes due to atmospheric and other factors thus for 2+2 method it would improve the quality by using 2 camera rather than one so that both shots can be taken together reducing any other difference in dc values. Another possible method is to use two different wavelengths so that the 2+2 method could be performed in a single shot by using color camera. But the phase map for a different wavelength is different hence it would be not as easy as using polarisation.

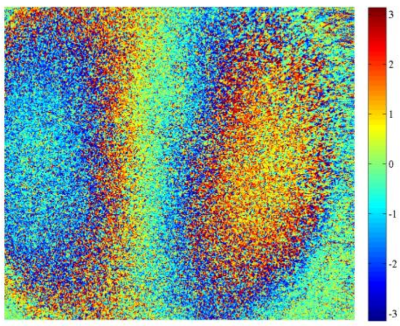
If we compare the same shearogram used in 2+2 and single-shot we can clearly see 2+2 has superior quality.

2+2 Shearoghaphy

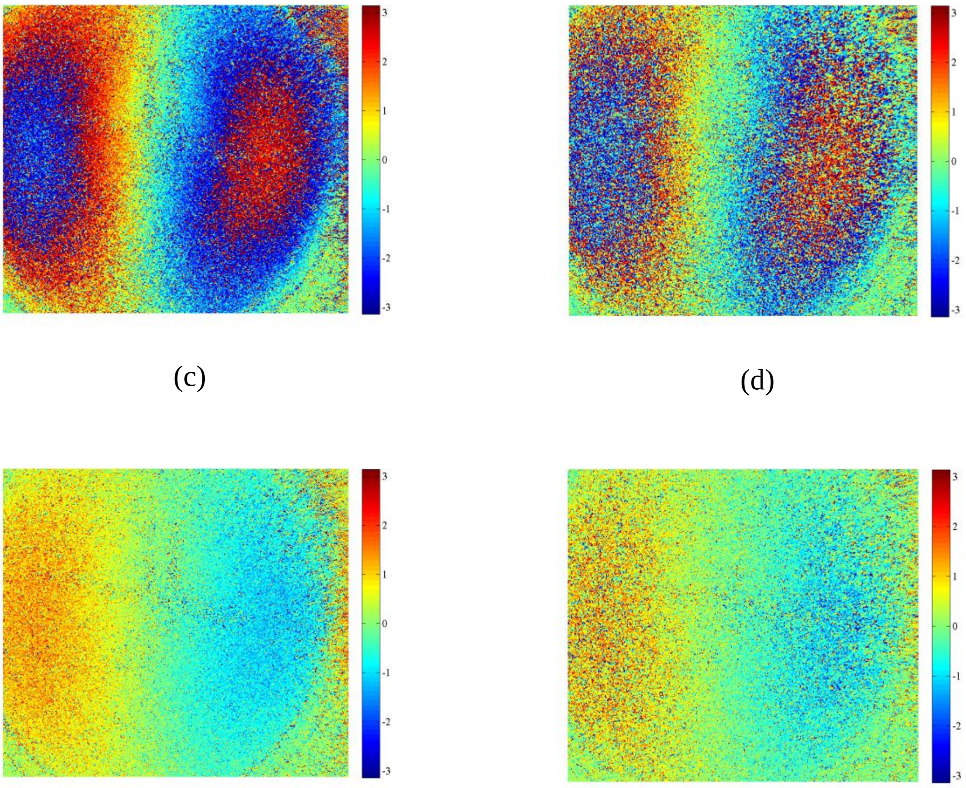


(a)

Single-shot Shearograph



(b)



(c) (d) (e) (f)

Fig 11 shows difference between the single shot and 2+2 for high, medium and low deformation. (In both the case initial deformation, shear, carrier and cut-off frequency are the same.)

VI. Conclusion

The 2 methods single-shot and 4+4 have theirs advantages and disadvantages , 4+4 is too slow that the time spend on taking more shots will introduce, more noise into the system, if we attempt to do it by using different quadrant for different phase we will end up reducing the spatial resolution just like single-shot. By using different camera for the different phase difference will solve the problem but aligning them will be a problem. So the best possible middle ground would be a 2+2 method it has better quality than single-shot and less noise than 4+4. As mentioned we might be able to use this idea with multi-wavelength someday which would be fast like single-shot and yet have good quality like the 4+4 method..

VII. Acknowledgement

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VIII. References

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