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Invited Paper

Speckle Interferometry Single-shot Applications with Multiple Carrier-fringe Information

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ABSTRACT

The need for robust equipment that allows identifying defects or measuring small displacements in a harsh environment has been a requirement in the aeronautical and principally in the Oil & Gas industry. In this field, Digital Speckle Pattern Interferometry and shearography had been the optical techniques more used. Recently, advances in the process of phase images through multiple carrier frequencies had allowed compact optical configurations that can combine multiple acquisitions or even multiple techniques in an simple process of capture. This article shows the different applications, versatility, and compactness of the use of carrier frequencies through the multiple aperture principle.

Keywords: Digital Speckle Pattern Interferometry, Spatial Phase Measurement, Robust Measurement, Carrier-fringes, Single-shot applications

1. INTRODUCTION

Speckle, in optics, refers to the pattern of bright and dark spots that appear when coherent light illuminates a surface.[1] When an image of a surface is captured after being illuminated by an expanded laser beam, speckles are formed by constructive and destructive interference coming from different parts of the surface. The advantage of speckle is that each speckle contains information on the phase and intensity, making it possible to measure small displacements (in the order of the light wavelength).[1]

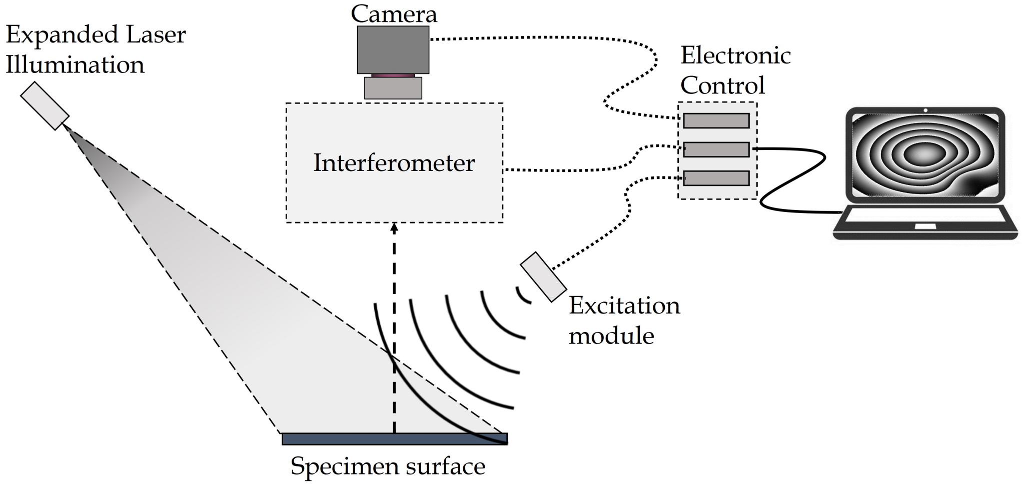

Figure 1. Basic setup for DSPI or shearography measurement.

Digital Speckle Pattern Interferometry (DSPI) and shearography are non-destructive optical techniques that allow the measurement of small displacements or displacement gradient fields on the surface of materials.[2] A basic DSPI or shearography setup requires a coherent illumination module, an interferometer, an excitation module,

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a camera, an electronic control, and specialized software to perform the phase calculation and measurement procedure, as shown in Fig. 1. For phase calculation, there are two approaches. First, there is a Temporal Phase Measurement (TPM) method, which requires the acquisition of at least three interference images with a known phase shift between them.[3] Then the phase values are obtained for each image pixel and represented in a matrix known as a phase map. One of the challenges of this application is its application in dynamic measurements where the sample experiment significant changes between each image acquisition.[4] To overcome this difficulty, techniques such as Spatial Phase Measurement (SPM) are the most appropriate.

In the SPM method, phase shifting is not made between images but within the interior of the pixels of an image.[3] This means that in an interference image, each pixel has an added and known phase shift. Different approaches have been used to achieve this, including the use of a pixelated phase mask,[5] a single different path for phase neighbor phase shifting, and the addition of carrier fringe.[6] The main advantage of the latter is that the carrier frequency can be added by a small difference in the optical path. Several authors have explored this approach and are using different configurations to make the carrier frequencies. For example, the use of Mach-Zender interferometers with controlled misalignment,[7] a double aperture for DSPI or shearography,[8] or even multiple aperture configurations.[9] This application allows the system to be more easily implemented and cheaper. It also has a great advantage that only two images are needed, a single image for each moment. With the application of multiple apertures, it is even possible to get multiple results or combine techniques with the same two images.

This paper shows the advantages, challenges, and applications of the use of multiple apertures in DSPI.

2. CARRIER FRINGE IN SPECKLE

The introduction of the interferometric technique that uses carrier frequencies, also known as carrier fringes, and its processing in the frequency plane through Fourier transform was initially suggested by Takeda.[10] In interferometry and mainly in techniques related to speckles, the carrier frequency is added using small differences in the optical path. These differences cause constructive and destructive interference in the light beams, as in Young's double-slit experiment,[11] represented in Fig. 2.

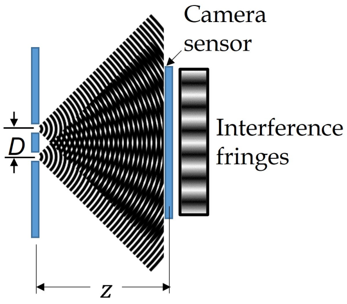


Figure 2. Carrier fringe formation by the double aperture principle.

When a coherent light passes through both openings, the interference of the beams that travel different paths produces a periodic structure, which in our case corresponds to the carrier fringes. The interference lines are perpendicular to the orientation of the openings. The distance h, between maximums or minimums, of the carrier fringes, will be determined by the distance z from the aperture to the camera sensor, the wavelength λ, and the distance between apertures D, Shape:

$$h = \frac{\lambda z}{D} \tag{1}$$

It's visible then, that generating a carrier fringe is relatively simple if we use the double slit principle and use a coherent light source such as a Laser. In the case of speckle interferometric techniques, each bright spot is the equivalent of a coherent source, and the double slit allows the carrier fringe to be introduced in each speckle. In this case, the intensity distribution in an interferogram with a carrier frequency $2\pi f_c(x)$ can be written in the form:

$$I_O(x,y) = I_b(x,y) + I_m(x,y)\cos(\phi_i(x,y) + 2\pi f_c(x)) \tag{2}$$

where I_b is the background intensity, I_m is the modulation intensity, and ϕ_i is the value of the unknown phase of the speckle, all of these in terms of the image coordinates (x, y). Applying a two-dimensional Fourier transform to the interferogram, it can be written as:

$$\mathcal{F}\{I_0(x,y)\} = A(f_x, f_y) + C(f_x - f_c, f_y) + C^*(f_x + f_c, f_y) \tag{3}$$

The resulting frequency spectrum contains three maximum regions, in the two-dimensional Fourier transform images known as halos, as shown in Fig 3. The zero-frequency located in the central halo of the spectrum is amplitude A. The desired information is present in the left and right halos $C(f_x - f_c, f_y)$ and $C^*(f_x + f_c, f_y)$, where f_x, f_y are the frequencies relative to the phase $\phi_i(x, y)$. Since the terms C and C^* are symmetric, a band-pass window filter is used around the carrier frequency to keep only the frequencies contained in the halo C. Applying the inverse Fourier transform, it is possible to obtain the complex signal $c(x, y)$ [7], from which the phase can be extracted as follows:

$$\Phi(x,y) = arctan\frac{Im[c(x,y)]}{Re[c(x,y)]} = \phi_i(x,y) + 2\pi f_c(x) \tag{4}$$

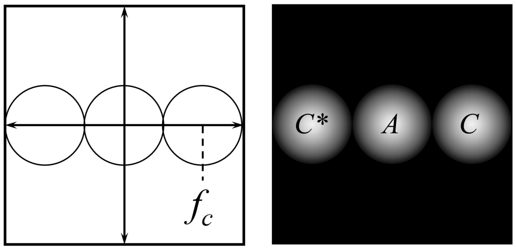


Figure 3. Representation of images with a carrier frequency in the frequency plane. On the left, is a representation of the axes and carrier frequency. On the right is a simulated representation of the two-dimensional Fourier transform, representing the intensity halo A, the frequency components C, and the conjugate C^*.

2.1 Double aperture

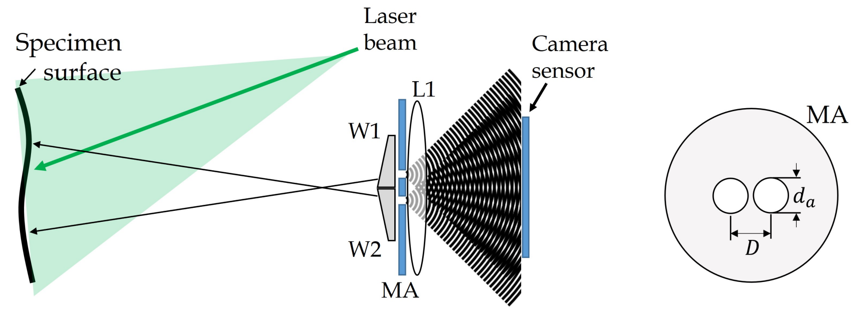


Figure 4. A shearography system configuration using a double aperture and wedge prism. The right part shows the location and diameter of the apertures.

Fig. 4 shows a basic configuration for shearography with a double aperture[8,9] The aperture mask MA is a circular plate with two circular apertures. The two apertures are aligned with two wedges and the imaging lens.

The wedge produces a lateral displacement or shear of images. The main advantage of this simple configuration is that the carrier fringe only depends on the distance D between the two apertures, the size of the speckle is controlled by their diameter d_a.

A similar configuration can be used to make a DSPI measurement,[8,12] as shown in Fig 5. In this case, only a reference speckle is necessary for the front of one of the apertures. To do that grounded glass is used and a deflected beam of the source is used to illuminate it.

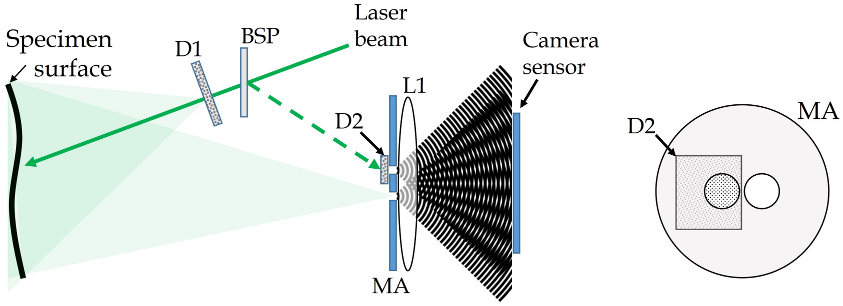
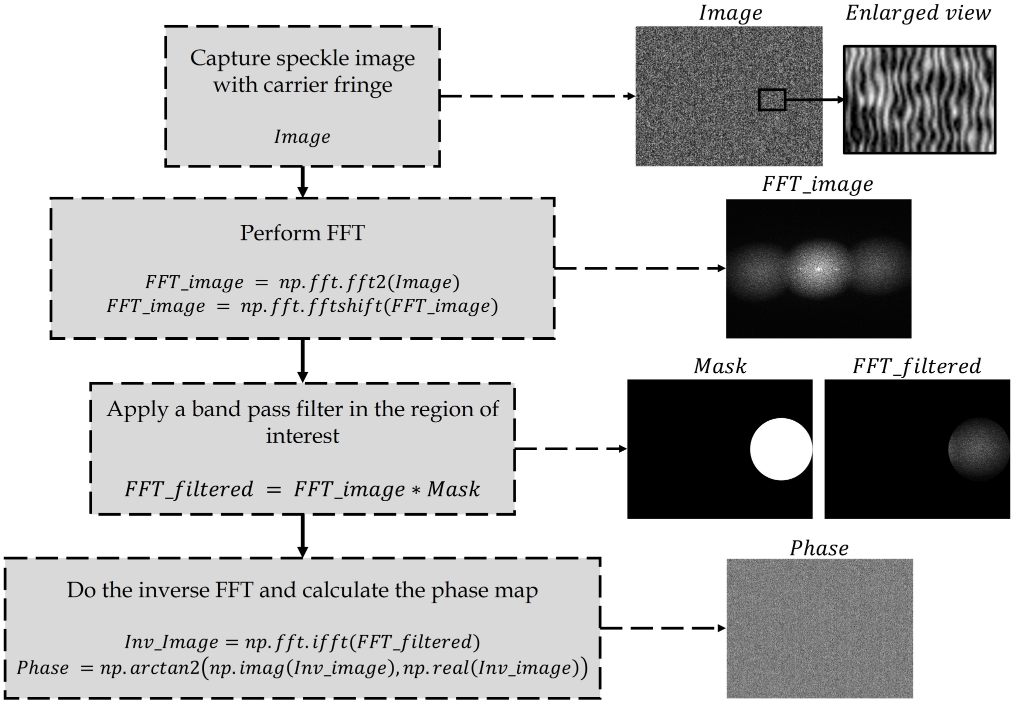


Figure 5. Optical setup for out-of-plane DSPI with double aperture. The right par shows a front view of the aperture mask MA with double aperture and the location of the diffuser D2 for speckle reference formation.



```
FFT_image = np.fft.fft2(Image)
FFT_image = np.fft.fftshift(FFT_image)
FFT_filtered = FFT_image * Mask
Inv_Image = np.fft.ifft(FFT_filtered)
Phase = np.arctan2(np.imag(Inv_image), np.real(Inv_image))
```

Figure 6. Diagram of the step-by-step processing of speckle images with carrier fringes.

In both cases shown in Fig 4 and 5, a carrier fringe is added to the speckle. Fig. 6, shows a speckle image capture with a double aperture configuration. The carrier fringe is visible in the enlarged view of a small region of the image. The step-by-step of the image processing and the steps with python's routine are present in Fig. 6. After capturing the speckle image with carrier fringe is performed the Fourier Transform Method (FTM). To do that a 2D Fourier transformation, with the cero frequency shown in the middle, is done for the speckle image. The result shows three halos, where the central halo corresponds to the background amplitude and the lateral halos contain the signal desired. To extract the phase value, a circular band pass filter is applied to one of the lateral halos and an inverse Fourier transform is applied. The phase value in modulo 2π is calculated by the relation between the imaginary and real parts of the complex result.

The phase result corresponds, to a random phase distribution, for that is necessary to acquire a second image after applying a stimulus to the specimen and repeat the process to obtain a new phase map. The difference, in modulo 2π, between the phase map of reference and the phase map after stimulus leads to an image with the phase changes, Fig. 7.

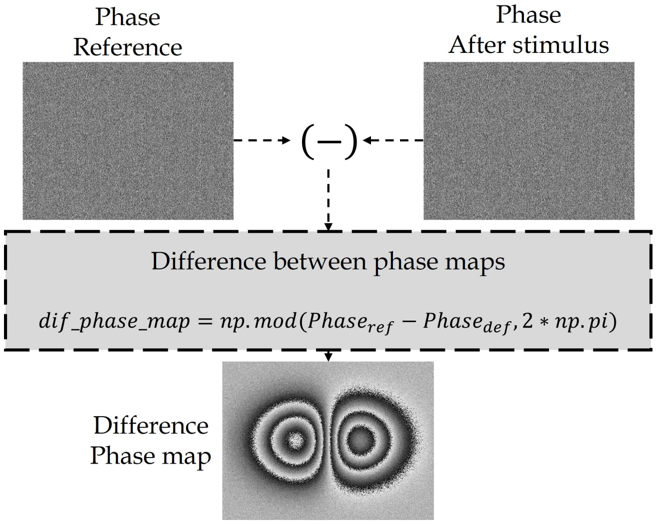


Figure 7. Difference between phase maps.

One of the advantages of the double aperture is its easy and cheap implementation, given that it reduces the number of specialized optical elements and makes a more compact configuration possible.

2.2 Multiple aperture

The use of multiple apertures in optical systems can produce interference patterns that are useful for various applications.[12] Instead of using two apertures, three or more can be employed to achieve the same effect. However, in such a multi-aperture system, multiple wavefronts interfere with each other, leading to the need for proper adaptation of the aperture locations to avoid overlaps of results and to potentially separate information in the Fourier domain.[9] To illustrate this, Fig 8 presents the results of a simulation in which was varied the number of apertures and examined the resulting Fourier components.

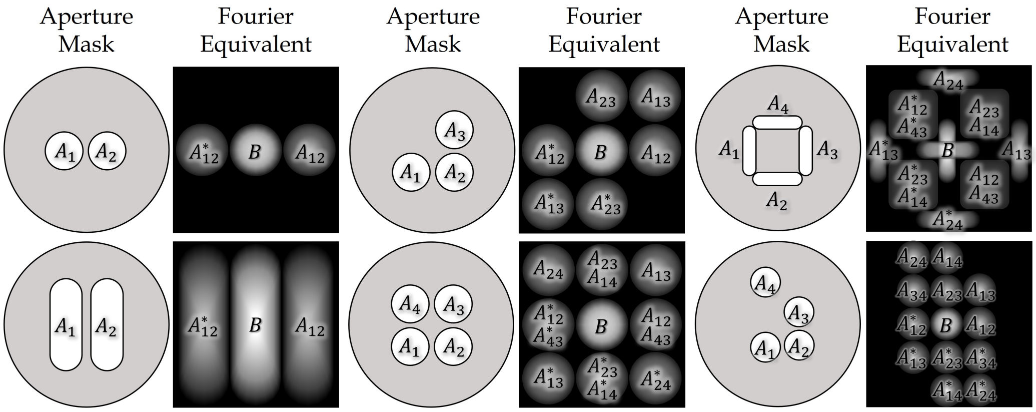


Figure 8. Multiple aperture configuration and their bi-dimensional Fourier equivalent.

Using multiple apertures allows getting not only one phase map for each image but three or more, depending on the number of apertures, as shown in Fig. 9 However, there is a sacrifice when multiple fringes are used. First, to guarantee the separation of the halos in the Fourier images is necessary to reduce the aperture size, reducing the intensity of light captured for the camera. That means using a more powerful laser or increasing the exposure time is necessary. The increase in the exposure time could be undesirable in the case of dynamic inspections. Second, when the filtering of frequencies is done the real resolution of the image is reduced, losing information.

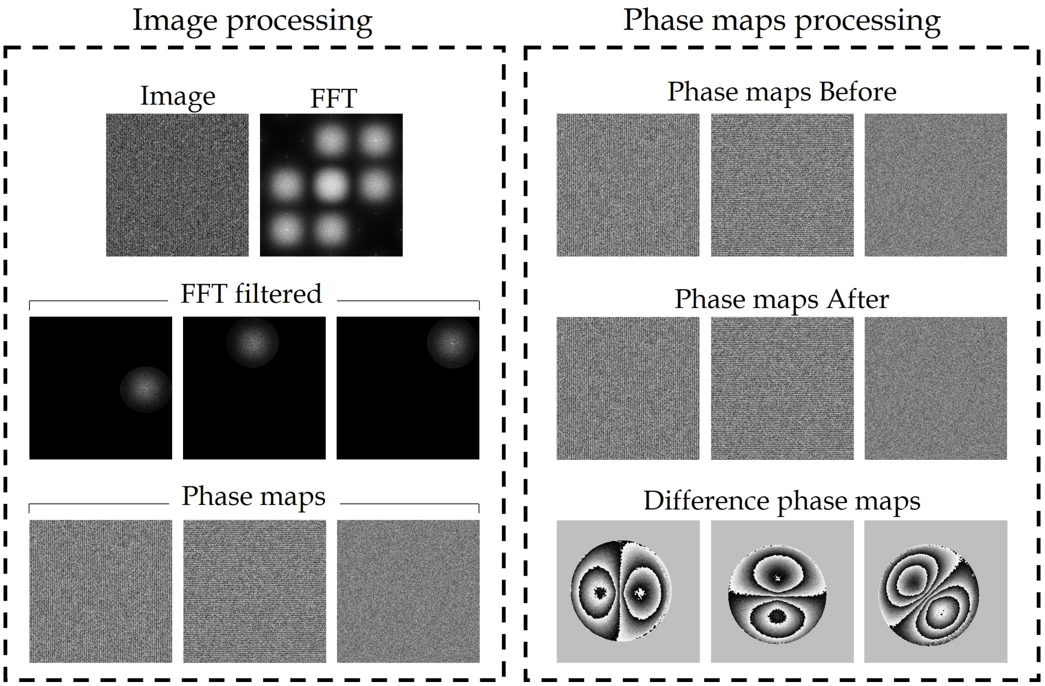


Figure 9. Phase maps processing and extraction for multiple carrier fringes.

3. APPLICATION EXAMPLES

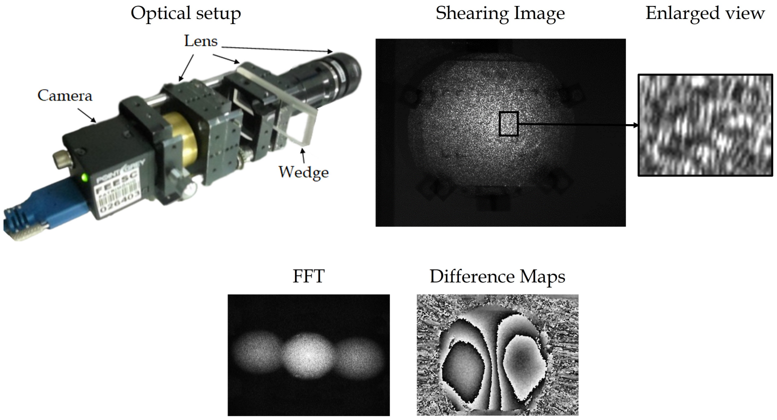


Figure 10. One-direction shearography setup with double aperture, equivalent bidimensional FFT, and sample result of difference Phase Maps.

The first application is a double aperture configuration and single carrier fringe for shearography, as presented in Fig. 4. That configuration is a simplified version of the Bahadury setup.[8] In this case, the optical elements have been reduced to only an image lens and a couple of wedges,[9] as shown in Fig. 10. The main vantage is the robustness and compaction possibility. The disadvantages are the fixed amount of shearing between images.

Replacing the wedge with a ground glass and deviating a small part of the laser beam to hit the ground glass, is possible to get a DSPI result. As shown in the configuration of Fig. 5. The real application and phase results are shown in Fig. 11.

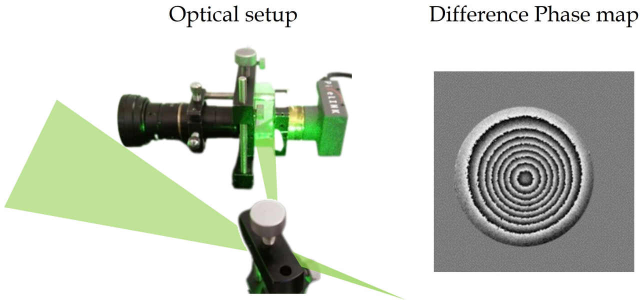


Figure 11. Optical setup and Difference phase map for a DSPI One-shot and double aperture configuration.

In the same way, it's possible to adapt the configuration to see vibration modes of membranes or leaves inspection, shown in Fig 12, using the same principle shown in Fig. 5 and 11. In this case, an ultrasonic module is used as excitation to induce vibrations in membranes.

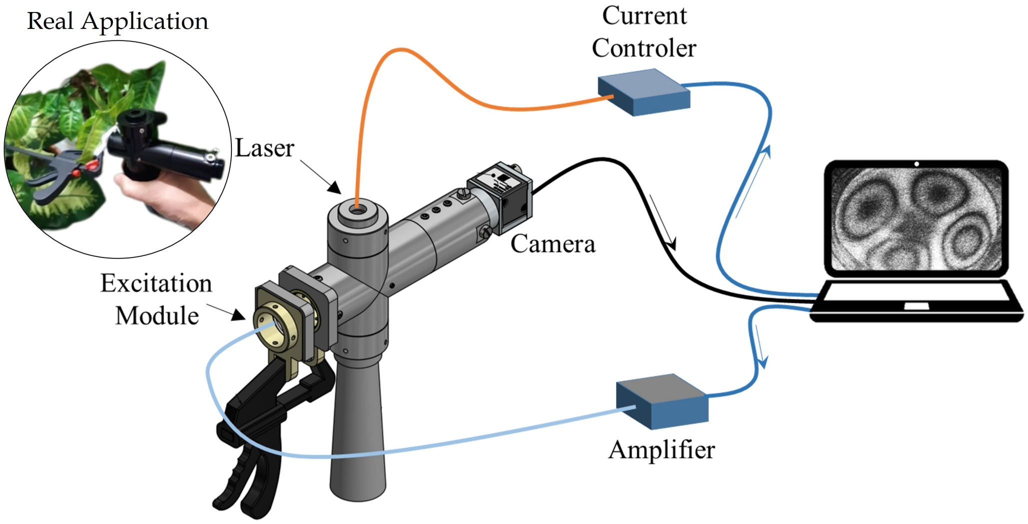


Figure 12. One-shot DSPI with a temporal average for vibration modes visualization.

The multiple apertures configuration for the shearography application is shown in Fig. 13 That setup was suggested by Barrera et al.[9] and the principal modification is the use of a Mask with three apertures, aligned with three wedges, or a custom prism with three inclinations. The prism creates a triple-shearing image and the interference of the waves passing through the three apertures produces the formation of speckles with different carrier fringes orientations.

A real application of the triple shearography setup and his results are shown in Fig. 14. In the triple-shearing image, the superposition of the images with different shear directions is visible. The enlarged view shows the fringe formation in each speckle, and the Fast Fourier Transform shows the three components of frequencies present in the image. The Difference phase maps show the result of a complete measurement after applying a mechanical load to the inspection surface.

Like the modification used in the setup for compact DSPI, if one of three apertures has a reference beam then a measurement of DSPI and shearography can be extracted simultaneously. Fig. 15 shows the optical setup, and

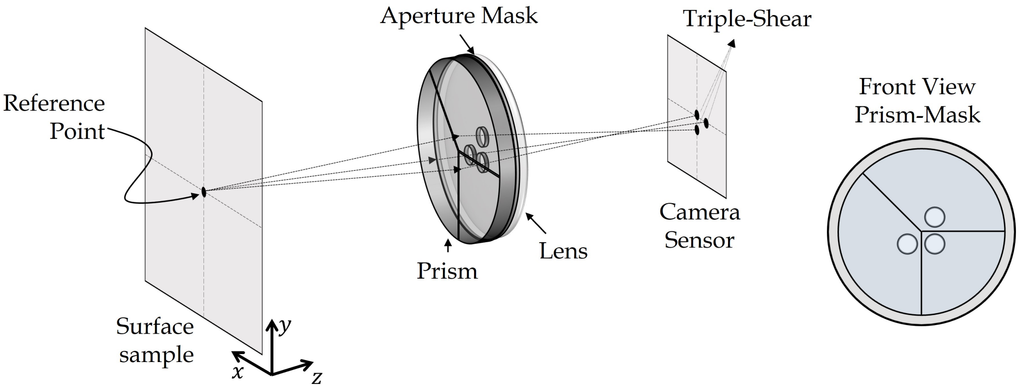


Figure 13. Optical compact setup for triple-shearing interferometry.[9]

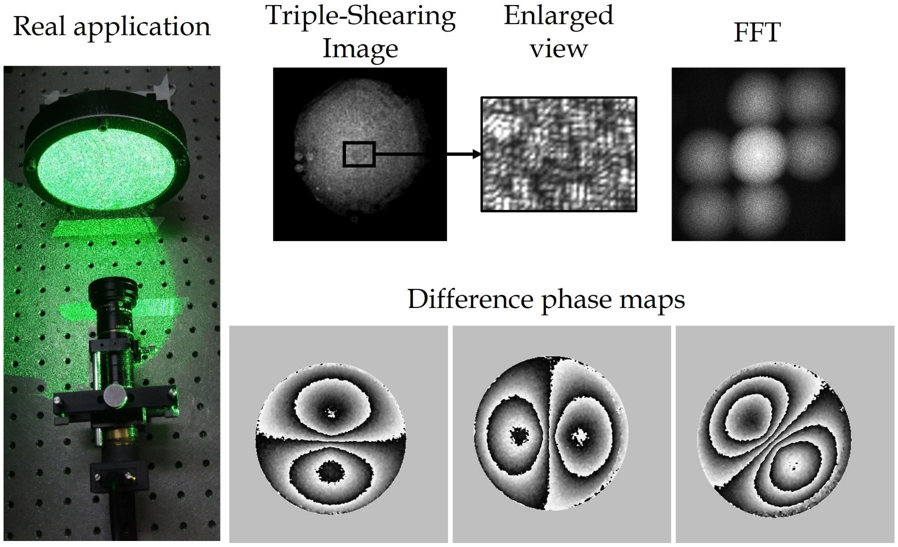


Figure 14. Triple-shearing application and results.

Fig. 16 shows the real application with the simultaneous results of DSPI and shearography, the FFT remains the same as shown in Fig. 14, because the mask doesn't need to be changed.

It is seen then that the use of multiple apertures allows getting compact and simple configurations.

4. CONCLUSIONS

The use of multiple carrier-fringe information in speckle interferometry has proven to be a powerful technique for the measurement of small displacements or surface deformations in materials. By using multiple carrier frequencies, it is possible to obtain accurate and reliable measurements, even in harsh environments. The compactness and versatility of the technique make it an attractive option for a wide range of applications. Further research is needed to explore the full potential of this technique and to develop new applications in different fields. Also remains a challenge to how o lead with the reduced intensity of the light or how to change the shear amount still with a compact solution.

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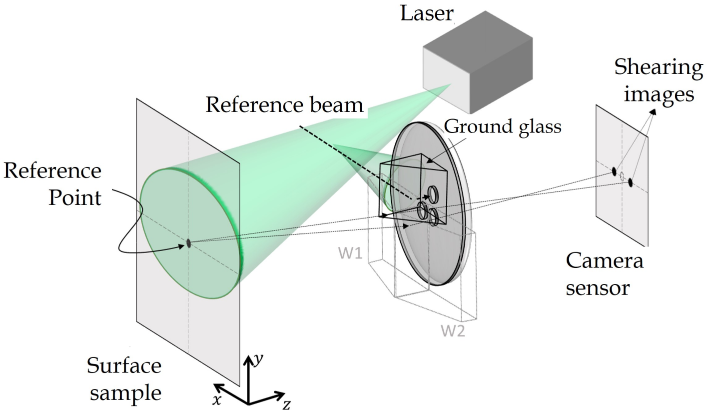

Figure 15. Optical compact configuration for simultaneous DSPI and shearography interferometry.

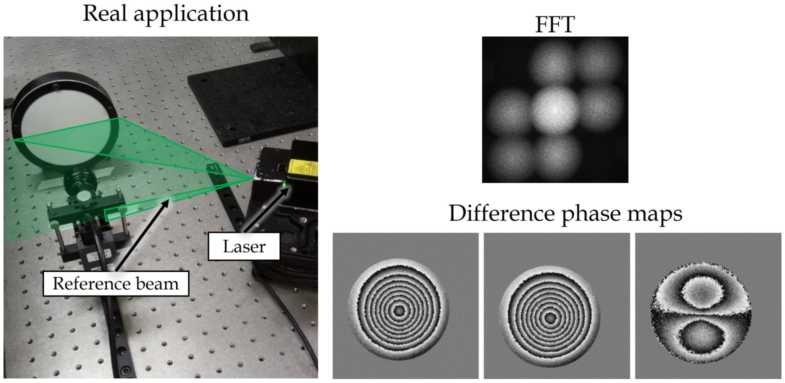

Figure 16. Simultaneous DSPI and shearography application.

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