A computational tool to highlight anomalies on shearographic images in optical flaw detection

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ABSTRACT

Shearography is an optical and nondestructive technique that has been largely used for damage detection in layered composite materials where delaminations and debondings are found among the most common flaws. Shearography is a relative measurement on which two images are recorded for different loading conditions of the sample. The applied loading induces some deformations into the sample generating a displacement field on its surface. The absolute difference between two phase maps recorded at two different loading instances produces an interference fringe pattern which is directly correlated to the displacements produced on the material surface. In some cases, depending on the loading level and mainly on the sample geometry, interference patterns will contain fringes resulting from geometry changes. This will mask those fringes correlated to flaws presented into the material, resulting in an image misinterpretation. This phenomenon takes place mainly when the sample has curved geometries, as for example pipe or vessel surfaces. This paper presents an algorithm which uses a mathematical processing to improve the visualization of flaws in shearographic images. The mathematical processing is based on divergent calculation. This algorithm highlights defected regions and eliminates fringes caused by geometry changes, providing an easier interpretation for complex shearographic images. This paper also shows the principle and the algorithm used for the processing. Results, advantages and difficulties of the method are presented and discussed by using simulated fringe maps as well as real ones.

Keywords: Shearography, non-destructive inspection, image processing, defect detection.

1. INTRODUCTION

Non-destructive techniques (NDT) based on laser interferometric imaging such as holography and shearography have had performance improvements in the last decade. They also have had wide acceptance in industry as tools for high-speed and cost effective inspection as well as for manufacturing process control. These performance advances have been possible by the growth of the personal computer, high resolution CCD sensors and digital video cameras, high performance solid-state lasers and the development of phase stepping algorithms. Shearography is a special case of the DSPI techniques where the interfering wave fronts coming from the sample, both speckled, are at the same time reference and object. Since it is a common path interferometric technique [1][2], shearography has the advantage of allowing short coherence length illumination and being less sensitive to environmental disturbances than other holographic techniques [3]. This important distinction is responsible for less sensitivity to environmental vibration. Shearography systems may be built as portable units for scanning large structures.

Shearography images show changes in surface slope, in response to a surface modification generated by an applied load. Shearography is sensitive to subsurface disbonds, delaminations, core damage, core splice joint separations as well as surface damage [4]. The changes in the applied load required to reveal subsurface anomalies frequently induce significant deformation. Shearography is sensitive only to the deformation derivatives and usually tend to show only the local deformation on the target surface due to the presence of a surface or subsurface flaw. But, when the surface to be inspected has a complex geometry, the resulting phase image can contain a complex fringe pattern which can completely hide defect indications.

The proposed method suggests a mathematical processing of the phase map to highlight defect indications even when a significant geometry deformation is applied. The method based on divergent calculation is detailed and demonstrated using synthetic and real phase images. The shearography system, used to acquire the phase images is also showed.

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2. SHEAROGRAPHY APPARATUS

As shown in Figure 1, a traditional shearography setup requires some basic elements: an illumination module, an interferometer, an excitation module and software which drives the image acquisition procedure.

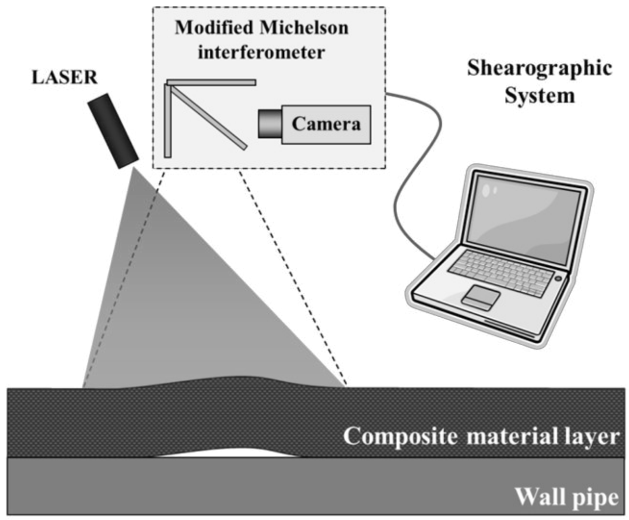

Figure 1: Shearographic setup

The surface under investigation is illuminated by an expanded laser beam which generates speckle patterns on the surface [5]. Within the sensor head, a modified Michelson interferometer [3] is designed to form the laterally sheared image of the surface.

Large rigid body motion needs to be avoided to keep good coherence between images. For that it is important to keep illumination and acquisition modules rigidly clamped together to the sample surface. Figure 2 shows the acquisition procedure used to calculate a difference phase map.

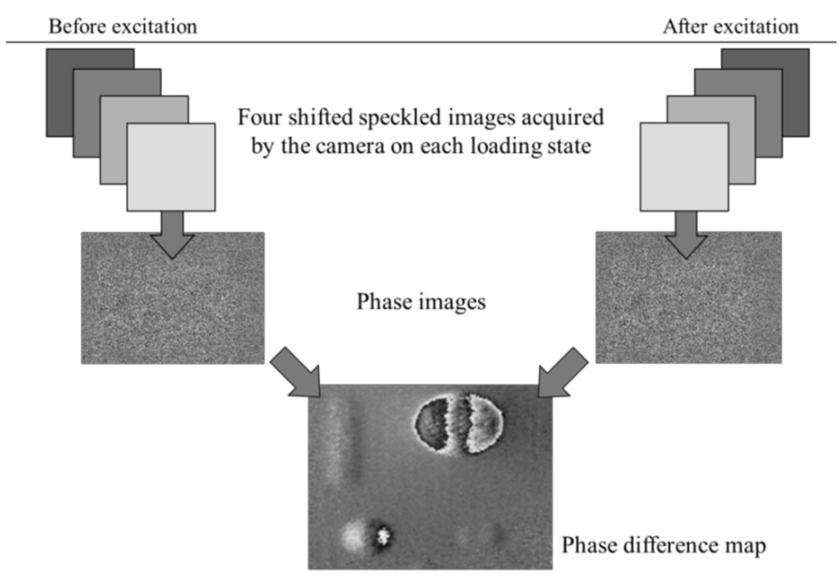

Figure 2: Shearographic inspection

A phase shifting algorithm [2] was applied to compute the shearographic phase maps. In this case, four images are acquired before loading the surface and four images after loading. The phase-stepping technique [2] is used to calculate the phase distribution in each loading state. Finally, a difference phase map is obtained by subtraction of these two phase maps.

3. PRINCIPLES OF THE PROPOSED METHOD

The images obtained can be analyzed by shearography through a phase distribution, which represents the deformation fields on the surface of the inspected sample. Typically, a flaw is represented on phase map by a symmetrical pattern, similar to a "butterfly" as shown in Figure 3 [7].

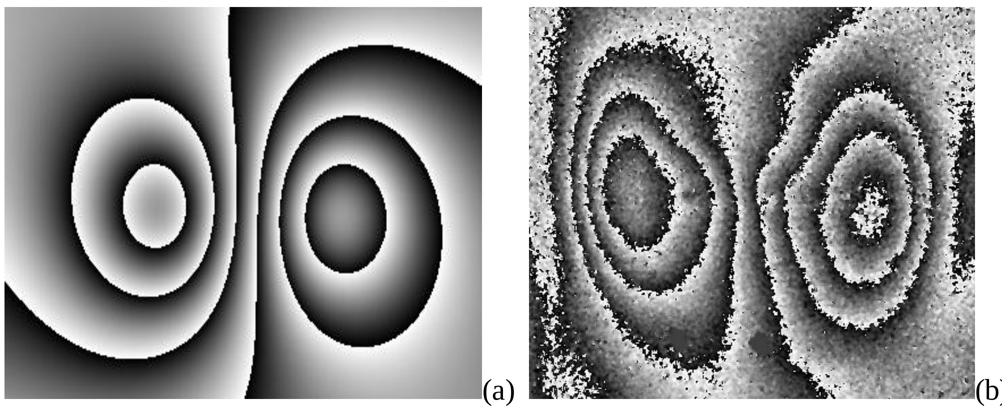

Figure 3: Typical shearographic pattern: (a) Simulated image, (b) Real image

The "butterfly pattern" is a pattern of deformation of a flaw similar to a bubble. Such flaws can be caused by debonding or delamination [4] of the composite liner.

The image processing method is proposed to highlight such "butterfly" typically found in shearography maps. The method calculates the divergent at a given point. The divergent can be understood as a scalar that measures the dispersion and divergence of the vector field at a given point. The divergent is especially significant when the region is composed by irregular fringes and it is inexpressive for regular fringes patterns as, for example, in the case of parallel fringes.

Consider an 8 bits synthetic phase image, where values range from 0 to 255 gray levels. Consider also a pixel of the image and a set of neighboring pixels symmetrically distributed over a ROI (Region of Interest) defined by two concentric circles, as shown in Figure 4.

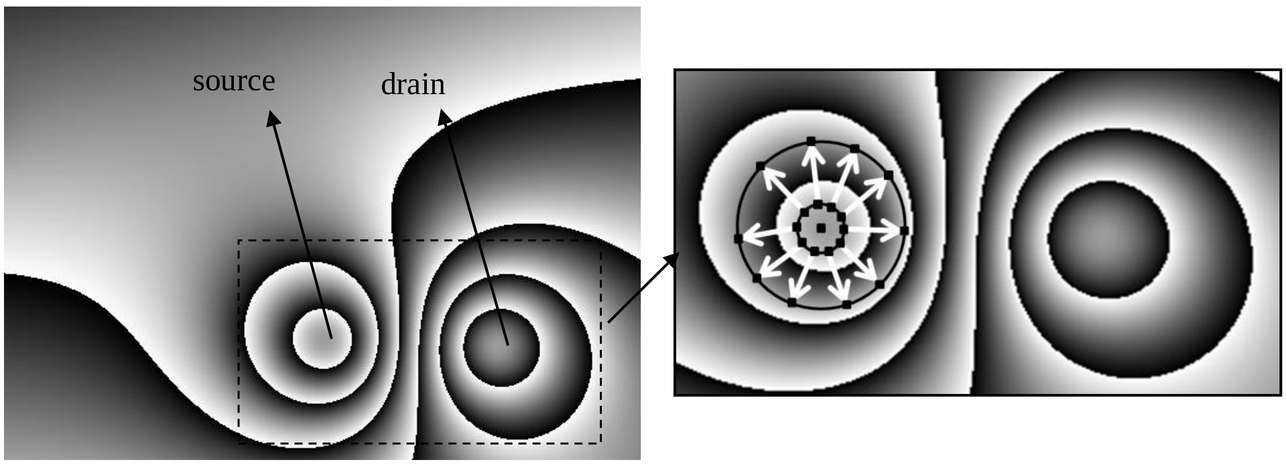

Figure 4: (a) Synthetic phase image with a “butterfly” pattern, (b) A pixel in the image and a set of neighboring pixels symmetrically distributed over a ROI defined by two concentric circles. The arrows show the correspondence between two pixels in the same angular position at the ROI.

The divergent at a given point can be calculated through the sum of phase differences between two pixels located in the same angular position, each one belong one circle.

$$D_i = \sum_i \left(\phi_i^E - \phi_i^I \right) \tag{1}$$

ϕ_i^E : phase of i^th pixel on external circle

ϕ_i^I : phase of i^th pixel on internal circle

In the Figure 4, just 10 points were used to illustrate the pixel distribution on the ROI, but in practice a larger number of points may be used for the calculation. The maximum of pixels used is limited by the smaller circle perimeter.

The phase pattern in the region with defects has a source and a drain which differ by the phase change sense. In the source region the phase variations are positive, while in the sink region the changes are negative. As phase variations are computed closer to the source or sink, larger values are found. Thus, positive phase changes result in a peak, and negative phase changes result in a valley, as shown in the Figure 5.

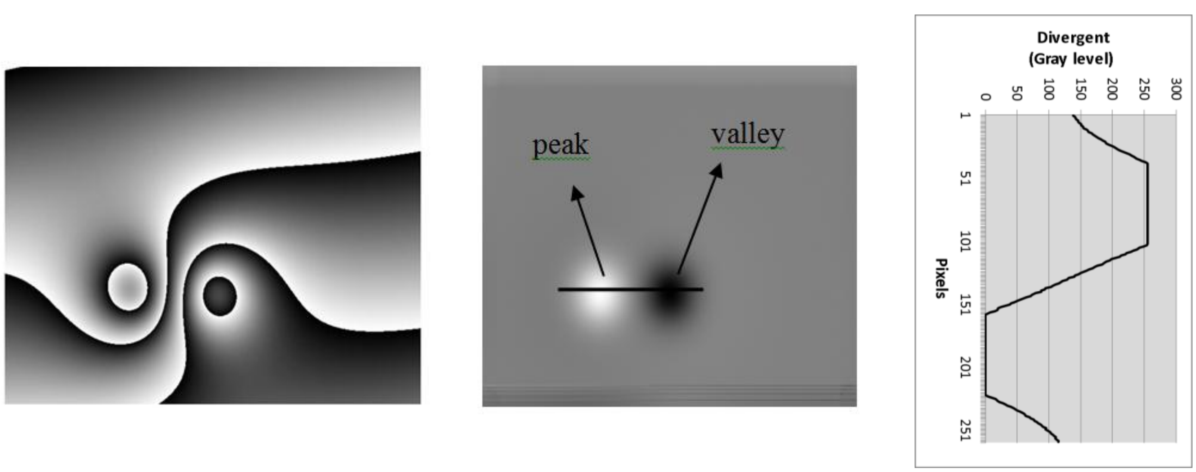

Figure 5: Phase map with an artificial defect, a divergent map and phase profile on the defect region.

The next example illustrates the method for a regular fringe map. A synthetic phase image with resolution of 800 x 600 pixels was numerically created. The ROI used is composed by a internal circle with radius of 20 pixels and an external circle with radius of 30 pixels. For each circle 20 pixels were sampled along the perimeter and used in the processing. The divergent was calculated for each image pixel and then the image was scaled to 8 bits [0 255]. For this example the divergent is the same for all pixels, so the result is a constant gray level image, as shown in Figure 6 (b).

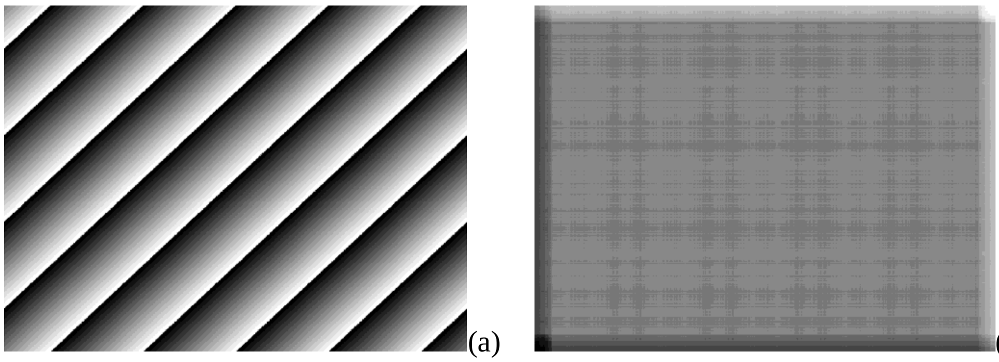
(a) (b)

Figure 6: (a) Synthetic phase map of a regular fringe pattern, (b) Processed image

Large deformation and geometry changes, often caused by the loading applied during the inspection, may result in a large fringe concentration in the phase map. In these cases, localized flaws often become hidden in a shearographic phase image. The shearographic phase map can also be complex if the inspected geometry has a non-regular geometry. In this case, the phase map not only contains fringes related to localized flaws but also contains a non-regular fringe pattern generated by the geometry deformation. The proposed method is also immune to this problem and is able to identify localized flaws.

The maps obtained by the divergent calculation can be compared with those obtained by spatial phase unwrapping algorithm [8][9]. In the proposed method the background fringes are eliminated and the resulting map presents better contrast facilitating the identification of regions with flaws. Otherwise, the unwrapped phase has large concentration of regular fringes gives rise to a ramp, which might mask minor flaws. The divergent processing eliminates and prevents that flaws remain masked. The image shown in Figure 7 was used for a comparison between these two methods. This image is a synthetic phase map of regular fringes containing a small flaw.

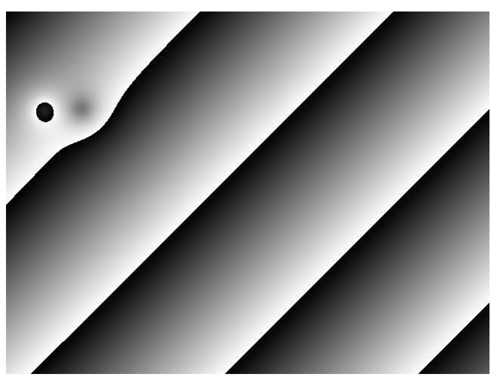

Figure 7: Synthetic phase map of regular fringes containing a small defect.

Figure 8 shows the map obtained by spatial phase unwrapping algorithm and the map obtained by divergent algorithm.

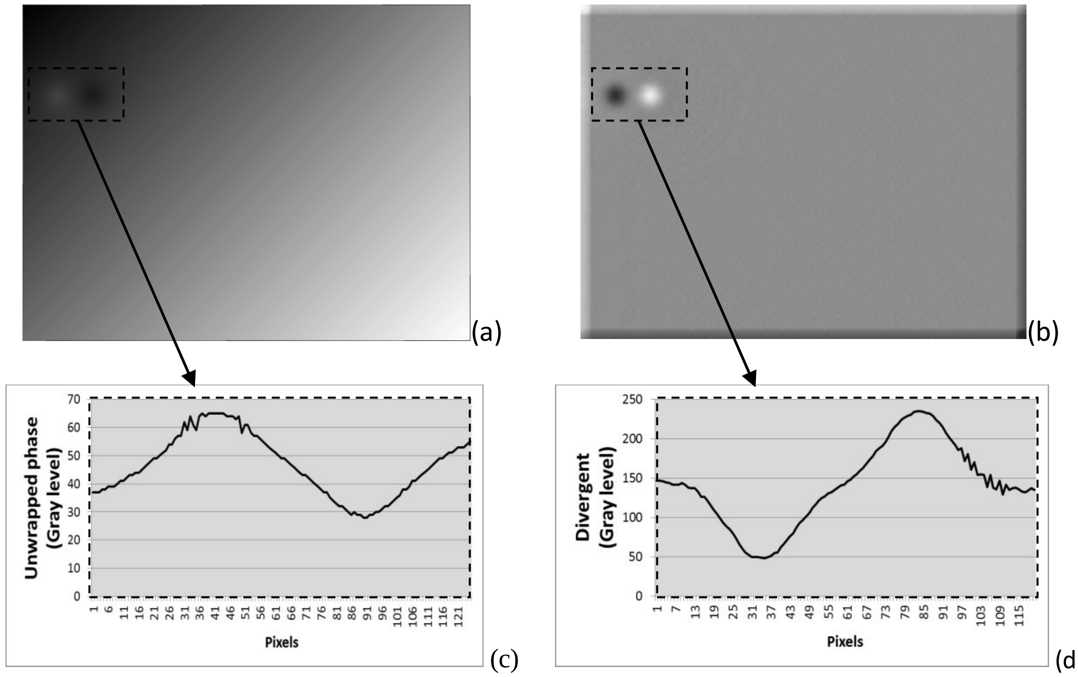

Figure 8: Image processed: (a) Spatial phase unwrapping algorithm, (b) Divergent algorithm, (c) Unwrapped phase profile, (d) Divergent profile

The defect is almost invisible in the map obtained by spatial phase unwrapping due to the presence of the phase ramp, while in the map obtained by the proposed method the flaws are easily identified. The profile curve extracted by the unwrapped phase map contains a gray level range nearly four times lower than the profile range resulting from processing by the proposed method.

4. RESULTS WITH REAL PHASE IMAGES

The proposed method has been evaluated in field for real measurements. Figure 9 shows an example got from a real structure. A composite material sleeve has been applied to repair a hole (corrosion defect simulation) in the wall of a 6 inch steel pipeline [15]. Internal pressure variation was applied as excitation method for the shearography inspection. Lateral shear has been applied transversally to the pipeline.

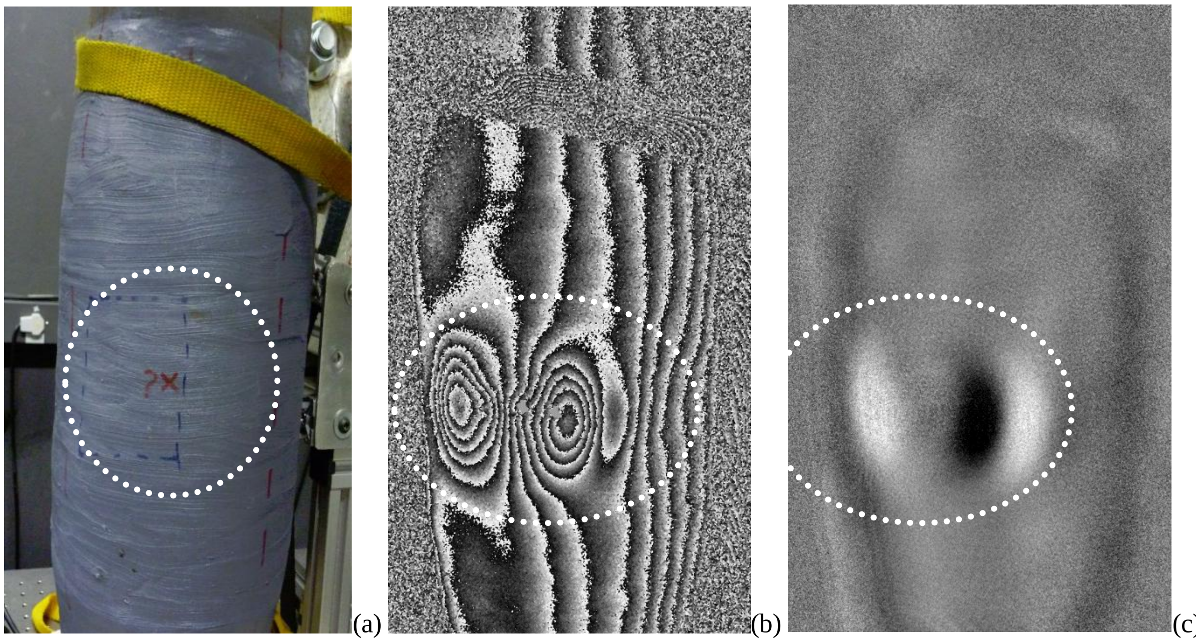

Figure 9: (a) Real composite sleeve; (b) Phase map obtained with shearography and pressure excitation; (c) Map obtained with the proposed method

Figure 9 (a) shows a picture of the investigated sample and in the Figure 9 (b) the phase map obtained with the shearography system is pointed out. Figure 9 (c) is the result obtained after processing the phase map with the proposed method. Again, fringes induced by the cylindrical geometry have been smoothed and the flaw has been highlighted with better contrast. This new image is more easily interpretable and facilitates the inspector activities. The flaw position is indicated by dotted lines.

5. CONCLUSIONS

A computational tool to highlight flaws and to make easier the interpretation of shearography results has been implemented and evaluated. The method is based on divergent calculation. The divergent can be understood as a scalar that measures the dispersion and divergence of the vector field at a given point. The divergent is especially significant when the region is composed by irregular fringes and it is inexpressive for regular fringes patterns as, for example, in the case of parallel fringes.

Large amounts of deformation and, many times, geometry changes caused by the applied excitation during the inspection procedure generate high fringe density. In these cases, localized flaws can be obscured in a shearography phase map.

The results achieved with synthetic phase maps proved that the proposed method is efficient to highlight localized flaws, even when the phase maps present a large concentration of fringes. The method also confirms its immunity to the complex shapes of the structures under test, extracting better results of the flaws hidden by the messy patterns.

The new tool has been compared to the phase unwrapping algorithm demonstrating higher robustness to enhance the flaw detection with shearography systems. An example got from a real structure was evaluated and fringes induced by the cylindrical geometry have been smoothed and the flaw has been highlighted with better contrast.

However, the success of the proposed procedure is directly related to accurate definition of ROI (Regions of Interest) dimensions which are employed in the divergent calculation. The ROI dimension should be compatible with the flaw size to be highlighted. The method may be improved if a set with different sized ROI is considered during the image processing. Future results will show that the combination of the results obtained with every ROI will make possible to point out different sized flaw in a same image.

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