Pixel Quality Evaluation and Correction Procedures in ESPI

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Abstract
A significant concern when using Electronic Speckle Pattern Interferometry (ESPI) to measure surface displacements is the modest signal-to-noise ratio. The noise content causes the measured phase map to be very irregular, often leading to difficulties when phase unwrapping. Common filtering techniques tend to average the noise with adjacent pixels, thereby ameliorating the bad data by distorting the good data. This paper describes simple procedures to evaluate individual pixel quality and identify defective pixels. The phase data at these defective pixels is replaced by interpolations from the adjacent good pixels. In this way, defective pixels are “repaired” without damaging the adjacent good pixels. The quality evaluation is done by examining the saturation, visibility and variation of each pixel. The suggested evaluation and correction procedures are demonstrated using a phase map from a hole-drilling residual stress experiment. The results show that the procedures provide an effective method for enhancing the quality of ESPI measurements.

Introduction
Electronic Speckle Pattern Interferometry (ESPI) is a full-field optical technique for surface displacement measurement [1]. It uses measurements of the phase changes within the speckle pattern created by the interference of two coherent light beams that illuminate the measured surface. In phase-shifting ESPI [2,3], a piezo actuator is used to step the phase of one of the light beams used to create the speckle pattern. The local phase at each pixel within the measured images is determined by mathematical evaluation based on the light intensities at that pixel within a sequence of stepped images [4]. The phase calculation uses the arctan function, which is limited to giving angle results within the range [-π, +π], with modulo 2π repetitions for angles outside that range. Phase unwrapping [5] is then used to remove the 2π ambiguities to create a continuous phase map.

ESPI phase maps typically contain substantial noise because the speckles have random shapes that do not neatly correspond to the rectangular grid of the pixels used for the measurement. A given pixel may happen to be poorly placed to make an accurate measurement of local phase, and so may be prone to noise. The presence of this noise can impede the phase unwrapping process, causing local phase errors of 2π or more. In adverse cases, such unwrapping errors can extend over large areas, seriously damaging image interpretation.

Average and median filtering [6,7,8] are common methods to reduce the noise within a raw phase map. However, such filters tend to redistribute noise to adjacent areas rather than eliminate it. In effect, this type of filtering improves defective pixels by damaging nearby good pixels. Here, a selective filtering approach is taken where the pixels within a measured phase map are individually examined. Defective pixels are identified according to various measures, and have their phase values interpolated from the adjacent good pixels. In this way, the defective pixels are “repaired” while keeping the adjacent good pixels intact.

Evaluation of Pixel Quality
When the two coherent light beams used for ESPI measurements combine, they interfere to create a speckle pattern. The intensity I at a given pixel is:

\[ I = I_A + I_B + 2 \sqrt{I_A I_B} \cos \phi \]  \hspace{1cm} (1)

where \( I_A \) and \( I_B \) are the intensities of each beam and \( \phi \) is the local phase angle. Equation (1) can be rewritten as:

\[ I = I_0 (1 + \gamma \cos \phi) \hspace{1cm} 0 \leq \gamma \leq 1 \]  \hspace{1cm} (2)

where \( I_0 \) is the mean intensity and \( \gamma \) is the contrast or “visibility” of the signal obtained from the interference.

A common method for determining the phase angle \( \phi \) involves using a piezo actuator to step the phase of one of the light beams used for the ESPI measurement. When using four light intensity measurements made at phase steps of \( \pi/2 \), the local phase angle is [4,9]:

\[ \phi = \arctan \left( \frac{I_A - I_B}{I_A + I_B} \right) \]  \hspace{1cm} (3)
Surface displacement is evaluated by making ESPI measurements both before and after the displacement. The change in local phase, $\Delta\phi$, indicates the displacement. Using Equation (3), the phase change caused by a surface displacement is [4]:

$$\tan(\Delta\phi) = \frac{I_4 - I_2}{I_1 - I_3}$$

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where $I_1, I_2, I_3, I_4$ are the light intensities measured before the surface displacement, and $J_1, J_2, J_3, J_4$ are the light intensities measured afterwards. $N$ and $D$ refer to the numerator and denominator of Equation (4).

The following sections describe some practical methods for evaluating pixel quality based on the measured light intensities and the relationships among them. Since Equation (4) combines two sets of measurements, a defective pixel in one set will give a faulty result even if it is satisfactory in the other set. Thus, a pixel is considered defective if is so identified in at least one data set by at least one of the following three criteria.

**Saturation**

In the ESPI technique, light intensity measurements are made at each pixel on a CCD camera. The intensities of light on the pixels are reported in integer format, e.g., 0-255 for an 8-bit camera. However, when a pixel receives excessive light, the reported light intensity stops at the maximum value. Such pixels give faulty readings, and contribute little but noise to the phase map. Thus all pixels that reach the maximum camera value in one or more of the stepped images are considered defective.

**Visibility**

In Equation (2), the factor $\gamma$ describes the visibility of the speckle pattern. The visibility controls the effective signal-to-noise ratio for the phase angle calculation. Figure 1 schematically shows the intensity variation at a given pixel with variation in step angle. The first curve shows a pixel with high visibility ($= \text{modulation amplitude} / \text{mean value}$). The local phase angle can be identified well, even in the presence of some measurement noise. The second curve shows a pixel with low visibility, for which the presence of some noise will greatly impair the phase angle identification.

The visibility $\gamma$ at a pixel can be evaluated using:

$$\gamma = \frac{2 \sqrt{(I_1 - I_3)^2 + (I_4 - I_2)^2}}{(I_1 + I_2 + I_3 + I_4)}$$

The maximum possible visibility $\gamma$ equals unity. Practical visibility factors are significantly less, averaging 0.3 - 0.6 for a well-functioning optical system. Individual pixels with visibility factors less than 0.1 are likely to be noise prone and unreliable, and are considered defective.
Variation

Saturation and visibility are measures of pixel quality that can be determined on an individual pixel basis. No reference need be made to any other pixels. An additional measure of pixel quality can be made by comparing the phase change $\Delta \phi$ computed using Equation (4) at a given pixel with the phase changes at adjacent pixels. These phase changes indicate the displacement of the measured surface, and so should be continuous among adjacent pixels. A difficulty arises because the arctan function required to evaluate the phase angle $\Delta \phi$ in Equation (4) gives results only within the range $[-\pi, +\pi]$. The computed phase maps therefore contain $2\pi$ steps at the points the phase angle goes outside that range. These phase steps can be removed by phase unwrapping [5]. However, measurement noise seriously impairs the unwrapping process, so it is desirable to identify and repair defective pixels first. A further difficulty then arises because the modulo $2\pi$ phase steps destroy the continuity of the phase map, thereby impeding consideration of phase variation among neighboring pixels. This difficulty can be removed by instead working with the sine and cosine components of the phase change [6]:

$$\sin(\Delta \psi) = \frac{N}{R} \quad \text{and} \quad \cos(\Delta \psi) = \frac{D}{R} \quad \text{where} \quad R = \sqrt{N^2 + D^2}$$

These phase components vary smoothly and do not have any step changes. The consistency of a given pixel with its neighbors can be assessed by comparing its sine and cosine values with the averages of the adjacent pixels. This can be conveniently done by considering a 5x5 block of pixels centered on the given pixel, as shown in Figure 2. Taking both the sine and cosine components into account, the combined variation of a given pixel from the trend expected from the adjacent pixels is:

$$\text{Var} = \left[ \frac{(25 \sin(\Delta \phi) - S\text{sum})^2}{24} + \frac{(25 \cos(\Delta \phi) - C\text{sum})^2}{24} \right]^{1/2}$$

where $\Delta \phi$ is the indicated phase change at the center pixel, Ssum is the sum of the $\sin(\Delta \phi)$ of all pixels in the 5x5 block, and Csum is the sum of the corresponding $\cos(\Delta \phi)$. Ideally, Var should approach zero. For well-functioning pixels, Var = 0 – 0.25, and for totally decorrelated pixels, Var ≈ 1. Pixels with Var > 0.5 are considered defective.

Identification of Defective Pixels

By evaluating the three pixel quality measures, pixels containing different defects can be identified. Figure 3 shows the pixel quality illustration for an example ESPI hole-drilling residual stress measurement [10]. A circular hole has been drilled in the specimen, causing surface deformations in the surrounding material due to the local stress relief. The measurements are entirely decorrelated within the hole because the surface material has been removed. Thus, no structured fringe pattern is observed within the circle shown in Figure 3(a). Outside the circle the ESPI fringe pattern is visible, although with a grainy texture caused by measurement noise.
Figure 3(b) shows the saturated pixels. There are some saturated pixels on the upper part of the image indicating slightly uneven illumination. In addition, there is a small group of saturated pixels within the hole caused by the polishing effect of the cutter during hole-drilling. Figure 3(c) shows the low visibility pixels. These pixels are concentrated within the marked circle because this surface was removed during hole-drilling. There are also several other low-visibility pixels scattered elsewhere within the image.

Figure 3(d) shows the high variation pixels. The points enclosed by the hole boundary are completely decorrelated because the surface material in that portion was removed by hole-drilling. The concentration of high variation pixels extends beyond the hole boundary because the adjacent surface was damaged by the flow of chips from the hole during the cutting process. As with the low-visibility case, there are many high-variation pixels scattered elsewhere in the image. Many of these pixels are also reported as having low visibility.

The diagrams in Figure 3 demonstrate the effectiveness of the defective pixel identification. The distribution of defective pixels is physically realistic, with the position of the hole clearly identified within the optical data. The large number of high-variation pixels indicates that the fringe map is of only modest quality overall.

Interpolation of Defective Pixels

As illustrated in Figure 3, defective pixels are distributed throughout the measured phase map. They can occur individually or in groups. Figure 4 schematically illustrates the variation of \( \sin(\Delta \phi) \) or \( \cos(\Delta \phi) \) along a line of pixels within an ESPI phase map. In this example, pixels 4 and 5 have been identified as defective by at least one of the three quality evaluation tests. The proposed interpolation scheme involves searching along lines of pixels within the measured image, identifying the defective pixels, and replacing their phase values with values linearly interpolated between the nearest adjacent good pixels. To remove a directional bias from this process, this interpolation is done along all rows and columns of the phase map, and also along the two diagonal directions. The "repaired" pixel value is set to the average of the values interpolated in the four directions. This interpolation procedure can handle groups of defective pixels of any shape, the only requirement being that each group must be surrounded by good pixels. Thus, the outline of the phase map must first be interpolated to ensure that this is the case for all interior pixels.

After the defective pixels within the \( \sin(\Delta \phi) \) and \( \cos(\Delta \phi) \) maps have been interpolated, the angle \( \Delta \phi \) is determined using the arctan function, and then the resulting phase map is unwrapped. Delaying the unwrapping until after the interpolation avoids interpolation errors at the modulo \( 2\pi \) steps within the wrapped phase map.

Filtering Example

Figure 5 shows an enlarged portion of the fringe pattern in Figure 3(a), just touching the right hand edge of the hole. The raw fringe image in Figure 5(a) shows the typical grainy texture due to measurement noise. Figure 5(b) shows the result after applying mild binomial smoothing [11]. This mild smoothing removes much high-frequency noise, but retains many local defects. Figure 5(c) shows the result after applying a greater amount of binomial smoothing, sufficient to remove most of the larger defects. The resulting fringe pattern looks smoother, but the large amount of filtering has also "smear" the fringes. The smoothing has "corrected" defective pixels by diluting their errors among the neighboring well-functioning pixels.

Figure 5(d) shows the result of interpolating defective (=saturated + low visibility + high variation) pixels. These are the pixels identified in Figures 3(b), (c) and (d). The definition of the fringes is greatly improved, particularly near the left edge, close to the hole. The majority of the major defects visible in Figure 5(a) are removed without causing smearing. Figure 5(e) shows the result of using interpolation followed by mild smoothing (the same amount as used in Figure 5(b)). Here, the mild smoothing is sufficient to reduce some remaining grainy texture without introducing significant fringe smearing. Figure 5(f) shows the result of using interpolation followed by greater smoothing (the same amount as used in Figure 5(c)). This amount of smoothing further reduces the grainy texture, but it starts to smear the fringe pattern.
Figure 5 – Comparison of interpolated and smoothed fringes.
(a) unfiltered, (b) with mild smoothing, (c) with greater smoothing,
(d) with interpolation, (e) with interpolation and mild smoothing, (f) with interpolation and greater smoothing.

Figure 6 – Comparison of unwrapped phase changes (in radians):
(a) unfiltered, (b) with mild smoothing, (c) with greater smoothing,
(d) with interpolation, (e) with interpolation and mild smoothing, (f) with interpolation and greater smoothing.
Figure 7 – Comparison of unwrapped phase maps:
(a) unfiltered, (b) with mild smoothing, (c) with greater smoothing,
(d) with interpolation, (e) with interpolation and mild smoothing, (f) with interpolation and greater smoothing.

A different view of the effects of interpolation and smoothing can be gained by observing the phase data in graphical format. Figure 6 shows the phase in radians at the first 120 pixels along the middle line in Figure 5, just to the right of the hole. The six graphs in Figure 6 correspond to the six images in Figure 5. The raw phase data shown in Figure 6(a) contain substantial high-frequency noise and several wrapping errors. Figure 6(b) shows that mild smoothing decreases the high-frequency noise and removes some of the unwrapping errors. The greater smoothing in Figure 6(c) continues this trend. However, a major unwrapping error remains near the center.

Figure 6(d) shows that interpolation of defective pixels has eliminated all the unwrapping errors visible in Figure 6(a). Since the “good” pixels are left intact, the original high-frequency noise remains. Figures 6(e) and (f) show the effects of smoothing the interpolated result. The mild smoothing in Figure 6(e) is sufficient to reduce the high-frequency noise significantly. In this case, the greater smoothing in Figure 6(f) also looks reasonable. However, the use of substantial smoothing, even after interpolation, is not recommended because it can distort (“smear”) image details in areas showing localized features.

Figure 7 shows a yet further view of the phase map corresponding to Figure 5. In this format, the phase change $\Delta \phi$ is represented in grey-scale, with high angles appearing light grey, and low angles appearing dark grey. Again, the sequence of images in Figure 7 corresponds to the sequence in Figure 5. Figure 7(a) clearly shows the wrapping errors in the unfiltered phase map as a patchwork of light and dark areas. The grainy texture of this image illustrates the high-frequency noise. Increased smoothing reduces the unwrapping errors and the high-frequency noise. Figure 7(d) shows that interpolation was effective in eliminating almost all unwrapping errors, and Figures 7(e) and (f) show some high-frequency noise removal by additional smoothing.

Discussion

The pixel quality evaluation and correction procedure described here is based on three principles:
1. Selective filtering based on measures of quality of each measured pixel. “Defective” pixels are adjusted while leaving “good” pixels unchanged.
2. Inclusion a-priori information from the stepped ESPI video images when making the quality evaluation.
3. Doing all filtering first to stabilize and to reduce the error sensitivity of the subsequent phase unwrapping.
These three principles, none new individually, are combined here to create an effective filter for phase maps measured using ESPI. The particular strength of the method is the focus on the defective pixels while leaving good pixels untouched. This allows a great reduction in the amount of smoothing needed to reduce remaining high-frequency noise, possibly even to eliminate the need for smoothing. Avoidance of substantial smoothing and the consequent smearing of the measured image is particularly useful in cases where detailed features are to be resolved. The example measurements illustrated in Figures 5, 6 and 7 demonstrate how the defective-pixel filter is able to rescue useful results from a data set of very modest quality. By their nature, EPSI measurements tend to have high noise content, so effective filtering is a very valuable tool.

Conclusions

An effective pixel quality evaluation and correction procedure for ESPI measurements has been presented. It filters an ESPI phase map by specifically targeting defective pixels. These pixels are identified on the basis of their saturation, visibility and variance. Their defective values are replaced by local estimates interpolated from the adjacent good pixels. The procedure preserves the information content of the ESPI data by leaving the good quality pixels intact. This arrangement differs from most typical filters, such as average or median filters, which ameliorate bad pixels by diluting their defects among the neighboring good pixels.

Some modest smoothing applied after defective pixel interpolation is shown to be useful for diminishing high-frequency noise. However, substantial smoothing is undesirable because it can smear resolution of detailed features. All filtering is done on the sine and cosine components of the phase map rather than on the phase map itself. This choice is made because these components are continuous, so avoiding the difficulty of working with the $2\pi$ steps contained within a wrapped phase map. Filtering before unwrapping a phase map is desirable because the high noise content in typical ESPI measurements easily disturbs most phase unwrapping algorithms, causing errors that can extend over large areas. Unwrapping algorithms are much more stable when working with filtered data. The character of the pixel quality evaluation and correction procedure is demonstrated on an example ESPI measurement. The results show that useful data can be extracted even from measurements of modest quality.

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References