Effect of Digital Filtering on the Analysis of Surface Deformations using Electronic Speckle Pattern Interferometer

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Abstract. Digital filtering is an essential part of electronic speckle pattern interferometer which is been used widely to study surface deformations. Raw speckle patterns needs digital filtering before it is used for further analysis. Many times multiple use of digital filtering leads to change in the quantitative information of surface under study. This paper reports effect of multiple usages of various digital filters on the calculated surface deformation values. Multiple usages of various digital filtering leads to loss in speckleness of the pattern indicating decrease in speckle noise and marginal and in some cases significant change in surface displacement values.

INTRODUCTION

Electronic speckle pattern interferometer (ESPI) is a technique which probe changes in the speckle patterns to quantify surface deformations [1-2]. Speckle patterns obtained before and after deformation are used for calculating changes in the surface [3]. Temporal multistep phase shifting technique of ESPI [4] is one of the widely used techniques along with bunch of others [5-7] for the quantitative analysis of surface deformations. At the beginning of the analysis digital filtering of speckle pattern is essential [8-9] as it is used for removing unwanted noise from the pattern. Various digital filters commonly used are Median [10-11], Average [12], Gaussian filters [13] and other effective filtering techniques [14-15]. Multiple use of above mentioned filtering techniques can lead to significant change in surface displacement values. Effects of multiple usages of various digital filtering techniques on the speckle pattern and on the retrieval of phase map are already reported in our previous article [16]. However, following points based on the previous study [16] needs further probing to get a complete picture.

- Effect of multiple usages of various digital filters on the 3D surface profile and corresponding line profiles needs to be probed
- Effect of kernel sizes of digital filter on the calculated surface profiles.
- Effect of multiple usages of the same digital filter on the surface profile values.

In this article, we present a detailed study on the multiple applications of Median, Average and Gaussian filters based on the above written points.

EXPERIMENTAL SETUP

FIGURE.1 shows the schematic of the temporal phase shifting method of electronic speckle pattern interferometer (ESPI). Laser light from the continuous wave Helium Neon laser ($\lambda$=632.8 nm, Power = 2 mW, ...
coherence length = 10 cm) is divided into two half using a beam splitter. One beam is used to illuminate the object surface in the full-field manner via spatial filtering. Illumination of the object gives rise to speckle pattern which carries information regarding its surface.

![Experimental setup of temporal phase shifting ESPI technique.](image)

Generated speckle pattern is then collected and diverted using a mirror towards digital camera (1/4-inch CMOS sensor, Array element: 1,280 x 1,024, Image area: 3.6 x 2.9 mm, Pixel sizes: 2.8 x 2.8 μm and Maximum frame rate: 7.5fps). Second beam after multiple reflections for matching the path length with the first beam passes through polarizer and diffuser plate. It gives rise to reference speckle pattern. Two speckle patterns thus generated are superimposed onto each other and form a speckle interferogram. This is then imaged with the help of digital camera mentioned above and stored in a computer. This setup is called as out-of-plane setup because its deformation direction is nearly perpendicular to the object’s surface. We observed and recorded speckle interference pattern from mechanical deformed Aluminum metal disc. Known amount of deformation can be given to disc and respective speckle interferogram obtained via interference of object and reference beam. Speckle interferogram was recorded using digital camera and stored in computer. This speckle interferogram contains tremendous noise in it; hence we employed Median, Gaussian and Average filtering technique on the same speckle interferogram and use them to calculate phase map and surface displacement via temporal phase shifting ESPI method.

**RESULT AND DISCUSSION**

In the previous research article, we have already reported the effect of digital filtering on the speckle contrast and phase map with comparative study, after implementing the Digital filters namely, Median, Gaussian and Average (with 3X3 and 7X7 and latter with 17x17 kernel sizes). After achieving the phase information we have calculated the amplitude of deformation. FIGURE 2 shows the 3D surface displacement plots calculated from unwrapped phase maps reported in [16]. Note that mechanical deformation of 50 microns corresponding to piston movement of 1.2 μm was applied to metal disc.

FIGURE 2a, b, c and d shows surface profiles when average filter with kernel size 3x3 was used once, five times, ten times and fifteen times respectively. FIGURE 3a, b, c and d shows surface profiles when median filter was used once, five times, ten times and fifteen times respectively. FIGURE 4a, b, c and d shows surface profiles when Gaussian filter was used once, five times, ten times and fifteen times respectively.

From FIGURE 2, surface profiles seem to become cleaner after every iteration of each digital filter used. It seems from Fig 2i, j, k and l that Gaussian filter shows higher noise in surface profiles plot compared to other filter. Median filter stood second in terms of noise in surface profiles plot. Whereas average filter with both kernel sizes used gives much better results compared to other in terms of noise reduction from surface profiles.
FIGURE 2. Surface profile maps when average filter with kernel 3x3 was used a) once b) five times, c) ten times and d) fifteen times;
FIGURE 3. Surface profile maps when Median filter was used: 
(a) once, (b) five times, (c) ten times, (d) fifteen times.
FIGURE 4. Surface profile maps when Gaussian filter was used i) once j) five times k) ten times and l) fifteen times.

FIGURE 5a, b, c and d shows surface profiles when average filter with kernel size 3x3 was used once, five times, ten times and fifteen times respectively. FIGURE 6a, b, c and d shows surface profiles when average filter with kernel size 7x7 was used once, five times, ten times and fifteen times respectively. FIGURE 7a, b, c and d shows surface profiles when average filter with kernel size 17x17 was used once, five times, ten times and fifteen times respectively.
FIGURE5. Surface profile maps when average filter with kernel 3x3 was used a) once b) five times, c) ten times and d) fifteen times;
FIGURE 6. Surface profile maps when average filter with kernel 7x7 was used e) once f) five times g) ten times and h) fifteen times;
Average filter with different kernel sizes used gives much better results compared to other in terms of noise reduction from surface profiles. To dig deeper into this, we have plotted line profiles of FIGURE 2, 3 and 4 for pixel number [0-902, 451]. These line profiles of FIGURE 2, 3 and 4 are as shown in FIGURE 8.
FIGURE 8 Line profile of surface displacement plots after a) first iteration b) 5th iteration c) 10th iteration and 15th iteration of digital filters.

FIGURE 8a, b, c and d shows line profiles of surface displacement plots after a) first iteration b) 5th iteration c) 10th iteration and 15th iteration of each digital filters used respectively. After first iteration, average filter shows much cleaner line profile compared to other filters. For 5th and 10th iteration, all the filters yield almost same results with Gaussian and Median filter still showing noise to some extent. At 15th iteration, surface displacement values gets change for Gaussian filter whereas all other filter maintaining continuity in surface displacement amplitudes. This doubts multiple usages of Gaussian filter in obtaining realistic surface displacement values. Even median filter yields lot of noise in surface profiles.

FIGURE 9 shows the one dimensional line profiles of filtered maps when average digital filter with different kernel size is used.
FIGURE 9 Line profiles of surface displacement after a) first iterations b) 5th iteration c) 10th iteration and 15th iteration of average digital filters with kernel sizes 3x3, 7x7 and 17x17.

Further we have tracked peak surface displacement value assigned to the pixel [480,451] over number of iteration of each digital filter. It is then plotted against number of iterations as shown in FIGURE 10. It shows that average filter with kernel size 3x3 saturates to final surface displacement values in the first iteration itself. Gaussian filter takes longer time to get to a stable value of surface displacement. From 5th iteration onwards all the filters shows almost similar and stable value of surface displacement. Over usage of Gaussian filtering for cleaning speckle pattern destroys surface displacement map when it is near to 15th iteration. However others still shows stable surface displacement values even at 15th iteration.
FIGURE 10. Peak surface displacement versus iterations of various digital filters used.

FIGURE 11. Peak surface displacement versus iterations of average digital filters with different kernel sizes used.
To see the effect of multiple filtering on stability of surface profiles values, peak surface displacement corresponding to pixel [480, 451] was tracked throughout all the iterations. It is as shown in FIGURE 11. Standard deviations of peak surface displacement values for multiple iterations of the average filters with 3x3, 7x7 and 17x17 kernel size had found to be 5.4 x 10-10, 1.1 x 10-07 and 5.3 x 10-9 respectively. It implies that only the average filter with kernel size 7x7 shows large variation in surface displacement values as compared to average filters with kernel sizes 3x3 and 17x17. Performance of average filter with kernel size 3x3 and 17x17 are almost identical. Visually usages of 17x17 kernel size yields less noisy phase map and surface profiles as discussed before.

CONCLUSIONS

Detail analysis concerning effect of multiple usages of various digital filtering techniques on speckle pattern, wrapped and unwrapped phase maps and finally to surface profiles calculated from it is presented in this paper. It was observed that, digital filtering of speckle pattern is an essential step in obtaining meaningful surface displacement plots from ESPI. Multiple usages of digital filtering lead to some loss of speckleness but ultimately yields realistic surface displacement values of the object under study. Average filtering technique is faster way to get to realistic surface displacement values than any other filtering technique used in the study. Average filtering with larger kernel size reduces noise quicker than with the same filter having smaller kernel size. Median and Gaussian filtering are good at preserving speckleness of pattern but not reliable for obtaining phase map and surface profiles from it. In fact, median filtering is better than Gaussian filtering method but inferior to average filtering method. Average filtering with 17x17 kernel size seems to be topmost choice for obtaining cleaner phase maps and realistic surface displacement plots.

ACKNOWLEDGEMENT

Authors are very much thankful to Head of the Physics department, Sant Gadge Baba Amravati University, Amravati for providing us necessary facilities.

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