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Quantitative Study of Deformations using Electronic Speckle Pattern Interferometer (ESPI)

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Abstract
This paper discusses a research proposal to use temporal phase shifting technique of Electronic Speckle Pattern Interferometer (ESPI) for qualitative and quantitative study of deformations of various kinds. Proposed method for quantitative study is a five step phase shifting algorithm for extraction of phase information from the deformed object. Mechanical and thermal deformations in metallic thin films, metal plates and acoustic deformations are been planned for the study.

Keywords: *Temporal phase shifting Electronic Speckle Pattern Interferometer (ESPI), five step phase shifting algorithm, mechanical and thermal deformations*

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INTRODUCTION

The image of any object with a rough surface that is illuminated by a laser appears covered with a random granular pattern known as laser speckle as shown in Figure 1. In speckle interferometer, the speckled image of an object is made to interfere with a reference field. Any displacement of the surface then results in changes in the intensity distribution in the speckle pattern. Changes in the shape of the object can be studied by superimposing two photographs of the object taken in its initial and final states. If the shape of the object has changed, fringes are obtained which are corresponding to changes in the degree of correlation of the two speckle patterns. To record speckle pattern, Speckle photography was used by Burch and Tokarski [1] in 1968. Later on Archbold *et al*. [2] designed Speckle interferometer to study surface deformation using a telescope. He observed that speckle moves when surface undergoes deformation. Later on Speckle interferometer was developed by Leendertz *et al*. [3], Butter and Leendertz [4], Jones and Leendertz [5]. Leendertz [3] modify Michelson interferometer by replacing mirror with optically rough surface to measure out-of-plane displacement and in-plane displacement.

Electronic Speckle pattern Interferometer was first developed by Butter and Leendertz [6] using electronic system in speckle interferometer and Macovski *et al*. [7] simultaneously. Butter and Leendertz [6] developed Electronic Speckle Pattern interferometer using two beams. In this, both beams illuminate the test object at equal angle from opposite side of the normal. The resultant fringe called correlation fringe can be obtained by subtraction of two recorded speckle patterns corresponding to two different object positions with help of charge couple camera (CCD). This system is used to measure the vibration of disc. Later on with the help of algorithms amplitude of displacement was obtained [8].

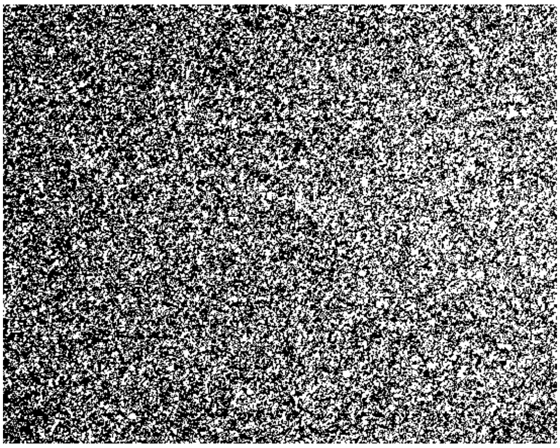
Fig. 1: *Image showing Laser Speckles.*

Macovski *et al.* [7] developed time average speckle interferometer to measure out-of-plane displacement of metal sheet of different shapes. Cookson *et al*. [9], developed ESPI to minimize the mechanical and airborne disturbances by using pulsed ruby laser as a source. Lokberg [10] developed an alternative ESPI system to obtain laser pulses from a continuous laser light to study vibrations of unstable objects. Lokberg and Hogmoen [11] developed ESPI using reference beam phase modulation, which was a general technique in holography, to obtain amplitude and phase of the test object. Several types of deformations can be studied using ESPI. However extracting quantitative information out of ESPI is highly non trivial. For extracting the quantitative information from ESPI, phase of the light reflected from the deformed object should be known. Deformation amplitude map can be calculated for the entire illuminated object by knowing the phase map. Over the years many phase evaluation methods were developed. Some of the famous methods are phase shifting methods [12], Fourier transform [13], phase stepping algorithms [14] and image processing algorithms [15]. Phase shifting technique is reasonably popular among them. Phase shifting technique uses either temporal or spatial phase modulation for the quantitative phase determination [16–17]. In temporal phase shifting method, phase-shifted data are acquired in a temporal sequence of camera frames whereas in spatial phase shifting method data are required recorded simultaneously, either by several cameras with the appropriate static phase shift for each of the images or encoded by a carrier fringe pattern on one video target. Both the methods have their advantages and disadvantages and should be considered in respect to the applications. There are other techniques also, which do not involve any phase modulation [18] but requires a much complex algorithms and mathematics. Active research is going on to develop simple, efficient, fast and accurate technique for quantitative analysis of phase especially for dynamic deformation [19]. Processing of interference signal in the temporal domain instead of spatial domain can improve the measurement range making it more accurate with less noise compared to spatial phase shifting method [20]. Electronic speckle pattern interferometer (ESPI) technique is used to quantify different types of mechanical or thermal deformation on object. It also used on to find out the crack detection of metal plates [21] and photovoltaic cells [22]. Recently Zhu *et al.* [23] used ESPI technique for dynamic thermal measurement of the printed circuit board with a chip. ESPI is used to check up aging artwork [24] and to study drying of coatings [25–26]. Roughness of the thin films was also studied using ESPI technique [27].

PROPOSED EXPERIMENTAL SET-UP

Schematic of the ESPI set up is as shown in Figure 2. Light from the laser will be first divided into two half (50:50) using a beam splitter as shown in Figure 2.

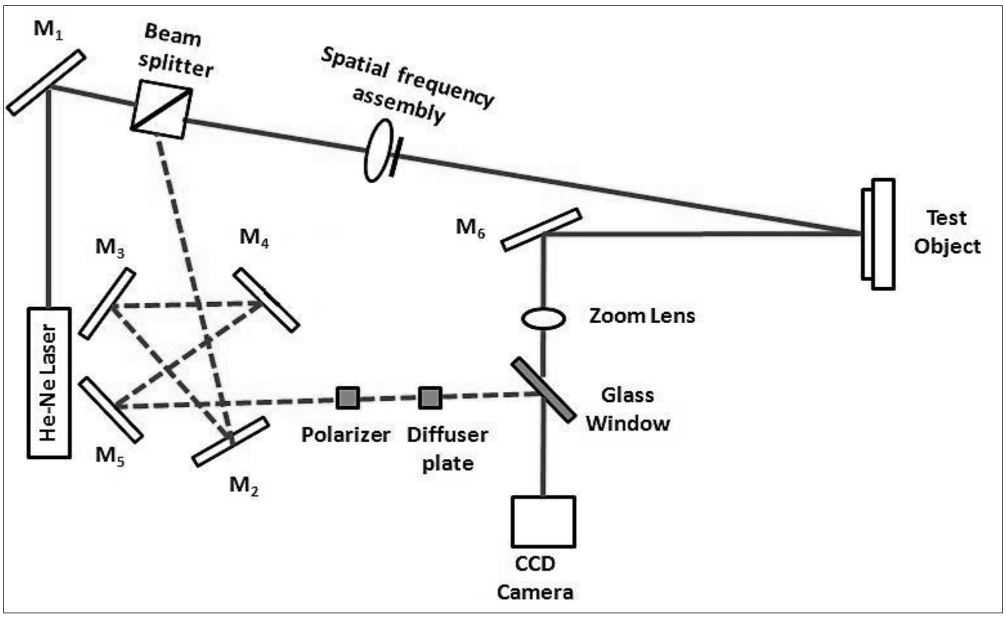

Fig. 2: *Experimental Set up of Electron Speckle Pattern Interferometer (ESPI).*

One beam will be used to illuminate the object surface in the full-field manner using spatial filter assembly. The illuminated object then forms speckle pattern which will be having information about the surface of object. The speckle pattern will be collected with a zoom lens and imaged on the charged couple device (CCD) camera. Second beam (reference beam), after reflecting from series of mirrors whose paths are matched with the first beam, will be made to diverge and superimposed with the light reflected from the object via beam splitter on the CCD.

This setup is generally called as out-of-plane setup because its measurement sensitivity is nearly perpendicular to object surface. Both wave fronts back scattered from the object and of the reference beam interfere and form a speckle pattern. This speckle pattern of non-deformed object is digitized and stored by a computer. By processing, generally subtracting the two speckle images obtained before and after deformation, electronic speckle fringe pattern or correlation fringes can be obtained. However for obtaining complete information regarding deformation, we should know the phase of the light reflected from the deformed object, which unfortunately cannot be determined from the experiment directly.

Proposed Study of Work

Our aim is to study quantitatively, deformations of various kinds in varieties of materials using temporal phase shifting electron speckle pattern interferometer. For this we have planned to work in following manner sequentially

To design and Fabricate Electron Speckle Pattern Interferometer Set up for Employing the Temporal Phase Shifting Method

As discussed before in the present article, temporal phase shifting approach is a popular method in ESPI in which phase shifting data are obtained in a temporal sequence of camera frames. Temporal Phase shifting in the interferometer can be introduced by adding known phase shift (β) with the help of piezoelectric transducer (PZT) which can be attached to one of the mirrors which is responsible for guiding reference or object beam. The proposed experimental setup of temporal phase shifting speckle interferometer is as shown in Figure 3. Experimental setup of temporal phase shifting interferometer is essentially the same as discussed in methodology section (i.e. Figure 3) with one modification. One of the mirror's (M_4) which is guiding the reference beam has to be moved with known distance (and hence phase) to introduced known phase in the reference beam. To achieve this, we will use piezoelectric transducer. With different known phase shift, the corresponding correlation fringe patterns will be recorded using CCD camera. More traditional approach to get phase from the mentioned method is via five-step phase shifting algorithm [28]. For that we will capture five images with known phase shift and then develop the algorithm for determination of phase of the un-deformed and deformed state of the object.

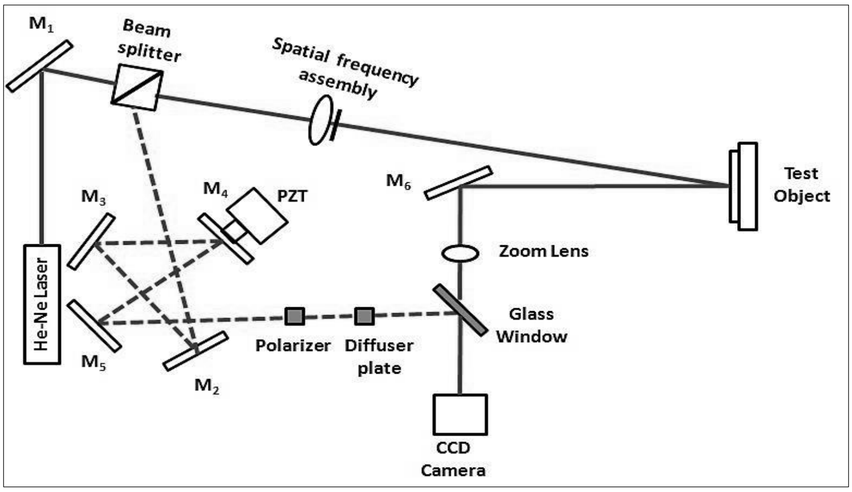

Fig. 3: *Experimental Setup of Temporal Phase Shifting ESPI.*

To Develop Algorithms for Extracting the Phase Information obtained from Temporal Shifting Method

We planned to use phase shifting method for extracting the phase information from deformed object. For that we will record five speckle interferograms before and after object deformation by adding known phase shift (β) using piezoelectric transducer (PZT).

Correlation fringes can be obtained after taking difference between these interferograms. To extract phase information, traditional and famous approach which is called five-step phase shifting algorithm or Hariharan algorithm will be use [29].

Below is the brief description of the method. Let I_U be the intensity related to interference between reference beam and object beam when object is in un-deformed state. It is given as,

$$I_U = I_O + I_R + 2\sqrt{I_O I_R}\cos(\varphi_R - \varphi_O) \qquad (1)$$

Where, I_O and I_R are the amplitudes of object beam and reference beam, respectively, ϕ_R and ϕ_O are the phases of the reference light beam and the un-deformed object light beam and (ϕ_O - ϕ_R) is the random interferometric phase of speckle pattern. If the object is deformed then intensity (I_D) related to interference between object and reference beam becomes,

$$I_D = I_O + I_R + 2\sqrt{I_O I_R}\cos(\varphi_R - \varphi_O + \phi) \qquad (2)$$

Where, φ is phase change in interference pattern when object is in deformed state. This 'ϕ' is what we need to find. For that we will capture five images with known phase shift say *-2β, -1β, 0,1β, 2β* where, *β* is a known phase change and will develop the algorithm for determination of phase of the speckle pattern obtained from deformed object. Phase of the speckle pattern measured from the deformed state can be calculated using five-step phase shifting algorithm which is given by,

$$\varphi = \tan^{-1}\left[\frac{2(I_{D_2} - I_{D_4})}{(2I_{D_3} - I_{D_1} - I_{D_5})}\right] - \tan^{-1}\left[\frac{2(I_{U_2} - I_{U_4})}{(2I_{U_3} - I_{U_1} - I_{U_5})}\right] \qquad (3)$$

Where, φ is the phase shift and $I_{U_1}, I_{U_2}, I_{U_3}, I_{U_4}$, I_{U_5} and $I_{D_1}, I_{D_2}, I_{D_3}, I_{D_4}, I_{D_5}$ are the intensity maps of object before and after deformation. Using above equation we can calculate the phase (φ), but this equation gives a phase jump from one point to another this is why it is called as wrapped phase map.

We can obtain the phase difference by taking the difference of wrapped phase between deformed and un-deformed object, but this will gives us the random wrapped phase condition. To overcome the problem of wrapped phase there exist a technique called as 'unwrapping'. Using suitable algorithms [30–33] we can obtained unwrapped phase from this data.

Temporal phase unwrapping is the common method used to unwrap phase map as phase the changes with respect to time [34]. In this method phase from each pixel is record in temporal manner. Unwrapping is done for each and every pixel which are independent from each other on time axis.

To use above Developed Technique for Quantitative and Qualitative study of Deformations of various Kinds in Varieties of Material such as:

a) Thermal deformation in metal thin films.
b) Mechanical and thermal deformation in metals.
c) Deformations produced by acoustic waves

Thermal Deformation in Metal Thin Films

Using above developed method for quantifying deformation by quantifying phase, we will apply this technique for studying various types of deformation in varieties of cases. The first case will be that of thin films of metals. As we know thermal deformations of thin films is an important issue. Deformations in the thin films can be of advantageous or disadvantageous nature depending on the application one is looking into.

Tentative experimental set up is as shown in Figure 4, where the object is replaced by thin film mounted on the heating plate. Temperature of which can be monitor and control. After applying thermal stress to the thin films, surface of the thin film gets deform. Amount deformation for each variation of temperature will be monitored quantitatively using the temporal phase shifting ESPI method.

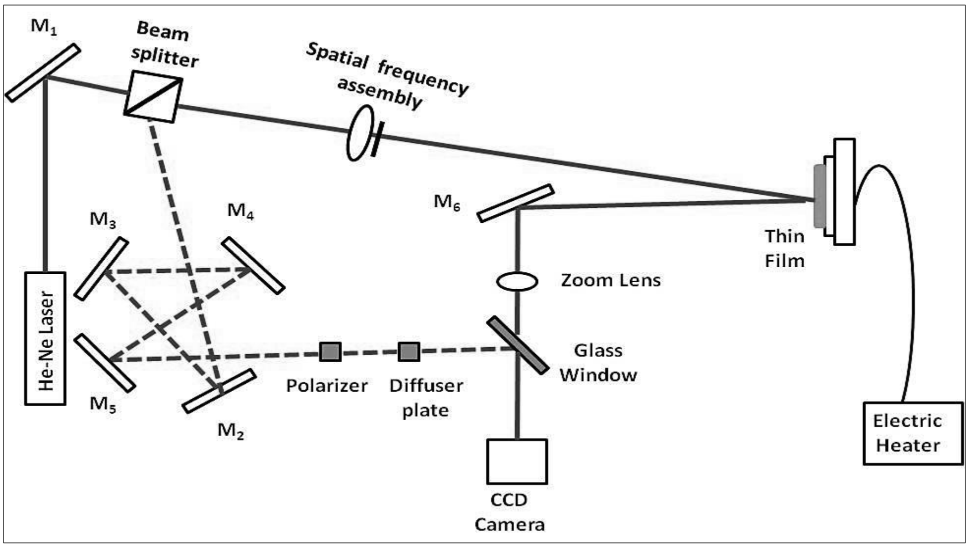

Fig. 4: *Tentative experimental setup for determination of Thermal Deformation in thin films using ESPI.*

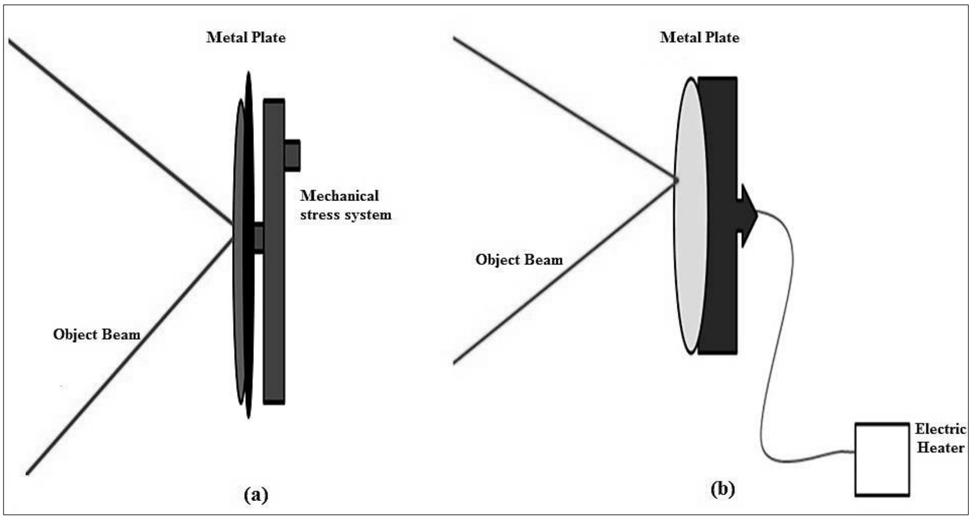

Fig.5: *Metal plate under (a) Mechanical stress and (b) Thermal stress.*

Mechanical and Thermal Deformation in Metals

Varieties of metal plates such as Brass, Stainless Steel and Aluminum can be studied for mechanical and thermal deformation using ESPI technique. It will be interesting to compare the deformations in bulk metals and their counterpart thin films using this technique. In this case, object will be replaced by circular disk of metal plates one by one for recording of speckle correlation fringes corresponding to thermal and mechanical stress of varying degree as shown in Figure 5. Again, temporal phase shifting method can be deployed for quantification of deformation in metal plates.

Deformations produced by Acoustic Waves

The most interesting dynamic deformation for study is the deformation created by acoustic wave. For this, a vibrating and reflecting diaphragm will be replaced in front of a loudspeaker as shown in Figure 6. Loudspeaker will emit mixture of audible frequencies.

We will use frequency generator to produce audible frequencies in speaker. Deformations which will be created in this manner will be studied by ESPI and phase shifting technique. Potential application of such study is in the voice recognition/identification/comparing area.

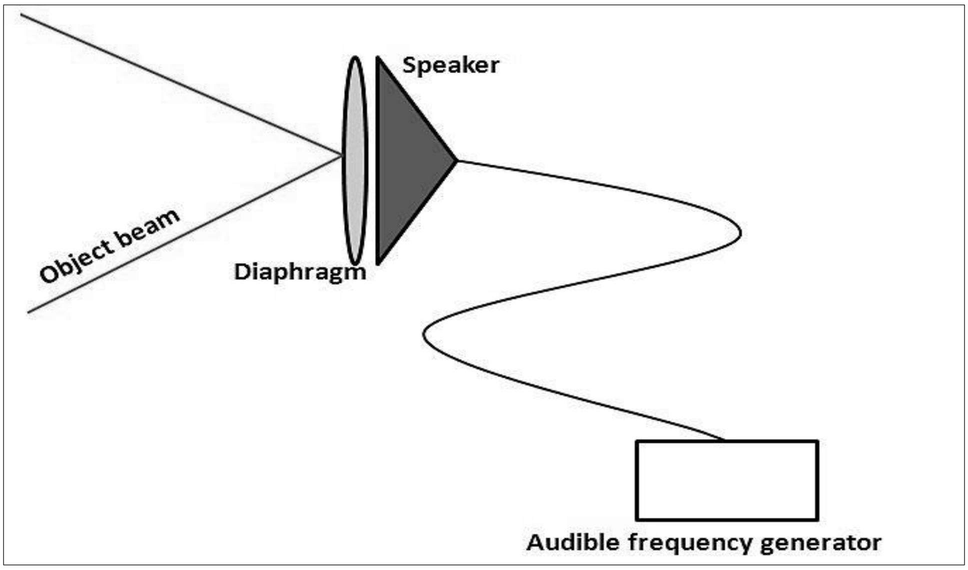

Fig. 6: *Experimental arrangement to study Acoustic Deformation.*

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