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INTERNATIONAL YEAR OF LIGHT- 2015: A New Dimension of Laser Speckle and its Applications

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***Abstract*— - This review paper deals about the main optical NDT (Non-Destructive Testing) method known as, electronic speckle Interferometry. Optical metrology is a field of physics, which includes theoretical and experimental methods to estimate physical parameters, using the light wavelength as fundamental scale. Most of the modern industries need quick and reliable measurement methods for measuring deformation, roughness, vibration and position etc. of the mechanical parts and products. The development and application of these optical NDT techniques are described.**

Keywords— ***Optical metrology, Laser speckle image, Non Destructive Test.***

I. INTRODUCTION

When laser is incident on an optically rough surface, it is scattered in all directions. This scattered wave interferes and forms an interference pattern. It consists of dark and bright granular spots called as speckle pattern. Speckle metrology is an optical non-contact, whole field technique to measure deformation/ displacement, surface roughness, object shape, vibration, and dynamic events on rough surfaces, with sensitivity of the order of a light wavelength. In particular, Laser speckle metrology technique combined with advanced computers, fast frame grabbers and image processing makes it very suitable for industrial applications. When a diffusely reflecting object is illuminated with laser light, a high contrast "speckle pattern" is produced. This was first reported by Rigden and Gordon [1] of Bell laboratory in 1962. The speckle phenomenon came into prominence after the advent of laser. In the earlier days, Laser speckle was considered as a nuisance, particularly in holography. But later, speckle pattern becomes a very good measuring tool in metrology. Laser speckle pattern viewed as fundamental carrier of information, about the surface of the materials. Speckle pattern is an interference pattern formed by wavelets, scattered by an optically rough surface.

II. SPECKLE INTERFEROMETRY

The speckle pattern formed in the space is known as objective speckle pattern. If, the speckle pattern observed at the image plane of a lens, then it is referred as subjective speckle pattern. Speckle interferometry (SI) has become a complete technique, widely used in many branches of experimental mechanics. Laser speckle interferometry is an efficient optical measurement technique, which combines with electronic detection and processing. It is widely used in the investigation of a wide range of physical parameters such as displacements, vibrations, strains and surface profiles of engineering structures. Speckle techniques can be classified into three broad categories: speckle photography, speckle interferometry, and speckle shear interferometry. Speckle photography (Archbold et al, 1970) [2], includes all those techniques where positional changes of the speckle are monitored. Speckle interferometry (Leendertz, 1970) [3] includes methods that are based on the measurement of phase changes and hence intensity changes. Instead of phase change, if we measure its gradient, then the technique known as speckle shear interferometry (Leendertz and Butters, 1973) [4].

J.W. Goodman [5] was among the first investigators to explore the speckle and gives the elaborate statistical aspect of speckle. Speckle photography, speckle holography, stellar speckle interferometry, and speckle interferometry using photographic recording have been explained in detail by J.C.Dainty [6].

Two-beam interference formula:

$$I_R = I_1 + I_2 + 2\sqrt{I_1 I_2}\ |\gamma| \cos\varphi \quad \text{….(1)}$$

Where, IR is the resultant intensity depending on whether the two waves are smooth or whether at least one is a speckle wave. I1 and I2 are the intensities of the two waves, φ is their phase difference and $|\gamma|$ is the normalized module of the cross-correlation of the two amplitudes [7-9]. Speckle interferometry is based on, the coherent addition of scattered light from an object surface with scattered field from a reference object. It involves the interference of two optical waves in which at least one is a speckle field [10]. One of the popular celebrity in the speckle metrology (R.S.Sirohi, 1993)[11] has mentioned in detail about advantages of Electronic speckle pattern interferometry (ESPI) or TV holography. These techniques are non-invasive nature of operation and the display of the measurement information in real-time and on whole field basis. The method allows for data storage and retrieval for analysis. This method enables quantitative evaluation using phase stepping offers variable measurement sensitivity and provides the possibility to make measurements at remote areas in machines.

The object deformation causes a path difference between the wave front scattered from its surface and the reference wave. This modified speckle pattern is either subtracted or added to the previously stored pattern and rectified (P.K. Rastogi, 2001) [12]. The bright and dark fringes displayed on the monitor are referred as correlation fringes and represent contour lines of constant surface displacement.

Relevant work in the optical configurations for extraction of out-of-plane displacement (C.Joenathan, 1991) [13] and its slope have been noted. Speckle shear interferometer, which can be used to yield lateral, radial, rotational, and inversion shear fringes in real time in conjunction with a digital image processing system (A.R.Ganesan et al, 1988) [14]. In this method a modification of the optical arrangement yields reversal or folding shear as well and unit contrast fringes obtained by resorting to nonlinear processing techniques such as level slicing.

The Speckle interferometer device described by G.L.Cloud [15] showed that it is possible to build a simple, inexpensive speckle interferometer that works well in noisy environments. It is easy to record the speckle patterns with a matrix CCD followed by a computer, which calculates 2-D cross-correlation of sub images to deliver distribution of speckle displacement. Speckle interferometry is a well-assessed experimental technique for investigating on deformations/displacements of specimen and real object in static and dynamic loading configurations. The optical devices to yield in plane displacement/out of plane displacement components of a deformation vector are classified as:

(i) Dual-beam symmetric illumination—normal observation [16].
(ii) Oblique illumination—observation [17].
(iii) Normal illumination—dual direction observation [18].
(iv) Dual-beam symmetric illumination—observation [19].
(v)

In dual-beam symmetric illumination observation configuration, the scattered fields from the object are observed along the direction of illumination beams and they are either imaged as two separate images or combined into one at the observation plane. Dual-beam symmetric illuminations in a Michelson shear arrangement [20] has been used for obtaining the partial derivatives of in plane displacements. B. Bhaduri and co- authors [21] describes (1,N) spatial phase-shifting technique in DSPI for non destructive evaluation (NDE) of quasi dynamic behavior of objects subject to slowly varying loads. This technique employs a double aperture arrangement in front of the imaging system to introduce spatial carrier fringes within the speckle. The prominent advantage of the proposed technique is it requires only a single frame prior to the object deformation and a number N of frames during the object deformation for NDE.

Quantitative measurement of a defect and its behavior in loading conditions are studied by recording spatially phase shifted frames before and during thermal stressing of the object for continuous deformation variation with time. The other prominent shearing devices are: split lens, shear element [22], birefringent crystals [23], holographic optical elements such as holo-shear lens (Krishna Mohan N et al, 1992) [24] and holo-gratings [25]. Of the many salient developments, the two that one could probably cite here concern the simultaneous measurement [26] of out-of-plane displacements and their derivatives, and the measurement of second order partial derivatives (P.K. Rastogi,1996)[27] of out-of -plane displacements.

III. Experimental Setup

In the laser speckle interferometer field, the two most important technologies are ESPI (Electronic Speckle Pattern Interferometry) and ESPSI (Electronic Speckle Pattern Shearing Interferometry). What should also be noted is the technology to combine speckle pattern interferometry together with digital image correlation (DIC), which has been the subject of intense research interest these years [13]. Electronic Speckle Pattern-Interferometry (ESPI) combines double ray interference technology with digital recording devices, and can be classified as in-plane ESPI and out-of-plane ESPI. Take the out-of-plane ESPI as the example, with the operating principle shown in Figure.2. The basic measurement system consists of an optical head, CCD camera, host computer, image processing system and a TV monitor. A specimen illuminated with an expanded laser beam forms a speckle pattern. The scattered speckle pattern is imaged onto a CCD.

A reference wave, which may or may not be speckled is added at the observation plane to achieve interference between the object and reference waves. The resultant speckle pattern is stored in the processor and displayed on the monitor.

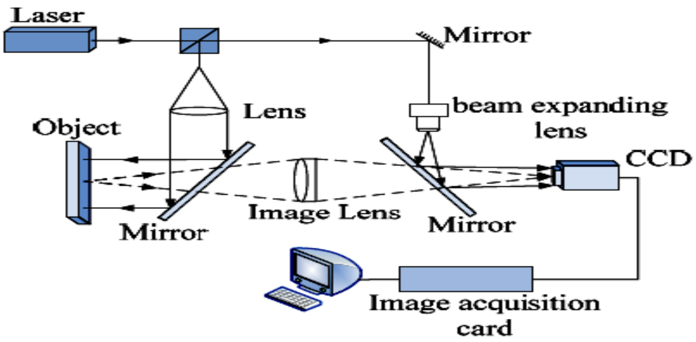

Fig.1 Laser speckle imaging setup

The object light reflected by object surfaces superimposes with the reference light which directly emits into CCD target, forming double ray interference patterns. ESPI is a whole-field optical technique widely used for measuring displacement components, shape and slope contours of surfaces, etc. This non-contact and highly sensitive technique has developed into a powerful online inspection tool for non-destructive evaluation.

The salient feature of ESPI is its capability to display the correlation fringes in real time on a TV monitor without the need of photographic processing or optical filtering. In conventional ESPI use the displacement of the laser speckle to study the displacement of object surface. This method used charge-coupled device (CCD) camera to record the object speckle before and after force is applied; and then electronically process and compare the measurements; similar to interference fringes, the final results will be display in the TV screen.

1.	Contact methods	Mechanical stylus
2.	Point wise measurement	Laser Probe
3.	Line wise measurement	Optical section
4.	Full field measurement	Moire method, Pattern projection method
5.	Close range	Confocal microscopy, Interferometry
6.	Short range	Moire method, Space encoding method
7.	Middle range	Pattern projection method
8.	Long range	Photogrammetry, Laser tracker

9.	Far range	Range finder
10.	Non optical method	Capacitance, Magnetism, Ultrasonics

Table-1.Types of measurements using various Profilometer methods.

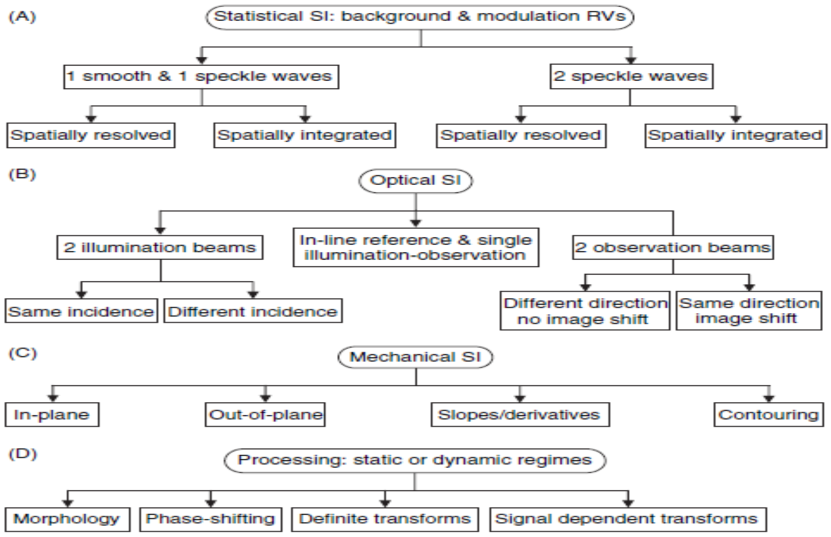

Fig.2 Different types of Speckle Interferometry

It is worth to mention that the developed laser speckle techniques are worked well within the limitation of errors. Reason for small measurement errors is the optical set up environment and imaging system. Both the mentioned techniques are important and indispensable in some applications of non destructive testing (NDT). The advanced computer-aided evaluation concept to these methods promises to have a major impact on image analysis. These developments augur well for the widespread use of these methods in engineering and medical sciences.

IV. CONCLUSION

Laser speckle inteferometry makes use of the intensity distribution pattern formed from space interference, generated by illumination of coherent light onto rough object surfaces. Laser speckle interferometry is an effective NDT technology with advantages of non-contact, the illumination over the surface of the object need not be uniform, high sensitivity and detection rate. It has been widely used in many industry areas. Laser speckle interferometry can be used in inspection of metal, ceramic, glass, rubber and composite materials. The surface stress can be also measured for highly accurate measurements of deformation, which means it has great application potential in aerospace, automotive, marine and high-tech materials manufacture.

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