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Photorefractive speckle techniques for displacement and vibration measurement

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Dedicated to Padma Shree Prof R S Sirohi, FNAE

When fairly coherent light is diffusely reflected from, or transmitted through a randomly rough surface, the scattered components with random phase fluctuations interfere with one another, giving rise to a pattern in which there appears a random distribution of bright and dark regions of intensity. Such a salt and pepper appearance has come to be known as the speckle pattern. Considered undesirable in certain situations, the speckle phenomenon has been put to many useful applications because the speckles are carriers of information pertaining to the scattering surface. In the early phases of development of the subject, photographic plates were used to record speckles. However, due to the time-consuming nature of the photographic processing, the spatial light modulators, photorefractive materials, and the CCDs began to be used for quasi real-time recording of the intensity patterns. In this paper, we present an overview of the research conducted on photorefractive speckle techniques as engineering tool for various types of displacement and vibration measurements, with special reference to the work carried out at IIT Delhi. We begin with a brief review of the speckle photography technique and photorefractive effect followed by a discussion of our research leading to progressive development of photorefractive-based speckle techniques for three-dimensional displacement and vibration measurements. We have also included our work on speckle correlation technique in some detail as it provides a simple and convenient tool for accurately measuring and assessing object displacements in real-time.

Keywords: Speckle metrology, Motion measurement, Optical correlator, Photorefractive crystals.

1 Introduction

Speckle is the name given to the grainy (salt and pepper appearance) nature of intensity pattern observed when coherent light is scattered by an object which is rough on the scale of the wavelength of light used. The speckle is produced by the interference of coherent components of light scattered by the diffuser. Depending on the object characteristics, the scattered components may have random amplitudes and random phases, or may have known amplitudes and random phases. When the scattered components with random phases are added together, they constitute what is known as a 'random walk'. Speckle pattern is characterized by its statistical properties and very extensive work has been carried out on its first-, and higher-order statistics. Considered 'nuisance' in certain situations such as in holography and laser-based projection systems, a number of techniques have also been developed to suppress the annoying effects of speckles. However, speckles have also been put to some useful applications because they are carriers of information. After the advent of laser, there has been phenomenal progress in both the theoretical aspects and experimental techniques concerning the subject [1-25].

Speckle techniques, photographic as well as interferometric, are now well-developed for applications in a myriad of situations [1-25] including non-destructive evaluation of displacement, deformation, rotation, vibration, tilt, and roughness of objects. Measurement of strain, fatigue, creep, temperature, and motion paths are some of the other applications. Because of its simplicity, speckle photography has been widely used in engineering metrology applications. It has also been used in particle velocimetry measurements and flow visualization. Some of the early publications [26-40] on the subject have now become highly cited.

Originally, a photographic plate was used as a recording medium to demonstrate speckle photography by recording speckle patterns before and after the object deformation. In this case, deformation of the object would cause a directional shift in the speckle pattern which produces Young's fringes when the photographic

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plate is illuminated by a parallel beam of coherent light. The technique became more attractive for metrology applications when dynamic media such as photorefractive (PR) crystal, spatial light modulator (SLM) and digital CCD camera began to be used instead of the photographic medium [41-44]. These media increase the speed of speckle photography.

PR crystals exhibit strong wave-mixing phenomena due to large optical nonlinearity at relatively low-light level. This makes them suitable for use as a holographic recording medium for dynamic interferometry, optical data storage, phase conjugation, and optical information processing applications [45-63].

In the present article, we review the research conducted at IIT Delhi using speckle photography in PR crystals as an engineering tool for various types of displacement and vibration measurements. For implementing dynamic SP, PR crystals have been used in real-time recording, multiplexing and read-out of speckle patterns in different optical arrangements. In the first part of this article, we will discuss the basic mechanism of speckle photography. The second part will review real-time photorefractive phenomena, and our studies on dynamic SP using PR crystals for displacement measurements.

2 Speckle Photography Method

In speckle photography, the diffuse surface of an object is illuminated by a coherent laser [19]. The resulting speckle pattern is recorded on a high-resolution photographic plate as shown in Fig 1a.

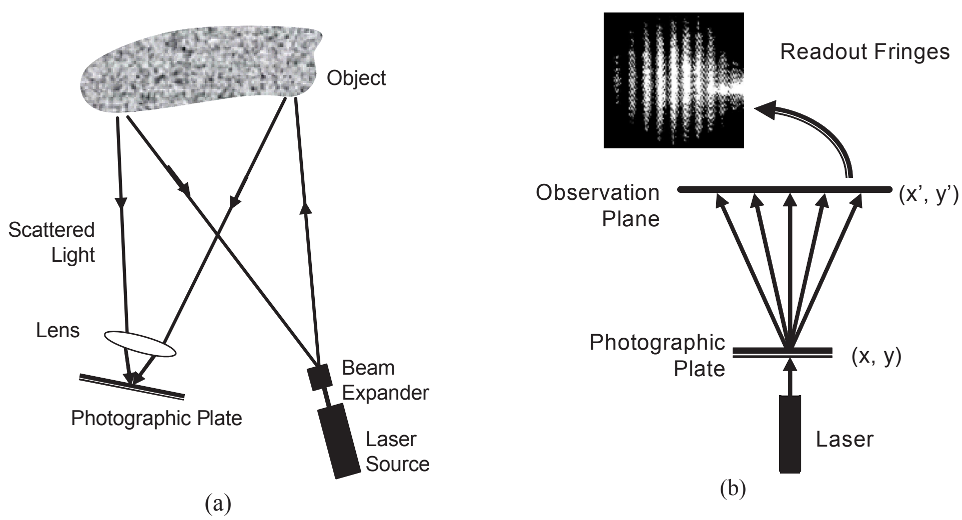

Fig 1. (a) Recording the double-exposure photograph (b) Read-out process to obtain the Young's fringes

The object then undergoes displacement (or deformation) and the speckle formed after deformation is recorded again on the same photographic plate via a second exposure. It can be easily shown that motion of the speckle pattern is correlated to the object displacement. For example, the distance that a speckle moves with respect to its pair is a direct measure of the object's in-plane vector displacement [1-5]. When the photographic plate (called 'specklegram') after recording is illuminated by a collimated laser beam (Fig 1b), each recorded speckle pattern causes diffraction of the laser light and produces a diffraction halo in the far-field whose spread is decided by the average speckle size. The displaced speckle pairs present in the random speckle pattern cause the diffraction halo to be modulated by Young's fringes. These fringes are conveniently observed at the back focal plane of a lens by collecting the diffracted light. Displacement data (both magnitude and direction) are recovered by measuring the fringe spacing and fringe orientation. The displacement vector can also be measured locally by passing a narrow collimated laser beam through a specific location on the photographic plate, thus allowing one to generate a deformation map corresponding to the object.

Following mathematical description can be used to explain how Young's fringes are formed in speckle photography [2-5]. SP involves a two-step process: i) recording (i.e. double exposure) of speckle patterns on a photographic plate, and ii) read-out using a collimated laser beam. To simplify our discussion, we assume each speckle in the speckle pattern to be very small in size so that it can be mathematically approximated as a point source, or a delta-function. One can describe the transmittance $t(x, y)$ of the photographic plate in terms of the recorded speckle intensities: $I_1(x, y)$, before deformation an $I_2(x, y)d$, after deformation as:

$$t(x, y) = \beta T\, [I_1\,(x, y) + I_2\,(x, y)] \qquad (1)$$

where $I_1(x, y) = \iint I(\zeta, \eta)\ \delta(x - \zeta, y - \eta) d\zeta\, d\eta$

and $I_2(x, y) = \iint I(\zeta, \eta)\ \delta(x + L_x - \zeta, y - L_y - \eta) d\zeta\, d\eta$

where (ζ, η) represents the location of each speckle in (x, y) spatial coordinates, β is a constant related to the transmission of photographic medium, and T is the exposure time for recording. L_x and L_y are components of the speckle displacement $\vec{L}$ vector produced by object displacement. The read-out of 'specklegram' recorded on the photographic plate using a collimated laser beam will produce a Fourier transform (FT) of the transmittance $t(x, y)$ due to diffraction of light involved in free-space propagation or by propagation through a lens. Thus, the intensity distribution in the observation plane can be obtained by finding the magnitude square of FT of transmittance $t(x, y)$ which is given by

$$I_{FT}(u, v) \propto \beta^2\ T^2\ I(u, v)\ [1 + \cos 2\pi(uL_x + vL_y)] \qquad (2)$$

where the spatial frequencies (u, v) in the Fourier plane are defined as $u = x'/\ \lambda f$ and $v = y'/\ \lambda f$. Here (x', y') represent spatial coordinates in the FT plane, $I(u, v) = \mathrm{FT}\,[I(x, y)]$ represents the intensity distribution of the speckle pattern in the observation plane, and f corresponds to the focal length of the lens used. Equation (2) shows that intensity in diffracted field is modulated by fringes similar to the fringes observed in Young's experiment by interference of two mutually coherent light waves. Fringe spacing ($\Lambda = \lambda f / L$) is measured to obtain the magnitude of displacement whereas the fringe orientation is useful in determining the direction of displacement.

In case of axial (or out-of-plane) displacement of the object, the speckles undergo a radial displacement. Instead of linear fringes, diffraction of incident light from the specklegram produces circular fringes in the observation plane. In this case, the magnitude of displacement is obtained by measuring the radius of a circular fringe of particular order. Kumar and Singh [64-72] demonstrated a number of recording and reconstruction geometries suitable for analyzing the out-of-plane motion in SP using photographic plates. In particular, they investigated the effect of multiple exposures on the interference fringes formed due to axial motion by considering a diverging illumination on a diffuse object. It was shown that diverging illumination facilitates recording of a large number of exposures by maintaining correlation of speckles between exposures. Multiple exposures produce fringe sharpening, thereby allowing one to measure axial displacement more accurately. During reconstruction of the fringes, converging beam illumination and aperture filtering techniques were used in the arrangement to enhance the fringe contrast.

Speckle photography technique discussed above can also be used to analyze in-plane oscillatory motion of the object [3]. In this case, each speckle in the speckle pattern will trace a line with a length proportional to the amplitude of vibration. A simple analysis can be used to show that a time-averaged recording (i.e. exposure over a number of oscillations) of the speckle pattern for an oscillating object will produce an intensity distribution modulated by zero-order Bessel function fringes. In such a case, the oscillation amplitude can be determined by locating the zero (null) values on the fringe intensity distribution. Similarly, a time-averaged recording of an object moving with uniform velocity will produce fringes with intensity distribution modulated by a 'sinc' function. A vibratory movement perpendicular to the object surface (i.e. out-of-plane vibration) can be studied by observing reduction in speckle contrast. Additionally, double-exposure SP has also been used in velocimetry for flow visualization and velocity mapping.

As mentioned earlier, for quite some time in the early phases of the development of the subject, photographic emulsions were used as the recording media requiring cumbersome wet processing, thus making the measurements very slow and non-real time. However, progress in the area of material science and engineering has resulted in the development of several new materials for recording of light. Of these materials, photorefractive crystals (PRCs) are dynamic recording materials [45-63] that exhibit write, storage, and read-out properties in quasi real-time. The refractive-index change produced at relatively low optical power densities in PRCs has been used for a number of applications including in speckle-based techniques.

To alleviate the problem of using photographic plates, digital (or electronic) SP has been introduced in which the speckle pattern is recorded using a CCD sensor, and reconstructed using digital Fourier transform. However, a CCD sensor has much lower resolution and a limited dynamic range compared to a photographic medium. Digital FT can also make the real-time analysis difficult. This problem can be addressed by displaying the recorded specklegram on an SLM and then using optical Fourier transform for quasi real-time measurements. However, the problem of low resolution still remains for CCD- or SLM-based SP. Sensitivity of SP to displacement measurement is limited by the speckle size which could be further limited by the resolution of the recording medium or device. Speckle recording and reconstruction using photorefractive (PR) crystals holds a greater promise for metrology applications since they provide higher resolution, low-light operation and real-time (or quasi real-time) response. As we will discuss later, SP in PR crystals is implemented by a holographic recording of complex-amplitudes (i.e. amplitude and phase) of speckle patterns. This is different from intensity-only recording used in conventional photographic medium or a CCD sensor. This process also provides much higher diffraction efficiency (near 100%) during holographic reconstruction of specklegram. In the following section, we briefly discuss the electro-optical properties of PR crystals, and formation of photorefractive holograms before reviewing our work on dynamic speckle photography using PR crystals.

3 Photorefractive Effect

Photorefractive effect is observed in materials which are photoconductive and exhibit the linear electro-optic effect [45-56]. These materials include bulk inorganic crystals such as ferroelectrics ($BaTiO_3$, $LiNbO_3$, $KNbO_3$ and SBN etc.), sillenites (BSO, BGO and BTO etc.), II-VI and III-V group compound semiconductors (GaAs and InP etc.) and also polymers. When a PR material is illuminated by an interference pattern $I(x)$ created by two laser beams, a space-charge distribution $\rho(x)$ builds up in the material in phase with the interference pattern as shown in Fig 2. The electric field $E_{sc}(x)$ associated with $\rho(x)$ produces a refractive index grating $\Delta n(x) \propto r_{eff} E_{sc}$ due to the linear electro-optic effect, where r_{eff} is the linear electro-optic coefficient of the PR material. In the ferroelectric-type PR crystals, charge transport is purely diffusive, and a phase shift of 90° is present between the interference pattern and the refractive index grating.

Such crystals distinctly produce gain (or amplification) of the beam in wave-mixing. For example, a PR $BaTiO_3$ crystal can produce high gain with gain coefficient Γ exceeding 60 cm^{-1}. Unlike ferroelectrics, charge transport mechanism in sillenites and semiconducting PR crystals is dominated by drift caused by an applied electric field. The phase-shift in this case departs from 90 ° leading to small energy transfer (or gain) in wave-mixing. Although the magnitude of the photorefractive effect in the steady-state is independent of the illumination, the response time (or speed) of photorefractive effect varies inversely with the illumination intensity. Photorefractive holograms can be written with millisecond response time using CW beams with intensity values ranging between mW/cm^2 to MW/cm^2. High gain PR crystals are particularly used in beam amplification, parametric oscillation and self-pumped phase conjugation applications. In general, real-time holography in the PR crystals offer several useful functions such as high diffraction efficiency, energy transfer or dynamic feedback between the writing beams, adaptability to changing optical field and distortion correction via phase conjugation. Some of these functions have also made PR crystals useful and attractive for holographic interferometry and dynamic speckle photography as discussed in the next section.

4 Dynamic Speckle photography using photorefractive two-beam coupling

Photorefractive crystals are well-suited for recording slow changes in speckle patterns required in implementation of dynamic SP. Figure 3 shows an optical arrangement for dynamic SP used by Kumar *et al* [73] for real-time measurement of in-plane displacement by utilizing two-beam coupling in a PR $BaTiO_3$ crystal. In this setup, the speckle pattern is generated in free-space by illuminating a diffuse object, and recorded holographically in the PR crystal using a pump beam intersecting at nearly 20° angle with respect to the speckled (or signal) beam produced by the object. Beam-coupling and energy transfer between pump and signal beams produce amplification of the speckle pattern during a simultaneous read-out (or reconstruction) by the pump beam. Figure 4a shows the interference fringes observed in the observation plane (i.e. back focal plane of the lens used after the PR crystal shown in Fig 3) by giving a 30 μmμm in-plane displacement to the diffuse object. In this case, the PR crystal serves as a real-time holographic recording medium for recording speckle patterns produced before and after the displacements. Figure 4b shows interference fringes observed by recording five speckle patterns in the same crystal by giving a fixed 30 μm in-plane displacement to the object between successive recordings of speckle patterns in the PR crystal. As discussed earlier in sec. 2, recording multiple speckle patterns produces a fringe sharpening effect whose intensity distribution is given by $I_{FT}(u,v) \propto A_p^2\, I(u,v)\left[\dfrac{\sin\,(N\pi u l_x)}{N\,\sin\,(\pi u l_x)}\right]^2$, where N corresponds to number of recordings by giving equal displacements L_x to the diffuse object along the x-direction and A_p is the amplitude of pump beam.

Kumar *et al* [73] utilized the slow response time of the PR $BaTiO_3$ crystal has to create sharp fringes by recording multiple speckle patterns. This allowed them to measure fringe spacing more accurately from microdensitometer traces of fringe profiles, thereby improving the accuracy of in-plane displacement measurement. It is important to note that photorefractive recording and read-out are accompanied by erasure of previously stored speckle patterns. In order to achieve identical diffraction efficiencies for all stored speckle patterns for maximum fringe contrast, the recording time t_N for the Nth new speckle pattern should be chosen shorter than the recording time of all previously recorded speckle patterns.

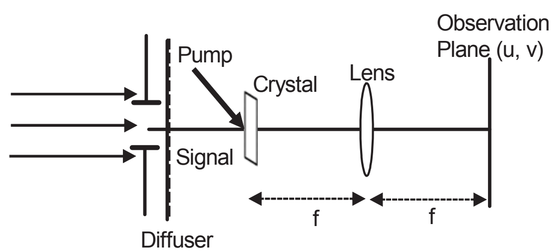

Fig 3. Optical arrangement for dynamic speckle photography

Kumar *et al* [73] used a recording schedule defined by the formula $t_N = t_1/N$ to form speckle interference fringes during PR read-out with high contrast. The method also provided a simple and convenient way of analyzing rigid body motions in real-time. Beam-fanning noise produced by the self-amplified scattered light in the PR crystal was found to be significantly small to affect displacement measurements. The method also provided a simple and convenient way of analyzing rigid body motions in real-time where the separation distance between the diffuse object and the PR crystal does not affect the displacement measurement. Kamra *et al* [74,75] have carried out further investigations on the measurement of in-plane and out-of-plane displacement measurement using multi-exposure technique. Some other groups [76-78] have also made noteworthy contributions to the literature on photorefractive speckle techniques.

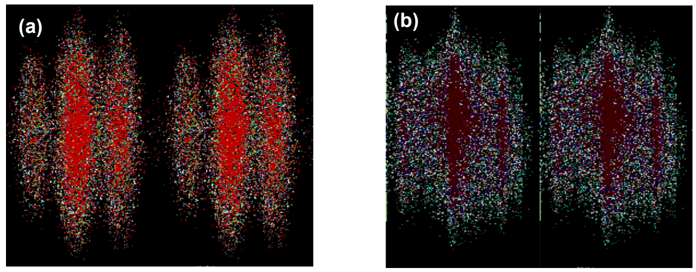

Fig 4. Interference fringes observed in the back focal plane for a 30 μm in-plane object displacement: (a) Double exposure; (b): five exposures

5 Photorefractive speckle correlator

Tripathi *et al* [79] demonstrated an improved dynamic SP method using a PR speckle correlator. The technique was first developed for a general purpose displacement measurement by recording speckle patterns in the PR crystal using converging beam illumination, and introducing a digital interface through an electrically-addressed SLM for correlation measurements. Converging illumination offered the following advantages: i) the speckles remain correlated in the presence of large movement of the object in three-dimensional space, and ii) fringes produced by photorefractive specklegram were localized close to the focal plane of the converging illumination. Photorefractive two-beam coupling was utilized to take advantage of recording very low intensity speckle patterns while detecting object motions. Use of digital interface enabled introduction of digital processing techniques for improved fringe contrast, and for implementing the optical correlation technique to achieve higher accuracy and reliability in displacement measurement. Instead of fringe period or radius measurement, Tripathi *et al* [80,81] employed an optical correlation technique which allowed them to measure the total displacement with effective in-plane and out-of-plane displacement components without ambiguity.

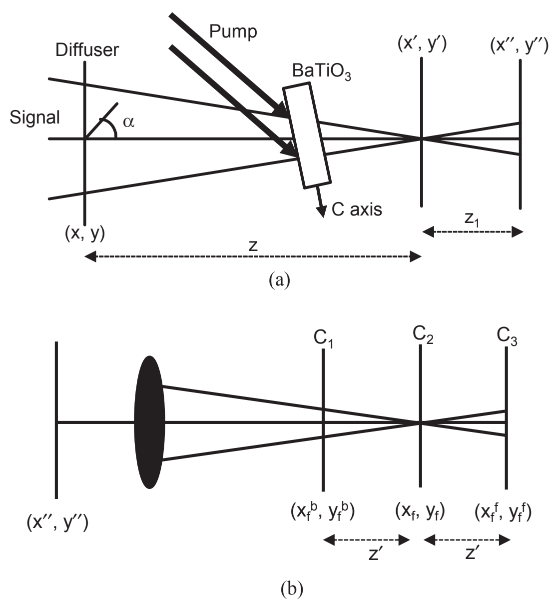

Fig 5. (a) Dynamic speckle recording geometry; (b) Optical correlation using Fourier transform setup

Figures 5(a, b) show the recording geometry, and the FT geometry for correlation used by Tripathi *et al* [80] to measure 3-D rigid body motion. A given displacement of the object in a direction defined by an angle α with respect to the optical axis produces coupled in-plane and out-of-plane displacement components ε tan α and ε, respectively. Tripathi *et al* [80] calculated the resultant intensity distribution I (x'', y'') produced by the read-out of speckle patterns recorded in the PR crystal at the observation plane (x'', y''), which is given by

$$I(x'', y'') = D(x'', y'') \otimes \left\{1 + \cos \frac{\pi\varepsilon}{\lambda(z+z_1)\, z_1} \left[(x'' - z_1 \tan\alpha)^2 + (y'')^2\right]\right\} \tag{3}$$

with $$D(x'', y'') = e^{-\frac{j\pi}{\lambda z_1}(x''^2 + y''^2)} \iint D\left(\frac{x'}{\lambda z}, \frac{y'}{\lambda z}\right) e^{-\frac{j2\pi}{\lambda z_1}(x'' x' + y'' y')}\, dx' xy'$$

where $D(x, y)$ defines the complex amplitude distribution, the diffuse object and ⊗ denotes the convolution operation. PR crystal parameters were not included in the calculation since the intensity distribution given in Eq (3) is not affected by the inclusion of these parameters.

The intensity distribution contains a quadratic phase (or chirp) term inside the argument of the cosine function. This produces curved fringes with the fringe center located at $(z_1 \tan \alpha, 0)$. The effect of chirp on the fringe is decided by its magnitude γ. which is related to the out-of-plane displacement component as: $y = \varepsilon/z_1$. Tripathi *et al* [80] implemented an optical correlation technique to delineate the in-plane and the out-of-plane displacement measurements by using the FT geometry as shown in Fig 5b. In this geometry, the intensity distribution produced by the PR read-out is detected by placing a CCD sensor in the (x'', y'') plane. This is displayed on an SLM as an input to the FT geometry. The optical Fourier transform of the intensity distribution is obtained by using a lens with focal length f. Mathematically, such a step can be described by FT of the intensity distribution in Eq (3) which is found to contain three correlation outputs. The autocorrelation term $D(x'', y'') \odot D(x'', y'')$ gives rise to a focused spot at the center of the back focal plane (x_f, y_f) of the lens. The two other correlation outputs containing information on out-of-plane displacement component generate focused spots in (x_f^b, y_f^b) and (x_f^a, y_f^a) planes, respectively as shown in Fig 5b. These two correlation outputs are described as

$$0(x_f \pm x_0, y_f) = \iint |D(x'', y'')|^2\, e^{-\frac{j\pi}{\lambda}\left[\frac{1}{z'} \pm \frac{\tau}{(z+z_1)\, z_1} - \frac{1}{f}\right](x''^2 + y''^2)}\, e^{-\frac{j2\pi}{\lambda z_1}(x_f x'' + y_f y'')}\, dx' xy' \tag{4}$$

where $x_0 = 2\pi\varepsilon \tan \alpha/\lambda\, (z + z_1)$ is the position of correlation signal in the transverse plane which can be measured to find the in-plane displacement due to object motion. Equation (4) shows the presence of a quadratic phase terms in correlation which will act like lens, and therefore, produce longitudinal shift in the focus of correlation peaks by a distance $\pm\, \varepsilon/(z + z_1)z_1$, where plus and minus signs indicate distances measured from the back focal plane (x_f, y_f) of the lens. This shift can be measured experimentally to measure the out-of-plane displacement component ε. For a particular value of ε, the focusing of correlation peaks will be more pronounced by setting z_1 to a small value.

Figure 6 shows the basic layout of the photorefractive correlator used by Tripathi *et al* [79-81] for three-dimensional displacement measurements. The signal beam consisting of a random speckle pattern is created by illuminating a diffuse object with converging illumination from a lens. Reference speckle pattern produced by a static object is first recorded in the PR crystal using a two-beam coupling geometry shown in Fig 6.The diffuse object is then given a known 3D displacement, and the speckle pattern resulting from object motion is recorded in the same volume of the PR crystal. The resulting speckle interference fringes are formed in a quasi-real-time read-out of the PR holograms which attain maximum visibility when the diffracted amplitudes of recorded speckle patterns become equal in magnitude. The interference fringes formed with high contrast are detected by a CCD sensor and stored in a computer as shown in Fig 6. Speckle correlation is produced by displaying the fringes on an SLM, illuminating SLM with a collimated laser beam, and performing FT using a lens. This operation can be performed at high speeds. The same CCD sensor can also be utilized to detect the correlation output, and subsequently to perform displacement measurements.

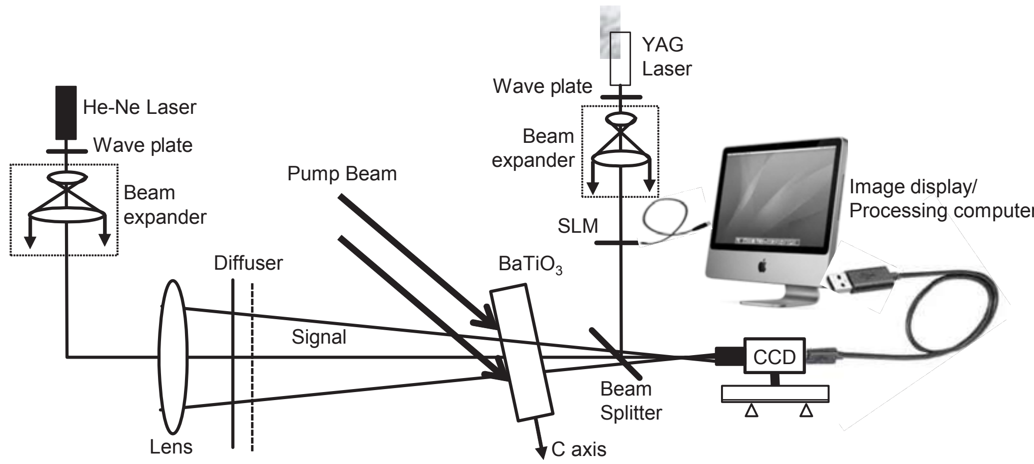

Fig 6. Basic layout of a photorefractive correlator

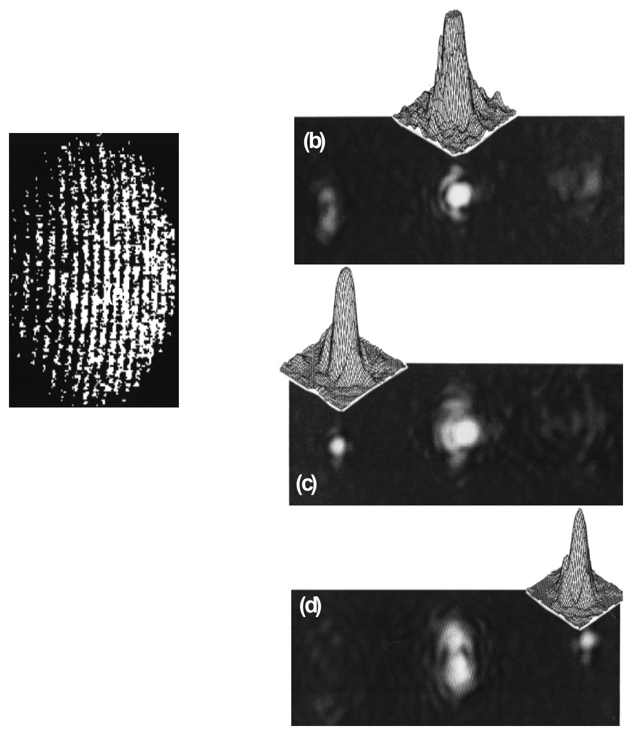

Fig 7. (a) Experimentally obtained double-exposure speckle pattern for a 3-D displacement comprising of $\varepsilon = 1.0$ mm, and $\varepsilon \tan \alpha = 200$ µm; (b-d): correlation outputs : (b) at back focal plane C2 of the FT lens; (c) at plane C1 (~ 7 cm before C2); and (d) at plane C3 (~ 7 cm further after C2)

Figure 7a shows the interference fringes obtained from a dynamic read-out of the PR speckle holograms corresponding to 3D displacement comprising of an out-of-plane displacement $\varepsilon = 1.0$ mm and an in-plane displacement $e \tan \alpha = 200$ µm. The fringes are binarized applying a threshold. Figures 7b to 7d show correlation results acquired by moving the CCD sensor in the longitudinal direction to three different planes where the correlation outputs were found to be focused. Figure 7b shows the autocorrelation output acquired at the back focal plane C_2 of the FT lens which also shows faint spots corresponding to two defocused correlation peaks on either side. Figure 7c shows the output acquired in the plane C_1 (approximately 7 cm behind the back focal plane) where the correlation peak formed on the left side comes to focus. Similarly, Fig 7d shows the focused correlation peak on the right side formed in the plane C_3 which is located nearly 7 cm after the back focal plane. Independent measurements of in-plane and out-of-plane displacement components can be obtained using the correlation technique. For instance, the distance between autocorrelation peak at the center and any one of the correlation peaks on the side gives a measure of in-plane displacement. The longitudinal distance between (C_1 and C_2) or (C_2 and C_3) can be measured to obtain the out-of-plane displacement.

Displacement measurement using correlation technique was found to be more accurate than direct fringe-based measurement due to higher visibility of the correlation peaks in the FT plane. Tripathi *et al* [80] have also extended this technique for object tilt (or a fixed out-of-plane rotation) measurement. Tilt measurement is important for metrology applications. A slightly different PR recording geometry consisting of collimated beam illumination was employed in the tilt measurement.

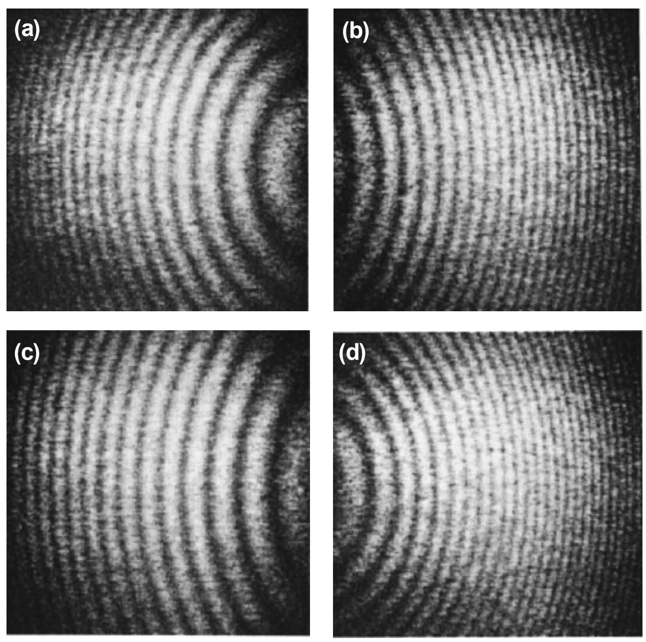

Fig 8. Speckle fringes obtained for a forward object position and tilt angle of (a) 4 mm, 1.58; and (c) 5 mm, 18; and (b) and (d) respective parameters for a backward object position

Tripathi *et al* [81] have carried out a theoretical analysis to show that intensity distribution of speckle interference fringes in this geometry is governed by spatially varying linear and quadratic (or chirp) phase modulation terms similar to the 3D displacement case discussed earlier. They also found that in this geometry, the amplitudes of the phase modulation terms are proportional to object tilt angle α, longitudinal displacement ε of the object, and shift s_x of the object from the center of axis of tilt (or rotation) along the transverse direction. The analysis showed that the effect of small object tilt α on fringe intensity distribution can be accentuated by the presence of components ε and s_x which can be deliberately introduced with known object motions between PR recordings. Instead of direct fringe analysis, a correlation technique was adopted for the tilt measurement. Figure 8(a-d) shows the interference fringes obtained using dynamic PR read-out for different object tilts when the center of axis of rotation of the diffuse object is shifted 5 mm away from the optical axis (i.e. $s_x = 5$ mm) and the object is positioned either forward (i.e. $\varepsilon = 4$ mm or 5 mm) or backward (i.e. $\varepsilon = -4$ mm or -5 mm) with respect to the reference position along the longitudinal direction. The fringes obtained for forward and backward positions are oppositely curved.

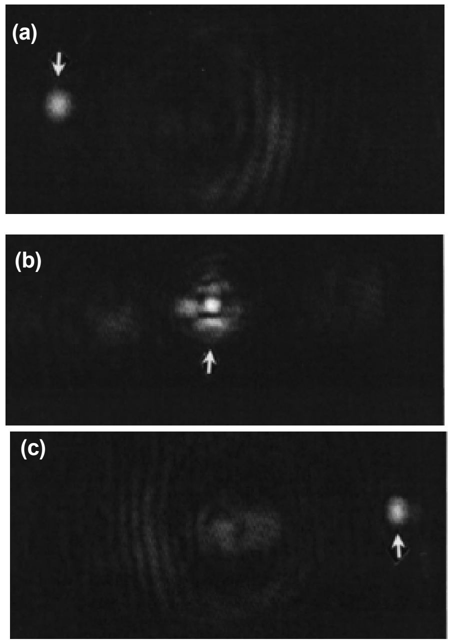

Fig 9. Correlation results obtained for the interference pattern shown in Fig. 8(c) at the observation planes (a) C1; (b) C2; and (c) C3

Figure 9 shows pictures of the focused correlation ps corresponding to the fringe shown in Fig 8c which were acquired by placing a CCD sensor in different longitudinal planes behind the FT lens. The correlation peaks are sharply focused when the quadratic (or chirp) phase modulation in the correlation output gets cancelled by a similar, but opposite modulation created by the Fresnel diffraction in planes on either side of the Fourier plane. Tripathi *et al* [81] measured the longitudinal distances between the planes where the correlation peaks get focused and used the known values ε and s_x to estimate the object tilt. Their measurements showed very good accuracy and sensitivity. Dharmsaktu *et al* [82] utilized photorefractive 'beam fanning' phenomenon, instead of two-beam coupling for PR recording of speckle patterns, and demonstrated tilt measurements using the correlation technique.

Vibration measurement is also useful for structural reliability and stability analysis in engineering metrology. Speckle photography and interferometry are commonly used in vibration measurement and analysis. Dharmsaktu *et al* [83,84] reported a simple approach for a low frequency and small amplitude out-of-plane vibration measurement using speckle photography in a photorefractive crystal. Instead of using a time-average recording, Dharmsaktu *et al* [83] employed interference between vibrating object speckles, and reconstructed circular fringes formed by a conventional double-exposure PR recording created by using a known out-of-plane displacement to the object. Such interference has been shown to produce oscillating (or evolving) circular fringes. Using this technique, Dharmsaktu *et al* [83] have measured vibration amplitude by counting the number of fringe evolutions, and vibration frequency by measuring the time cycle of the evolving fringes. The technique was demonstrated to measure small vibration amplitudes up to 0.22 μm, and low vibration frequencies to within 3% accuracy. Generation of the circular fringes (due to a given out-of-plane displacement ε) facilitates easy and accurate measurement of vibration with small amplitude and low frequency. The technique provides a simple engineering tool for vibration analysis. Some more relevant investigations by Dharmsaktu *et al* [85-87] and a brief review [88] can be mentioned. Some other groups [89,90] have also made notable contributions to the subject of photorefractive speckle metrology.

Finally, it may be remarked that normally the aberrations of the imaging optical system are not considered when used in speckle techniques for metrological applications. However in certain conditions the aberration considerations become important and have been the subject of some investigations [91-99].

6 Conclusions

The understanding of speckle phenomenon and its capabilities for solving problems related to engineering metrology have established several milestones in the development of optical techniques for measurements. Speckle metrology, one of the key areas of 'speckles' has now been established as a simple, convenient, and powerful tools in nondestructive testing.

In this article, we have reviewed our research on speckle techniques conducted by our group at IIT Delhi by using photorefractive media. To assist the reader, we presented a basic overview of the speckle photography technique and photorefractive effect at the beginning. We then discussed our research leading to progressive development of photorefractive-based speckle photography for three-dimensional displacement and vibration measurements. In this context, we also reviewed our work on the speckle correlation technique in some detail as it provides a simple and convenient tool for accurately measuring and assessing object displacements in real-time.

As already stated, speckles though undesirable in certain applications have found many uses. This reminds us of the advice given by Benjamin Franklin to Poor Richard, reproduced below (as quoted in 3).

"Eliminate that which is bothersome,

And your work shall be the better for it; but-

Find a use for that which offends thee,

And thou shalt be twice rewarded".

Speckle is an excellent example of saying that "One man's bane is often another man's boon".

Keeping in view the importance of-, and rapid advances in the subject of laser speckles, efforts were initiated as early as 1972 to compile and publish bibliographic reviews [100-108] on the subject for the benefit of interested persons. This activity had to be kept in abeyance due to the other commitments of one of the authors (KS). It is proposed to take up the task again and compile bibliographic reviews for the remaining years.

It is with great pleasure that the authors wish to dedicate this paper in honor of Professor Rajpal Singh Sirohi who has been a pioneer researcher in engineering optics. His outstanding contributions to the area of optical metrology in general and to speckle metrology in particular, have enriched the literature during the past nearly four decades.

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