Direct and real-time holographic monitoring of relative changes in two random rough surfaces

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This paper presents a direct one-step and real-time holographic method for the comparison of two diffusely scattered wave fields originating from two random rough surfaces. The possibility of comparing two random rough surfaces by a straightforward real-time holographic procedure adjoins holographic interferometry with a wide range of application possibilities.

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Holographic interferometry is a very useful tool to obtain interferometric comparison of wave fronts originating from a random rough surface in its two states of deformations. Since its discovery in 1965, holographic interferometry has been the subject of many theoretical and experimental studies directed towards an understanding of the basic phenomena underlying the technique, expanding its horizons, and rendering it more user friendly and practical to handle. This procedure is now widely used in metrology and nondestructive testing applications. However, a major restriction linked to the holographic comparison of diffusive wave fronts is that the two wave fronts should originate from the same source point on the rough surface in its two states. Therefore, one is unable to obtain holographic comparison of diffuse wave fronts, which originate from two different rough surfaces, to detect, for example, relative changes of the order of a submicrometer between the two surfaces. The dissimilar randomness of the two waves prevents a pure form realization of the holographic interferometric monitoring of the relative change in the two rough surfaces. Recently, we have been able to measure holographically and in real time the relative change between two physically distinct random rough surfaces. The holographic comparison of two random rough surfaces opens significant application possibilities in metrology and nondestructive testing or inspection in broadly ranging fields.

The experimental setup is shown in Fig. 1. A laser beam is used to illuminate two nominally identical but physically distinct rough surfaces in directions making equal angles with the surface normal. The natural roughness of these surfaces produces two uncorrelated and coherent wave fronts. The two wave fronts are superimposed onto a photosensitive medium in an image-plane holographic configuration. An off-axis collimated reference beam is made to fall on the photographic plate. The complex amplitude functions of the two object and reference fields in the plane of the photographic plate can be written as

$$O_1 = \exp(i\varphi_1), \quad O_2 = \exp(i\varphi_2), \quad R = \exp(i\eta) ,$$

where φ_1 and φ_2 are the random phases of the two object waves and η is the phase of the reference wave. The corresponding amplitudes are taken to be unity. Since the waves are coherent, they give rise to a system of interference on the photographic plate. The intensity distribution is

$$I = |\exp(i\varphi_1) + \exp(i\varphi_2) + \exp(i\eta)|^2 . \tag{1}$$

After development, the holographic plate is replaced in its original position. The method consists of illuminating the hologram by waves scattered from the two rough surfaces. The reference beam is blocked. The amplitude of the transmitted wave is proportional to

$$A = [\exp(i\varphi_1) + \exp(i\varphi_2)] I . \tag{2}$$

The expansion of Eq. (2) results in a series of terms, of which the wave represented by the term

$$[\exp(-i\varphi_1) + \exp(-i\varphi_2)][\exp(i\varphi_1) + \exp(i\varphi_2)]\exp(i\eta)$$

travels in the direction of the reference wave. This term describes the reference wave reconstructed by the hologram. The irradiance distribution that the eye sees when looking in this direction follows as

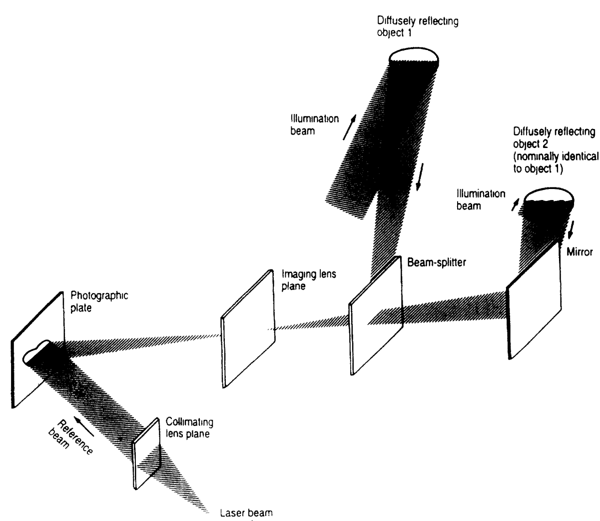


FIG. 1. Schematic of the optical layout to obtain the interferometric comparison of uncorrelated and coherent wave fronts issuing from two laser lit random rough surfaces.

$$I_f = |[\exp(-\varphi_1)+\exp(-\varphi_2)][\exp(i\varphi_1)+\exp(i\varphi_2)]\exp(i\eta)|^2 \ . \tag{3}$$

The two surfaces are now supposed to be deformed. The new object waves illuminating the hologram undergo a slight change in phase while retaining the same amplitude distribution. The random phases experience incremental phase shifts Ψ_1 and Ψ_2,

$$\varphi_1' = \exp i(\varphi_1+\Psi_1), \quad \varphi_2' = \exp i(\varphi_2+\Psi_2) \ .$$

The corresponding intensity distribution becomes

$$I_f = |[\exp(-i\varphi_1)+\exp(-i\varphi_2)][\exp i(\varphi_1+\Psi_1)+\exp i(\varphi_2+\Psi_2)]\exp(i\eta)|^2 \ . \tag{4}$$

Using the fact that the wave fronts issuing from the two rough surfaces are uncorrelated, Eq. (4) simplifies to

$$I_f = |[\exp(-i\Psi_1)+\exp(-i\Psi_2)]\exp(i\eta)|^2 = 2[1+\cos(\Psi_1-\Psi_2)] \ , \tag{5}$$

where the quantity $\Psi_1-\Psi_2$ represents the relative phase change undergone by the two surfaces due to deformation. The expression for $\Psi_1-\Psi_2$ can be calculated for any recording and observation geometry. Assuming that the two surfaces are each illuminated at normal incidence and observed through a telecentric lens system, Eq. (5) becomes

$$I_f = 2\left[1+\cos\left[\frac{4\pi}{\lambda}\Delta w\right]\right] \ , \tag{6}$$

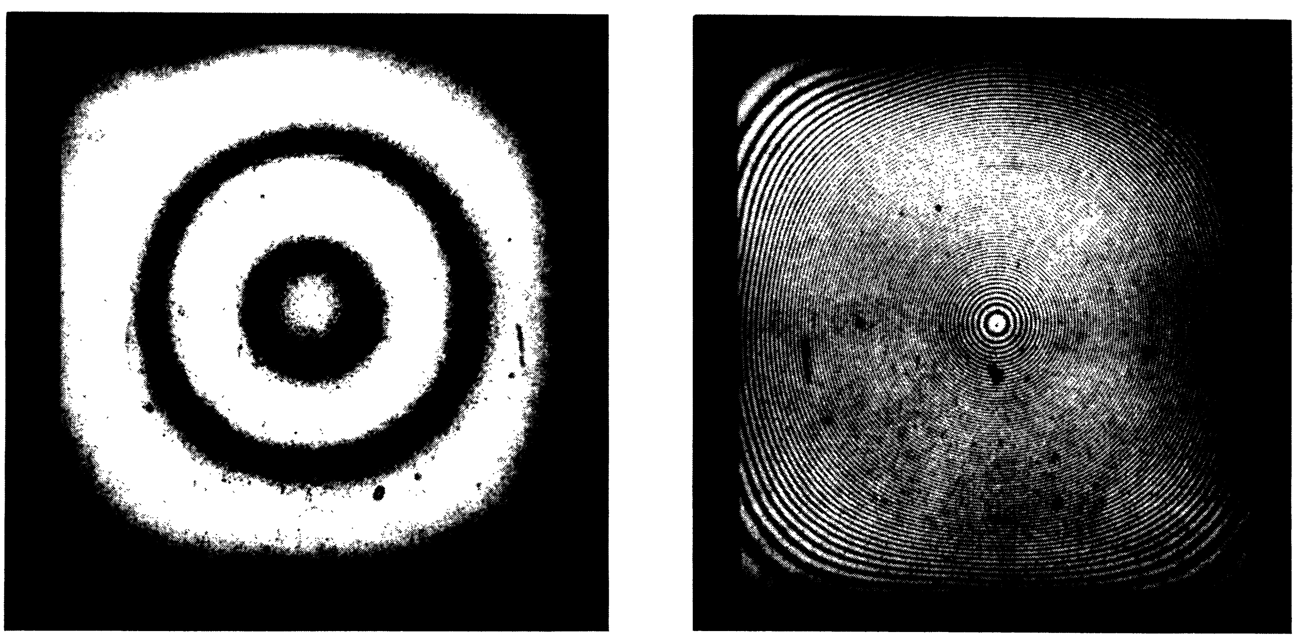
where Δw is the relative difference in the out-of-plane displacements undergone by the two surfaces. The increment in difference of displacement between two consecutive fringes is given by

$$\Delta w = \frac{\lambda}{2} \ ,$$

where λ is the laser wavelength. While studying the formation of fringes contouring the difference in displacements of two objects, we have assumed the corresponding points on the two objects to be in exact superposition. In the presence of faulty system alignment the corresponding points are no longer superimposed. This would, for example, introduce a term relative to the derivative of displacements in the fringe equation (6). The relative sensitivity of the method to the derivative term, however, depends on the degree of misalignment. For small imperceptible misalignments of the corresponding points (and that is at most what one might come across during experiments) this sensitivity is very low and thus could be neglected for all practical purposes.

An important specific feature of the technique is that it is sensitive to the direction of displacement of the two surfaces. Thus for displacements of the two surfaces along the same direction, one observes a continuous interferometric subtraction of the movements. On the contrary, for displacements along opposite direction one observes a continuous interferometric sum of the movements.

The results obtained in real time with two nominally identical random surfaces are demonstrated in Fig. 2.

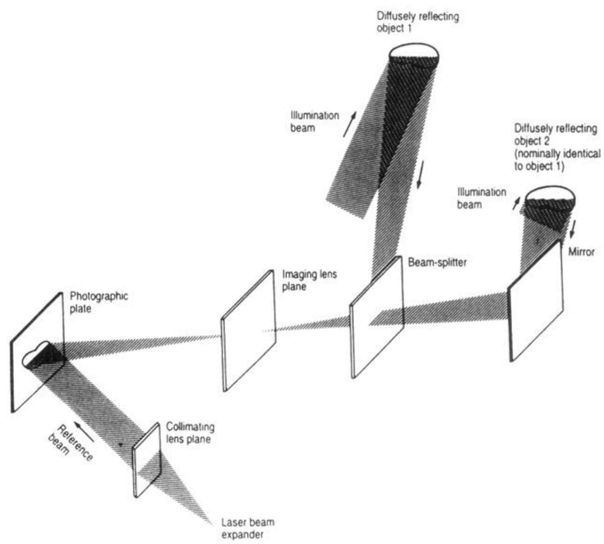


(a) (b)

FIG. 2. Typical examples of results obtained in real time. The interference fringes show (a) the difference and (b) the sum of displacements undergone by two nominally identical specimens subjected to stresses.

Figure 2(a) shows the interference pattern corresponding to the difference in displacements of two rough square plates clamped along the edges and subjected to centrally concentrated loads. Figure 2(b) shows the interference pattern corresponding to the sum of displacements of two rough square plates clamped along the edges and subjected to centrally concentrated loads. The increment of difference or sum of displacement between two consecutive fringes corresponds to $\lambda/2$ or approximately one-fourth of a micrometer in the case of a green line using an argon-ion laser. The results of the interferometric comparison of two rough surfaces are displayed in real time on a television screen.

To conclude, this paper presents a method whereby interference fringes corresponding to difference displacements are obtained in real time in a one-step process. The interference fringes are of good quality, similar to those obtained in classical holographic interferometry. The method is simple, accurate, and rapid to implement. The promising applications of the method are in the areas of interferometric comparison of certain important physical quantities such as displacements, densities, etc., in solid mechanics and flow problems. For example, the measurement of the difference in displacements of two nominally identical specimens subjected to similar stress levels can reveal critical areas in the specimen being tested with respect to an étalon specimen. Such a technique also provides a key to an interesting problem in experimental mechanics: to visualize the changes induced in the ensemble of the mechanical response of a specimen caused from a specific modification brought about in the work piece. Another example of application is in the interferometric comparison of the relative shapes of two nominally identical three-dimensional rough surfaces.



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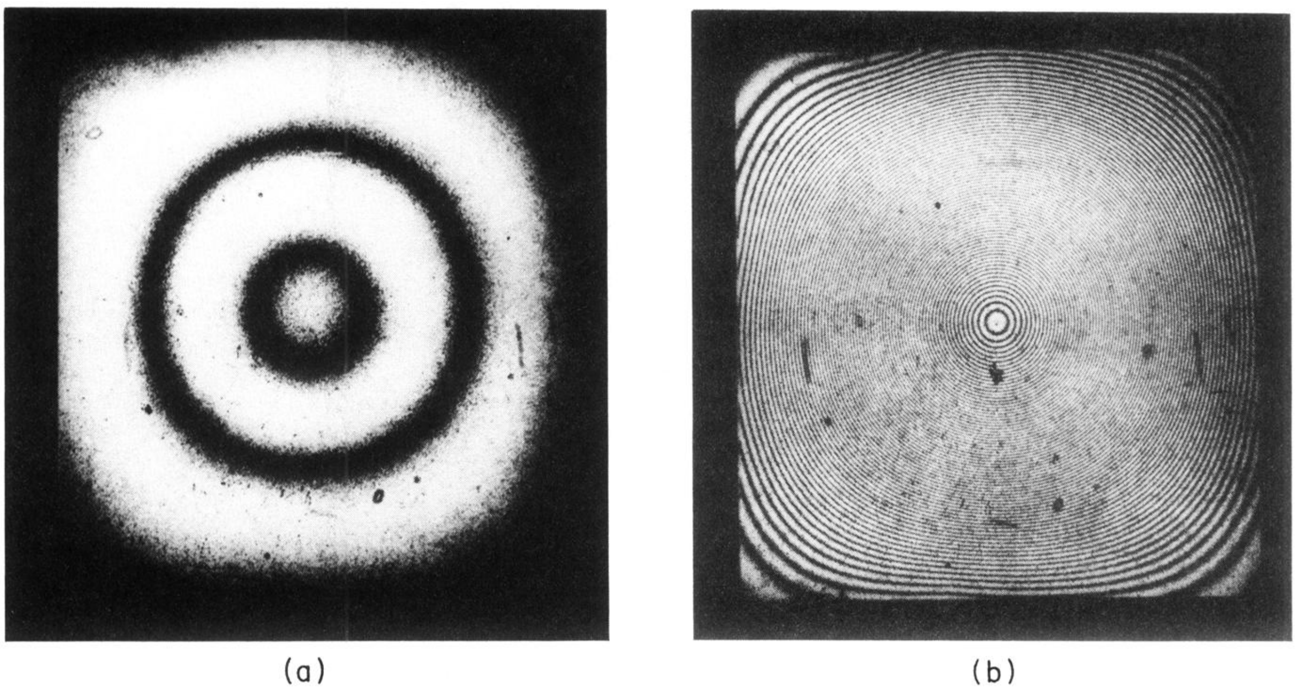

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