In-plane deformation measurement by digital phase-shifting speckle-interferometry

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ABSTRACT

Didital speckle-pattern interferometry systems for automatic measurement of in-plane deformation of a diffuse object are presented, based on phase shifting of a speckle interferogram. Before deformation, three digital speckle patterns are recorded as changing the phase of reference light such as $0, \pi/4$, $\pi/2$. After deformation, three digital speckle pattern are recorded with phase shifts - $\pi/2$, $3\pi/4$, π, respectivaly. A calculation of the arctangent with phase-shifted speckle pattern gives the optical path difference which is proportional to the deformation.

1.INTRODUCTION

The method of digital speckle-interferometry is based on correlation comparison of two speckle patterns corresponding to object shape before and after deformation respectively. For reduction of measurement errors, caused by specle-structures of correlation fringes pattern, we introduced controlled phase shifts between object and reference waves, as observed in usual phase-shifting interferometry.

However the difference in the nature of formation of in-terference and correlation fringes prevents from the using of standard phase calculation algorithms for the complete elimination of specle-noise.

The phase calculation algorithm is offerred based on introduction of certain sequences of phase shifts and comparisons the values of intensities, relating to the same point of specklegram, to remove completely the influence of speckle-noise on accuracy of measurement. It is achieved by registration several speckle patterns obtained at a priori choosen phase shifts of the of object and reference waves of a speckle in-terferometer before and after object deformation.

2.FRINGE FORMATION

We consider the conventional method digital speckle-interferometry. The method of digital speckle-interferometry is based on correlation comparison of two speckle patterns, registrated before and after deformation.

Let

$$E_S(x,y) = A_S(x,y)\exp(j\Phi_S(x,y)) \quad , \tag{1}$$

complex space amplitude of initial wave, reflected from surface of the object before deformation.

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Let

$$E_r(x,y) = A_r(x,y) \exp(j\Phi_r(x,y)) \quad , \tag{2}$$

complex amplitude of basic reference wave in the same plane.

Then the light intensity of the speckle image can be written as

$$I_0(x,y) = (\mathbf{E_s} + \mathbf{E_r})^2 = A_s^2 + A_r^2 + 2\, A_s\, A_r \cos(\Phi_s - \Phi_r). \tag{3}$$

After deformation of the object the phases of light waves from separate elements of surface in point (x,y) have been changed. However, if an object is deforming slowly, phase shifts of light waves from separate elements of surface in the same point can be considered identical [1].

Phase shift in a definite point of a surface resulted from object deformation is expressed by $\Psi(x,y)$. Then, complex amplitude of wave, forming speckle-pattern of deformed surface of object can be written as

$$\mathbf{E_{s1}}(x,y) = A_s(x,y) \exp(j\Phi_s(x,y)+\Psi(x,y)) \quad , \tag{4}$$

Hence, intensity of speckle-pattern from deformed surface of object can be written as

$$I_1(x,y) = (\mathbf{E_{s1}} + \mathbf{E_r})^2 = A_s^2 + A_r^2 + 2\, A_s\, A_r \cos(\Phi_s - \Phi_r+\Psi(x,y)). \tag{5}$$

Diffusely scattered ligth from object and reference surfaces is collected by an imaging lens and focused on the TV camers. In speckle interferometry, low-resolution devices, for example a TV camera, can be used because of the large size of the speckle in image plane which can be adjusted by the aperture of the imaging lens.

In digital speckle-interferometry the ligth intensity of the speckle pattern is converted to an electric video signal and sampled to form a digital picture. A speckle interferogram is generated arithmetically between digitized speckle pattern before and after deformation of the object

$$I_s(x,y) = [I_0(x,y) - I_1(x,y)]^2 \; . \tag{6}$$

From (3) and (5) follows, that

$$I_s = N - N \cos(\Psi) \quad , \tag{7}$$

where

$$N = 8\, A_s^2\, A_r^2 \sin(\Phi_s - \Phi_r+\Psi(x,y)/2) \; . \tag{8}$$

Eq.(8) suggests that in these areas, where the phase shift Ψ is equal:

$$\Psi = \pm(2L+1)\,\pi/2\ ,\ L = 0,1,2\ \ldots\ , \tag{9}$$

the expression (7) becomes equally 0, such areas on the screen becomes dark, while the other areas, where this condition is not satisfied would be look like specles.

3.THEORY

The distribution of light intensities in picture of correlation fringes, is described by expression (7), where N is responsible for the speckle noise, and the amplitude As and phase Φ_s, and possibly Φ_r and Ar (for similar speckles of reference wave) define the form and size speckle in plane of picture. For reception of quantitative information, it is necessary to define the phase shift Ψ, connected with displace-ment or deformations caused deformation of object.

The method, based on allocation of centres of fringes and interpolation of values among them, results in large errors. Because of the presence of speckle-noise results in ambiguity in centre positions of fringes.

With the purpose of minimization of errors cause by relatied speckle-noise the authors of [2] offerred to introduce the controlled phase shifts between by object and reference waves, as observed in usual phase-shifting interferometry.

The distribution of intensity before deformation of object has been registrated. Then, after deformation by continuous introduction controlled phase shifts - 0, $\pi/2$, $3\pi/4$, π, between object and reference waves the pattern of correlation fringes can be calculated as

$$I_{s,k}(x,y) = [I_0(x,y) - I_{1,k}(x,y)]^2\ . \tag{10}$$

where the indices k=1,2,3,4 correspond introduced phase shifts.

The distribution of intensity in pattern of correlation fringes could be presented as

$$I_{s,k} = N_k - N_k \cos(\Psi_k)\ , \tag{11}$$

where $\Psi_k = \Psi + \varphi_k$, and

$$N = 8\,A_s^2\,A_r^2\,\sin^2(\Phi_s - \Phi_r + \Psi(x,y)/2 + \varphi_k)\ , \tag{12}$$

$\varphi_1 = 0$, $\varphi_2 = \pi/2$, $\varphi_3 = 3\pi/4$, $\varphi_3 = \pi$, The authors of [2] offered to define Ψ, phase changes introduced by deformation, from

$$tg\Psi = (\bar{I}_{s,4} - \bar{I}_{s,2}) / (\bar{I}_{s,1} - \bar{I}_{s,3}) \tag{13}$$

where $\bar{I}_{s,k}$ - pattern of correlation fringes, averaged on to small areas $\Omega(x,y)$, within the limits of which the phase shift $\Psi(x,y)$, caused deformation of object, can be considered almost constant.

Eq. (12) can be derived on the base of assumption, that the average level of speckle-noise is identical in appropriate areas of averaging of correlation fringes pictures, thus

$$N_1(\Omega) = N_2(\Omega) = N = N_3(\Omega) = N_4(\Omega) = N\ . \tag{14}$$

This assumption is equivalent to the assumption, that the average size speckle much less of average size of areas $\Omega(x,y)$. However, low resolution of television systems of optical image input, requires the increasing of speckles size. Actually, average species size becomes compatable with the average size of area $\Omega(x,y)$, therefore the eq.(15) does not permit effectively to remove the influence of speckle-noise.

The following describes updating of method, enabling completely to remove the influence of speckle-noise on accuracy of determination of phase.

We offer to register the distribution of intensity $I_0(\alpha)$ in specklegram of initial surface of object, received by entering controllable phase shift α between reference and object waves of speckle-interferometer. After deformation of object, we register specklegram $I_1(\beta)$ of deformed surface of on object, received when entering controllable phase shift β. It is assumed, that the deformation level of an object is chosen so, that the speckle decorreletion affect is removed

Then

$$I_0(\alpha) - I_1(\beta) = 4 A_s A_r \sin(\Phi_s - \Phi_r + \Psi/2 + (\alpha + \beta)/2)\ \sin(\Psi/2 + (\beta - \alpha)/2)\ , \tag{15}$$

$$K_1 = I_0(\pi/4) - I_1(3\pi/4) \tag{16.a}$$

$$K_2 = I_0(\pi/2) - I_1(\pi/2) \tag{16.b}$$

$$K_3 = I_0(0) - I_1(\pi)\ . \tag{16.c}$$

From (16.a), (16.b) and (16.c) follows, that

$$\Psi = \arctan(2K_1 - K_2 - K_3/)/(K_3 - K_2)\ . \tag{17}$$

We note, that eq.(17) is local, as far as all values, used in the equation, entering are related to the same point of plane of image (x,y), the area averaging is not required.

4.EXPERIMENTAL RESULTS

The object to be measured is an aluminum plate covered with white magnesium oxide powder. The area observed by the TV camera is ~50 x 50 mm^2. The light from a He-Ne laser (50 mW) is expanded by an objective lens and split into object and reference surface beams by a beam splitter. Diffusely scattered light from object and reference surfaces is collected by an imaging lens and focused on the target of a TV camera. The optical path dufference between reference and object waves can be changed by applying a hight voltage to the PZT device attached to the reference surface. The light intesity of the speckle image is sampled to yield a digital picture made up of 512 x 512 sample points. Each sample point is quantized to 256 discret gray level. The stored picture is transferred to computer (IBM-PC). The speckle patterns before and after deformation of the object are stored on the disk. Before deformation, the reference surface is displaced by amounts of phase shifts - $0,\pi/4$, $\pi/2$, after deformation - $\pi/2$, $3\pi/4$, π, respectivaly. A calculation of the arctangent (17) gives the optical path difference which is proportional to the deformation. After processing of thus received speclegram we have displacement measurement with interferometric accuracy. The strain of an object can be determined from surface displacement.

The investigation of strain-deformed state of the object supports the theoretical results.

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7.REFERENCES

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