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2016

Song, C., Prasad, A. S. G., Chan, K. H. K., & Murukeshan, V. M. (2016). Characterization and optimization of illumination vector for contouring surface form and feature using DSPI. *Review of Scientific Instruments*, 87(6), 063116-. doi:10.1063/1.4953884

<https://hdl.handle.net/10356/89701>

<https://doi.org/10.1063/1.4953884>

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Characterization and optimization of illumination vector for contouring surface form and feature using DSPI

Chaolong Song,¹ Guru Prasad A. S.,¹ Kelvin H. K. Chan,^{1,2} and Vadakke Matham Murukeshan^{1,3,a)}

¹*Rolls-Royce@NTU Corporate Lab, c/o School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798*

²*Rolls-Royce Singapore, 6 Seletar Aerospace Rise, Singapore 797575*

³*School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798*

(Received 10 December 2015; accepted 1 June 2016; published online 20 June 2016)

Surface defect or damage is one of the critical factors leading to the failure of engineering materials and structures. The methodologies for the measurement of surface shape and feature or defect have been extensively explored and developed over the past few decades, including both contact and non-contact methods. Speckle pattern interferometry, as a non-contact optical method, has been demonstrated to effectively contour the surface shape through adjusting the illumination vector. However, few studies have been made to investigate the effect of the initial position of the illumination source as well as the source translation direction. In this paper, we report to carry out a study of measuring the surface form and feature using digital speckle pattern interferometry system via a slight translation of illumination source. Through theoretically analyzing the sensitivity factor along with the experimental validation, it is shown that the contouring fringe is more sensitive to the surface height with an off-axis illumination than the paraxial illumination. It is also found that translating the source along axial and lateral direction can be both used for the surface shape re-construction. *Published by AIP Publishing.* [<http://dx.doi.org/10.1063/1.4953884>]

I. INTRODUCTION

Functional surfaces are of great importance to the engineering components in a variety of industries ranging from aerospace, automotive, optics, to marine.¹ The integrity of the surface shape plays an essential role to determine the performance of those engineering components. Therefore, the methodologies for 3-dimensional measurement for surface form have been extensively explored and researched to monitor the integrity of surface properties.^{2,3} Among those methodologies, optical metrology, categorized as the measurement with light, provides more robustness and accuracy owing to its non-contact manner and high-precision instinct. Laser speckle pattern interferometry, as an optical full-field measurement method, can yield plentiful surface information, such as in-plane,⁴⁻⁶ out-of-plane⁷⁻⁹ displacements, strain distribution,¹⁰ defects location,¹¹ and surface shape.¹² Basically during a measurement, two recordings/exposures will be taken by a camera for later-on subtraction and a perturbation to the testing surface is introduced in between these two recordings. The subtraction of the two recordings can produce the dimensional information which is related to the perturbation.¹³

Change of illumination wavelength is one way to introduce the perturbation and finally reveals the surface shape information, which is referred as two-wavelength method.^{12,14} The wavelength of laser diode can be slightly tuned by adjusting the pumping current and further calibration of the wavelength-current relationship needs to be implemented for accuracy.

Another way to tune the illumination vector is via adjusting the geometries of illumination. The illumination scheme for the speckle pattern interferometry can be generally categorized as parallel beam incidence (planar wave) and point-source illumination (spherical wave). With the collimated beam illumination, tilting the measuring surface or the light beam as the perturbation can yield a fringe pattern whose phase is dependent on the surface contour.¹⁵⁻¹⁸ With the point source illumination, a slight translation to relocate the source position needs to be implemented to introduce the optical path change and subsequently generate the shape-dependent fringe pattern.¹⁹⁻²⁴ To investigate the dependence of fringe on the surface shape, the beam incidence angle should be analyzed for parallel beam illumination,²⁵⁻²⁸ whereas the source-to-object distance needs to be calculated to study the sensitivity factor of the fringe phase for the point-source illumination. Several groups have characterized the slope-sensitive fringe for the shearography configuration using a point-source illumination.^{20,29,30} It is found that the phase of fringe is related to the slope of the surface, and the translation direction of the point-source determines the sensitivity of the fringe phase to the slope. Different from the shearography system, the digital speckle pattern interferometry (DSPI) configuration can yield a surface-height-dependent fringe pattern via translation of the point-source.^{19,22,23} Both DSPI and shearography techniques have their unique advantages. For example, shearography system is more robust to the environmental noise than the DSPI system,³¹ but DSPI technique can incorporate diffusive referencing for non-diffusive surface measurement.³² However, few studies have been carried out to characterize the fringe sensitivity to the surface height by analyzing the illumination vector for the

^{a)}Electronic mail: mmurukeshan@ntu.edu.sg

FIG. 1. (a) Schematic of the experimental setup-digital speckle pattern interferometry system, (b) illumination of the test sample with a 45° incident angle, (c) perpendicular illumination of the test sample.

DSPI configuration. This characterization and optimization of the illumination vector can be critically important for the measurement of 3-D profile of small surface features/defects.

In this work, we will carry out an in-depth investigation to characterize and optimize the illumination vector for contouring the surface shape using a DSPI configuration. The impact of source position as well as the effect of translation direction will be mathematically evaluated through analyzing the directional derivatives of the sensitivity factors. The dominance of the height-dependent fringe can be maximized by optimizing the sensitivity factor. The experiment will be carried out to validate our theoretical analysis. A flat plate with a simulated dent will be used as the test sample and the measurement will be implemented using the optical configuration shown in Figure 1. Temporal phase-shifting will be applied to obtain the fringe phase map. The reconstruction of the surface and dent shape through the unwrapped phase will be compared to the 3-D scanning result of the same sample using a commercial coordinate measurement system (ALICONA, InfiteFocus).

II. EXPERIMENTAL SETUP

Figure 1 shows the optical configuration of the digital speckle pattern interferometry (DSPI) configuration (Figure 1(a)) as well as the geometries of optical path (Figures 1(b) and 1(c)). A fiber pigtailed laser of wavelength $\lambda = 635$ nm (OZ-2000, OZ Optics Ltd., power 1 mW) was used as the point source for illuminating the test sample and reference surface. The laser beam was split into two beams (split ratio 50%) using the fiber splitter with the object beam going to the test surface (illumination area ≈ 5 cm $\times$ 5 cm) and the reference beam guided to illuminate a rough reference surface (a flat aluminum plate) through a piezoelectric transducer (PZT) actuated mirror. The two reflections,

respectively, from the test surface and the reference rough surface interfere with each other and effectively form a speckle pattern at the image plane of the CCD camera. The distal end of the fiber, which delivers the object beam, is mounted on a XYZ translational stage (PT3-M, Thorlabs, Inc.) for the translation of light source. Generally, a double exposure method can be used to form a speckle fringe pattern through either subtraction or addition of the two exposures. The perturbation between the two exposures can be introduced by spatially translating the illumination source (fibre distal end).

The PZT actuated mirror is employed to introduce the temporal phase shifting. Generally for a phase shifting technique, a series of frames need to be recorded and a phase shift needs to be applied after recording each frame.^{33,34} The calculation based on reported algorithms and by using these frames can result in the phase map of the speckle pattern. In this work, Carré method, which is a self-calibrated phase shifting technique, has been employed to retrieve the phase maps before and after the translation of illumination source.^{19,35} The subtraction of the two phase maps can yield the phase change Δ . And the surface height information can be quantitatively evaluated based on the phase change Δ .

III. THEORETICAL ANALYSIS

In this work, we introduce the perturbation to the laser speckle pattern by slightly translating the illumination source. Figures 1(b) and 1(c) illustrate the illumination with a 45° incident angle and perpendicular illumination of the testing sample, respectively. The first exposure occurs with the light source located at its initial position $S(x_s, y_s, z_s)$, and the intensity recorded by the camera can be described as

$$I_1 = I_O + I_R + 2\sqrt{I_O I_R} \cos \varphi, \quad (1)$$

where I_O represents the intensity contributed by the reflection light from the object, and I_R denotes the intensity distribution of the reference beam at the imaging sensor, and φ is the phase difference between object light and reference light. After the initial recording, a slight translation of the light source to a new position $S'(x'_s, y'_s, z'_s)$ is implemented, which would result in a phase change Δ of the object light beam. This change on the optical path could introduce a small amount of intensity variation recorded by the camera,

$$I_2 = I_O + I_R + 2\sqrt{I_O I_R} \cos(\varphi + \Delta). \quad (2)$$

The subtraction between Eqs. (1) and (2) yields a fringe pattern modulated by a sinusoidal carrier described as follows:

$$\Delta I = 4\sqrt{I_O I_R} \sin(\varphi + \frac{\Delta}{2}) \sin \frac{\Delta}{2}. \quad (3)$$

The phase change results from the optical path difference (OPD) introduced by the translation of light source (refer to Figures 1(b) and 1(c)) can be derived as Eq. (4), if assuming a spherical wavefront of the emission from the single-mode fiber^{36,37}

$$OPD = \frac{\lambda \Delta}{2\pi} = S'P - SP, \quad (4)$$

where λ is the wavelength of illumination light, and $P(x, y, z)$ is an arbitrary point on the testing surface. The initial position

FIG. 2. Directional derivatives of sensitivity factor S_R : (a) derivative along lateral direction; (b) derivative along axial direction. The red colour represents the perpendicular illumination scenario, and the blue colour represents the 45° illumination scenario.

of the light source $S(x_s, y_s, z_s)$ can be assumed to be the origin of the coordinate system, and the light source translation vector can be denoted as $\vec{r}\{\sigma_x, \sigma_y, \sigma_z\}$. Thus, OPD can be formulated as

$$OPD = \sqrt{(\sigma_x - x)^2 + (\sigma_y - y)^2 + (\sigma_z - z)^2} - \sqrt{x^2 + y^2 + z^2} \approx -\frac{x\sigma_x + y\sigma_y + z\sigma_z}{\sqrt{x^2 + y^2 + z^2}} = -\frac{\vec{SP}}{|\vec{SP}|} \cdot \vec{r}. \quad (5)$$

Assuming that S_x , S_y , and S_z are the sensitivity factors of OPD to the light source translation, OPD can be simply described as

$$OPD = -\{S_x, S_y, S_z\} \cdot \vec{r}, \quad (6)$$

where S_x , S_y , and S_z represent

$$S_x = \frac{x}{\sqrt{x^2 + y^2 + z^2}}, S_y = \frac{y}{\sqrt{x^2 + y^2 + z^2}}, S_z = \frac{z}{\sqrt{x^2 + y^2 + z^2}}. \quad (7)$$

Since x and y directions have a mathematical symmetry, using a cylindrical coordinate system can further simplify the

following discussion:

$$S_R = \frac{R}{\sqrt{R^2 + z^2}}, S_z = \frac{z}{\sqrt{R^2 + z^2}}, \quad (8)$$

where $\vec{R}$ represents the 2-dimensional position vector on the test surface. The formation of the fringe pattern comprises the contributions from both lateral translation σ_R (along $\vec{R}$ direction) and axial translation σ_z (along $\vec{z}$ direction), which can be simply described by Eq. (9). The axis or axial direction should always be referred to as the optical axis of the imaging system in this work,

$$OPD = -(S_R\sigma_R + S_z\sigma_z). \quad (9)$$

Since sensitivity factors S_R and S_z are functions of the lateral and height coordinates of the testing surface, both of these factors can be used for the re-construction of the 3-D surface shape. Ideally if the sensitivity factors S_R and S_z are merely dependent on the surface height z , the fringe pattern would be linearly a latitude contour of the surface height. However, in this case using a DSPI system, the OPD could change with both lateral and height coordinate variation. In order to optimize the system and make the fringe phase more sensitive to the surface height variation, the directional derivatives of the factors S_R and S_z need to be investigated separately,

$$\frac{\partial S_R}{\partial R} = \frac{z^2}{(R^2 + z^2)^{3/2}}, \frac{\partial S_R}{\partial z} = \frac{Rz}{(R^2 + z^2)^{3/2}}, \quad (10)$$

FIG. 3. Directional derivatives of sensitivity factor S_z : (a) derivative along lateral direction; (b) derivative along axial direction. The red colour represents the perpendicular illumination scenario, and the blue colour represents the 45° illumination scenario.

FIG. 4. (a) Laser speckle fringe pattern obtained using the DSPI system and (b) extracted phase of the fringe pattern via a perturbation of light source translation along lateral direction. The illumination is perpendicularly incident on the flat test surface with a simulated dent. The axial distance between the light source and the surface centre is about 10 cm.

$$\frac{\partial S_z}{\partial R} = \frac{Rz}{(R^2 + z^2)^{3/2}}, \quad \frac{\partial S_z}{\partial z} = \frac{R^2}{(R^2 + z^2)^{3/2}}. \quad (11)$$

Suppose the translation is strictly along the $\bar{R}$ direction, the OPD would be linearly proportional to the sensitivity factor S_R . Assuming the axial distance z from the illumination source to the surface is about 1, and all the other dimensions are normalized accordingly. Figure 2(a) plots the directional derivative of S_R with regards to the lateral coordinate variation, and Figure 2(b) shows the directional derivative with respect to the surface height coordinate. To make the fringe phase more dependent on the surface height coordinate, $\partial S_R / \partial z$ should be made as large as possible.

Here, two illumination scenarios are taken into account: (1) illumination with a 45° incident angle ($R \approx 1$) illustrated in Figure 1(b), (2) illumination source located at paraxial region ($R \approx 0.1$) illustrated in Figure 1(c). Under the condition of paraxial illumination, the value of $\partial S_R / \partial R$ is about 10 times larger than that of $\partial S_R / \partial z$ (0.98 compares to 0.1 shown in Figure 2), which means the fringe phase would be more dependent on the lateral coordinates than the surface height, and thus the system is not sensitive to measure the surface height. On the other hand, the value of $\partial S_R / \partial z$ 0.35 is equal to that of $\partial S_R / \partial R$ under the condition of 45° illumination, which indicates that

lateral and axial coordinate variations would have equal impact on the fringe phase change.

If the translation of light source is along the axial direction, the OPD would be linearly dependent on the sensitivity factor S_z . Figures 3(a) and 3(b) plot the derivatives of S_z along lateral and axial directions, respectively. Again, two scenarios of illuminations are illustrated. And we found that the value of $\partial S_z / \partial R$ is also about 10 times larger than that of $\partial S_z / \partial z$ (0.1 compares to 0.01) when the illumination light is perpendicularly incident on the test surface, while the value of $\partial S_z / \partial z$ 0.35 is equal to that of $\partial S_z / \partial R$ under the condition of 45° illumination. Therefore regarding the factor S_z , illuminating the test surface with a perpendicular incident angle would make the fringe phase less responsive to the surface height variation. And on the other hand, a 45° illumination can make the fringe phase more sensitive to the surface height.

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

The analysis shows that the fringe phase Δ becomes more sensitive to the test surface height when the illumination source is located away from the optical axis regarding both factors of S_R and S_z . To evaluate this theoretical analysis, experiments have been carried out to test a flat plate with a simulated dent.

FIG. 5. (a) Laser speckle fringe pattern and (b) extracted phase of the fringe pattern obtained using DSPI via a perturbation of light source translation along lateral direction. The flat test surface has a superficial dent.

FIG. 6. (a) Laser speckle fringe pattern and (b) extracted phase of the fringe pattern obtained using DSPI via a perturbation of light source translation along axial direction. The illumination is perpendicularly incident on the flat testing surface with a superficial dent. The axial distance between the light source and the surface centre is about 10 cm.

The sensitivity factors S_R and S_z were tested separately via controlling the translation directions. Firstly, S_R was tested by translating the light source along the lateral direction with a small amount of σ_R , and two tests have been carried out with the light source located at paraxial region (perpendicular illumination) and off-axis region (45° illumination), respectively.

Figure 4 shows the experimental results obtained with a perpendicular illumination and the translation of light source along lateral direction. The axial distance from the light source to the centre of the sample is around 10 cm, and the translation amount is $50\ \mu\text{m}$. Figure 4(a) shows the speckle fringe pattern obtained via the subtraction of the two exposures. Through applying the temporal phase shifting technique, the phase of the fringe pattern can be retrieved as illustrated in Figure 4(b). The testing result shows that the fringe phase generally varies along the translation direction of the light source and increases with the lateral distance from the sample surface to the light source, and thus the fringe presents a bunch of parallel strips pattern. Whereas at the dent region circled in Figure 4, the fringe phase pattern shows a small abnormal area in which the phase edge gets anomalous. According to the

theoretical analysis, this can be because the sensitivity factor S_R is more sensitive to the lateral coordinates than the surface height ($\partial S_R/\partial R \approx 10\partial S_R/\partial z \approx 1$ illustrated as red colour in Figure 2), when the illumination is perpendicularly incident on the testing surface.

Figure 5 shows the experimental results with the light source located at the off-axis region (illumination angle $= 45^\circ$), and during this test, the perturbation to the speckle pattern is still the lateral translation of the light source ($50\ \mu\text{m}$). Compared to the fringe pattern in Figure 4, the fringe phase shown in Figure 5 varies prominently not only along the lateral direction, but also is very sensitive to the surface height variation, since a radical change on the fringe phase can be easily observed at the dent area (circled in Figure 5). This phenomenon agrees well with the above theoretical analysis, in which the sensitivity factor S_R is pointed out to be equally sensitive to the lateral coordinate and surface height ($\partial S_R/\partial R \approx \partial S_R/\partial z \approx 0.35$ illustrated as blue colour in Figure 2), when the testing surface is illuminated with a 45° incident angle and the perturbation is a lateral translation of light source. Therefore, compared to the on-axis

FIG. 7. (a) Laser speckle fringe pattern and (b) extracted phase of the fringe pattern obtained using DSPI via a perturbation of light source translation along axial direction. The flat testing surface with a superficial dent is illuminated with a 45° incident angle. Both axial and lateral distances between the light source and surface centre are about 10 cm.

FIG. 8. Unwrapped phase of the fringe pattern obtained via the translation of light source along lateral direction (a) and axial direction (b).

illumination, this off-axis illumination strategy provides mainly two advantages: 1. superficial feature/defect is more prominently reflected by the fringe phase pattern; 2. reconstruction of the 3-D surface form based on the fringe phase becomes more robust against the background noise and less affected by the lateral coordinate variation.

A similar test has also been carried out to evaluate the sensitivity factor S_z regarding the illumination locations at both paraxial and off-axis regions. Firstly, the light source was

positioned on the optical axis with a distance of 10 cm from the testing surface, and the fringe pattern was captured with an axial translation of light source $50\ \mu\text{m}$. Figures 6(a) and 6(b) show this speckle fringe pattern and its extracted phase, respectively. The fringe pattern presents a ring-shape which agrees well with Eq. (8), and the fringe phase does not show any prominent abnormality at the dent area. This is because the direction derivative of S_z along the lateral direction is about 10 times larger than that along the axial direction (illustrated as

FIG. 9. Extracted surface shape and feature from the fringe phases through the translations of light source along lateral direction (a) and axial direction (b); (c) 3-D surface shape of the testing sample obtained using a commercial coordinate measurement system (ALICONA InfiniteFocus).

the red colour in Figure 3 ($\partial S_z/\partial R \approx 10\partial S_z/\partial z \approx 0.1$), and thus the fringe phase is dominated by the lateral coordinate variation.

However, when the light impinges the testing surface with a 45° incident angle, the fringe pattern generated via axial light source translation (50 μm translation amount) also shows a radical phase change at the dent area (illustrated within the red circle in Figures 7(a) and 7(b)). This is also because that the sensitivity factor S_z is equally sensitive to the lateral coordinate and surface height ($\partial S_z/\partial R \approx \partial S_z/\partial z \approx 0.35$ illustrated as blue colour in Figure 3), which means the phase of the fringe would vary equally with both changes of lateral coordinate and surface height.

The test shows that the fringe pattern obtained by a DSPI system via translation of light source can be only sensitive to the surface height variation when the illumination source is positioned away from the optical axis. With this off-axis illumination, the DSPI system can be optimized to sensitively measure the small superficial dent through the fringe phase, and both the translations along lateral ($\vec{R}$) and axial ($\vec{z}$) directions can be used to generate a fringe pattern which is prominently sensitive to surface height variation. The phases extracted from both fringe patterns (Figures 6(b) and 7(b)) can be used for the re-construction of the 3-D surface shape as well as the superficial feature. Before the re-construction, the wrapped phases shown in Figures 6 and 7 are un-wrapped and illustrated as Figures 8(a) and 8(b), respectively. Based on Eq. (8), the un-wrapped phases can be used to re-construct the 3-D surface shape illustrated in Figures 9(a) and 9(b), respectively.

For further validation, a commercial coordinate measurement system (ALICONA, InfiTeFocus) has been utilized to obtain the 3-D profile of the testing surface. This commercial system is based on a focus variation technology,³⁸ with which a series of images are recorded along the vertical direction and the algorithm will recognize the sharpest image and thus retrieve the depth information of the testing surface. In this measurement, an entire volume of $12 \times 12 \times 6$ mm was scanned using this system within 2 h to obtain the topography of the testing surface (illustrated in Figure 9(c)) with a lateral resolution 7 μm and axial resolution 800 nm. The comparison in Figure 9 shows that the size of the superficial dent obtained via the DSPI system generally agrees with that obtained using the commercial system. But the result obtained by the ALICONA system presents more surface textures and features. There can be mainly two reasons for this: (1) the ALICONA system employs a $5\times$ objective lens to scan over the entire field; whereas the DSPI system only uses a normal imaging lens (Nikon AF 50/1.8D) for a full-field capturing. Therefore, the resolution of the DSPI system is much lower; (2) during the image processing, a low-pass filter has been applied to remove the high-frequency noise in the phase map, which could also smoothen the final re-constructed surface shape and result in the loss of texture information. However, the proposed methodology using DSPI system still can produce a fair surface contouring result. And importantly, this proposed methodology can measure the test surface through theoretically only two full-field recordings, whereas it takes hours for the ALICONA system to implement the scanning over the entire measurement field.

V. CONCLUSIONS

In this paper, we carried out a study to characterize and optimize the illumination vector for the contouring of surface shape and feature using the DSPI methodology. Through analysing the directional derivatives of the sensitivity factors, we found that both translations of illumination source along lateral and axial directions can effectively generate a fringe pattern which is sensitive to the surface height variation, and more importantly it is found that the phase of fringe becomes more sensitive to the surface height variation when the illumination source is located far from the paraxial region. This sensitivity of fringe phase to the height variation needs to be considered carefully when designing the DSPI system for small surface feature measurement. In order to validate the proposed theoretical analysis, experiments have been carried out using DSPI system with two illumination schemes: (1) illumination of 90° incidence; (2) illumination of 45° incidence. The experimental results found to correlate well with the proposed theory and the reconstruction based on the unwrapped phase of the fringe pattern have been illustrated. The obtained results were further compared by implementing the measurements using a commercial 3-D coordinate measurement system. It is demonstrated that the proposed whole field methodology is fairly effective and less time consuming for shape measurement and feature extraction.

ACKNOWLEDGMENTS

This work was conducted within the Rolls-Royce@NTU Corporate Lab with support from the National Research Foundation (NRF) Singapore under the Corp. Lab@University Scheme. The authors are also grateful for the support from COLE EDB funding.

- ¹E. Savio, L. De Chiffre, and R. Schmitt, *CIRP Ann.—Manuf. Technol.* **56**, 810–835 (2007).
- ²R. B. Bergmann, T. Bothe, C. Falldorf, P. Huke, M. Kalms, and C. von Kopylow, *Proceedings* 779102 (2010).
- ³D. J. Whitehouse, *Meas. Sci. Technol.* **8**, 955–972 (1997).
- ⁴N. K. Krishna Mohan, P. J. Masalkar, V. M. Murukeshan, and R. S. Sirohi, *Opt. Eng.* **33**, 2402–2409 (1994).
- ⁵V. M. Murukeshan, N. Sujatha, and A. R. Ganesan, *J. Hologr. Speckle* **1**, 63–68 (2004).
- ⁶J. Zhang, *Opt. Eng.* **37**, 1785–1789 (1998).
- ⁷A. Kishen, V. M. Murukeshan, V. Krishnakumar, and A. Asundi, *J. Dent.* **29**, 531–537 (2001).
- ⁸F. Labbe, R. R. Cordero, A. Martínez, and R. Rodríguez-Vera, *Meas. Sci. Technol.* **16**, 1677–1683 (2005).
- ⁹M. V. Matham and N. Sujatha, *Appl. Opt.* **43**, 2400–2408 (2004).
- ¹⁰L. Yang and A. Ettemeyer, *Opt. Eng.* **42**, 1257–1266 (2003).
- ¹¹N. Sujatha, V. M. Murukeshan, S. Rajendran, L. S. Ong, and L. K. Seah, *Nondestr. Test. Eval.* **20**, 25–34 (2005).
- ¹²D. Francis, D. Masiyano, J. Hodgkinson, and R. P. Tatam, *Meas. Sci. Technol.* **26**, 1–7 (2015).
- ¹³J. N. Petzing and J. R. Tyrer, *J. Strain Anal. Eng. Des.* **33**, 153–169 (1998).
- ¹⁴J. R. Huang, H. D. Ford, and R. P. Tatam, *Opt. Lasers Eng.* **27**, 321–333 (1997).
- ¹⁵C. Joenathan, B. Franze, P. Haible, and H. J. Tiziani, *Appl. Opt.* **37**, 3385–3390 (1998).
- ¹⁶C. Joenathan, B. Pfister, and H. J. Tiziani, *Appl. Opt.* **29**, 1905–1911 (1990).
- ¹⁷A. R. Ganesan and R. S. Sirohi, *Proc. SPIE* **954**, 327–332 (1989).
- ¹⁸R. S. Sirohi, A. R. Ganesan, and M. P. Kothiyal, *Proc. SPIE* **952**, 0952 (1989).
- ¹⁹K. Genovese, L. Lamberti, and C. Pappalettere, *Opt. Lasers Eng.* **42**, 543–562 (2004).

- ²⁰R. M. Groves, S. W. James, and R. P. Tatam, *Opt. Lasers Eng.* **41**, 621–634 (2004).
- ²¹Y. M. He, C. J. Tay, and H. M. Shang, *Opt. Eng.* **38**, 662–671 (1999).
- ²²L. S. Wang, K. Jambunathan, B. N. Dobbins, and S. P. He, *Opt. Eng.* **35**, 2333–2340 (1996).
- ²³L. S. Wang and S. Krishnaswamy, *Meas. Sci. Technol.* **7**, 1748–1754 (1996).
- ²⁴A. Anand, R. M. Groves, X. Schwab, G. Pedrini, and W. Osten, *Proc. SPIE* **6617**, 66170Q (2007).
- ²⁵P. K. Rastogi and L. Pflug, *J. Mod. Opt.* **38**, 1673–1683 (1991).
- ²⁶D. Paoletti, G. Schirripa Spagnolo, C. Carelli, and A. D’Altorio, *J. Opt.* **21**, 247–251 (1990).
- ²⁷P. DeMattia and V. Fossati-Bellani, *Opt. Commun.* **26**, 17–21 (1978).
- ²⁸M. Yonemura, *Appl. Opt.* **21**, 3652–3658 (1982).
- ²⁹C. J. Tay, H. M. Shang, A. N. Poo, and M. Luo, *Opt. Laser Technol.* **24**, 209–213 (1992).
- ³⁰C. J. Tay, F. S. Chau, H. M. Shang, V. P. W. Shim, and S. L. Toh, *Opt. Lasers Eng.* **14**, 13–24 (1991).
- ³¹D. Francis, R. P. Tatam, and R. M. Groves, *Meas. Sci. Technol.* **21**, 102001 (2010).
- ³²C. Song, M. V. Matham, and K. H. K. Chan, *Proc. SPIE* **9524**, 95242P (2015).
- ³³J. Burke, T. Bothe, W. Osten, and C. Hess, *Proc. SPIE* **4778**, 312–324 (2002).
- ³⁴V. M. Murukeshan, O. L. Seng, and A. Asundi, *Opt. Laser Technol.* **30**, 527–531 (1998).
- ³⁵K. Qian, F. Shu, and X. Wu, *Meas. Sci. Technol.* **11**, 1220–1223 (2000).
- ³⁶A. Chernyshov, U. Sterr, F. Riehle, J. Helmcke, and J. Pfund, *Appl. Opt.* **44**, 6419–6425 (2005).
- ³⁷N. I. Chkhalo, A. Y. Klimov, V. V. Rogov, N. N. Salashchenko, and M. N. Toropov, *Rev. Sci. Instrum.* **79**, 6419–6425 (2008).
- ³⁸R. Danzl, F. Helmli, and S. Scherer, in *Proceedings of 10th International Conference of the Slovenian Society for Non-Destructive Testing: Application of Contemporary Non-Destructive Testing in Engineering* (2009).