ROBUST SPECKLE METROLOGY

Techniques for Stress Analysis and NDT

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Preface

The invention of the laser in the early 1960s allowed for light sources with a high coherence degree, which generated many novel research lines in order to make use of them. People working with these light sources noticed that a high-contrast and fine-scale granular pattern was produced when a rough surface was illuminated with laser light. This effect was called a "speckle effect," characterized by a random distribution of scattered light. After recognizing that each speckle has a definite phase, several techniques were developed to measure deformations, displacements, stresses, vibrations, and inner defects.

Several multiauthor books have been published beyond the first one published in 1978 (*Speckle Metrology*, edited by R. K. Erf)—including *Digital Speckle Pattern Interferometry and Related Techniques*, edited by P. K. Rastogi, and *Advances in Speckle Metrology and Related Techniques*, edited by G. H. Kaufmann—show new branches in speckle metrology, new proposed schemes and improvements in processing techniques, and optical approaches that have occurred over the last 20 years.

The main goal of nondestructive testing (NDT) is to detect and characterize anomalies that can adversely affect the performance of the component under test without impairing its intended service.

Optical techniques can be considered as alternative approaches to traditional NDT methods. They are very attractive for NDT due to their noncontacting nature and their high relative speed of inspection. The application of digital techniques allows for automatic processing. Consequently, a fast inspection procedure enables the evaluation of large areas (e.g., aircraft wings and ship structures) or a large number of parts (e.g., automotive components). Speckle techniques have the advantages cited for optical methods. Additionally, they are appropriate for the evaluation of real components without further preparation of the surface or time-intensive analysis.

This book provides tips, ideas, and examples for the successful application of optical techniques (more specifically based on the speckle phenomenon) outside the laboratory room. Readers can see that the topics presented in the following nine chapters have been selected to benefit graduate students, engineers, and scientists who are interested in the in-field application of speckle techniques to solve specific problems related to optical metrology, experimental mechanics, and NDT.

Chapter 1 discusses aspects to consider when designing mechanical parts and structures for safe and reliable products because several applications are usually related with human life and ecology. This chapter also shows that the working conditions influence the performance and mechanical integrity of the part. This influence can sometimes cause an accident due to a lack of corrective actions. For this reason, the chapter highlights the use of NDT to foresee possible accidents and focuses on optical techniques, especially speckle methods.

Chapter 2 addresses the theoretical aspects of the origin and formation of the speckle phenomenon. The most important principles for speckle interferometry are then developed, showing how the phase of the speckle distribution carries essential information for measuring displacements fields, object shapes, etc. For this reason, several tools to quantify the phase of the speckle distribution are presented, as well as the phase-unwrapping principles that are used to deal with 2π jumps obtained after the use of phase-shifting techniques.

Chapter 3 presents traditional digital-speckle-pattern-interferometry (DSPI) optical configurations used to measure displacement fields and their derivatives. Measurements are divided into (a) out-of-plane and (b) in-plane displacements. For the former, the working principle is presented, as well as a possible laboratory optical setup. For the latter, traditional interferometers with in-plane sensitivity are presented; radial, in-plane interferometer setups capable of measuring polar coordinates are also presented. Finally, principles for shearography are shown.

Chapter 4 gives a more-detailed description of the requirements for robust optical setups. The chapter offers tools, tips, and reference parameters to guide the development and design of interferometers based on the speckle phenomenon for use outside of the laboratory. Additionally, various environment agents are described, showing the effect that they have on the measuring performance of the optical system.

Chapter 5 discusses the application of DSPI to measure mechanical stresses as an auxiliary tool for structural integrity assessment. After a short introduction, the principles for traditional strain-gage sensors are presented. Some interferometric solutions are shown in order to measure 3D displacements (along three sensitivity directions) and displacements in polar coordinates. For the latter, several tips are listed for the measurement of large strain fields without loss of correlation. Finally, an application example shows the effectiveness of the proposed solution.

Many service failures of structural or mechanical components are caused by a combination of residual stress fields in the material and mechanical stresses produced by applied loads. For this reason, Chapter 6 provides experimental solutions to compute residual stresses. The traditional method combines strain gages with the hole-drilling technique. In this case, a small hole is introduced into the material, allowing for local stress relief that enables stress measurements. The chapter also explores a combination of the hole-drilling technique and DSPI. A practical application outside the laboratory is described, showing the high potential of the technique as an integrity-evaluation tool.

Chapter 7 begins with a list of the traditional nondestructive techniques used in defect detection. The chapter highlights shearography as a NDT tool with important applications in the automotive, aeronautical, and petroleum and gas industries. Several optical configurations suitable for in-field applications are presented. One of the most important components in a shearographic device is the loading/excitation setup. For this reason, several possible methods are described. Finally, applications in some industries, mechanical parts, and structures are shown. Available commercial systems highlight the fast growth of shearography as a NDT technique. Some significant commercial devices are illustrated in this chapter.

Previous chapters address principles, optical setups, and application examples for interferometric techniques based on the speckle phenomenon. Another optical speckle technique that has grown quickly over the last two decades is digital image correlation (DIC), which is considered a noninterferometric technique. A short review of the available literature about this technique is presented in Chapter 8, which is oriented to NDT applications.

Finally, Chapter 9 briefly discusses all of the presented techniques to help readers select the best optical setup for their needs, or, beyond that, develop new solutions (for those cases where there are none) to measure a specific measurand.

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Florianópolis, Brazil *Matias R. Viotti*
August 2014 *Armando Albertazzi, Jr.*

List of Symbols and Notation

A	Cross-sectional area of a uniform conductor
$\mathbf{A}_i$	Camera calibration matrix
$\overline{a}_{ij}$, $\overline{b}_{ij}$	Matrices of calibration coefficients
AFM	Atomic force microscopy
AOM	Acousto-optical modulator
AOV	Angle of view of the camera
ASTM	American Society for Testing and Materials
atan2	Full four-quadrant arctangent function
b	Diameter of the aperture
BS	Beamsplitter
$\mathbf{c}$	Matrix operator that acts over the curvature of the solution for nonuniform residual stresses
CASI	Computer-aided speckle interferometry
C_{Ax}	External axial load
CCD	Charge-coupled device
CFRP	Carbon-fiber-reinforced polymer
CMOS	Complementary metal–oxide semiconductor
CT	Computed tomography
$\mathbf{d}$	Displacement vector
$\mathbf{d} = [u, v, w]$	Displacement vector at point P
d_f	Diameter of the conductor after application of the strain
DIC	Digital image correlation
d_o	Diameter of the conductor before the application of the strain
DOE	Diffractive optical element
$\mathbf{d}_{opt}$	Optimal displacement vector
$\mathbf{d}(\mathrm{P}')$	Displacement vector at point P′
DPSS	Diode-pumped solid state
DSCM	Digital speckle correlation method
d_{sp}	Averaged speckle size
DSPI	Digital speckle pattern interferometry
$(d_{sp})_{obj}$	Size of the speckle on the illuminated object
dx, dy	Distances between adjacent pixel in the x and y directions

$d\tau$	Time interval between successive registrations
E	Modulus of elasticity
ESPI	Electronic speckle pattern interferometry
f	Focal length of the optical system
F	Reference image
$\overline{F}$	Medium value for the subset
F_b	Numerical aperture of the optical system
$F_1 \ldots F_n$	Set of external loads
G	Image after displacement
$\overline{G}$	Medium value for the subset
G_e	Geometric factor associated with the directions of illumination and observation
GLARE	Glass-reinforced aluminum laminate
GPGPU	General-purpose computing on graphics processing unit
G_r	Modulus of elasticity in shear (also known as the modulus of rigidity)
$H_0(r_s)$	Zero-order Fourier coefficient
$H_1(r_s)$	First-order Fourier series coefficient
$H_2(r_s)$	Second-order Fourier coefficient
$H_{nS}(r_s)$	Total magnitude of the n^{th} harmonic
$H_{nS}(r_s)$, $H_{nC}(r_s)$	Sine and cosine components, respectively, of the n^{th} Fourier series coefficient
$\hat{\mathbf{i}}$, $\hat{\mathbf{k}}$	Unitary vectors for the x and z directions, respectively
I_0	Averaged (or background) intensity
I_{0f}	Averaged correlation intensity
I_1, I_2	Intensities of the interfering beams
I_{12}	Subtraction of the intensities of the interfering beams
I_c	Cosine intensity obtained from the wrapped difference phase map $\Delta\phi_w(m, n, t_1, t_2)$
IEEE	Institute of Electrical and Electronics Engineers
Im	Imaginary part
I_M	Modulation intensity
I_{ner}	Moment of inertia of the section
IR	Infrared
I_s	Sine intensity obtained from the wrapped-difference phase map $\Delta\phi_w(m, n, t_1, t_2)$
$\mathbf{k}$	Sensitivity vector
K_0, K_x, K_y	Constant fitting values of the bending plane
K_{0R}, K_{1C}, K_{1S}, K_{2C}, K_{2S}, K_0	Least-square fitting coefficients
K_{11} to K_{66}	Coefficients of elasticity of the material
k_c	Multiplicative constant for a speckle distribution
$\mathbf{k}_i$	Wave-propagation vectors corresponding to the illumination direction

$\mathbf{k}_o$	Wave-propagation vectors corresponding to the observation direction
L	Length of a uniform conductor
$l_0 \times l_0$	Cross-section of the illuminated area
l_f	Final length of the bar
l_o	Initial length of the bar
LUS	Laser ultrasound
M	Bending moment applied to the beam
M_1	45-deg mirror in the radial interferometer
M_2	Mobile mirror in the radial interferometer
M_3	Fixed mirror in the radial interferometer
M_g	Magnification of the optical system
M(T)	Middle-crack tension
(n, m, t)	Nondimensional coordinates of the discrete image
$\mathbf{n}_A$, $\mathbf{n}_B$	Illumination unitary vectors
NDT	Nondestructive testing
NINT	Rounding to the nearest integer
$N_n \times N_m$	Sensor pixel number (horizontal and vertical)
$\hat{\mathbf{n}}_o$, $\hat{\mathbf{n}}_i$	Unitary vectors
NSSD	Normalized sum of square difference
N_t	Number of successive acquired images
OMS	Optical measurement system
OPA	Operational amplifier
OPD	Optical path difference
$\mathbf{p}$	Parameter vector of the shape function
p, q, t	Combination variables between the strains ε_1, ε_2, and ε_3
P	Equal-biaxial stress
P_1, P_2	Points at the illuminated surface
P_1, P_2	Unwrapping paths
p_r	Period of the grating structure
PZT	Piezoelectric translator
Q	45-deg shear stress
$Q(x, y)$	Points at the imaging plane
q_{mult}	Multiplying factor
$\mathbf{r}$	Position vector
r, θ	Polar coordinates
R	Resistance of a uniform conductor
r_0	Radius of the hole
R_e	Real part
r_{ex}, r_{in}	External and internal radius, respectively, of the pipe
$\mathbf{r}_i$	Curvature center of the incident wavefront
$\mathbf{R}_i$	Rotation matrix
$\mathbf{r}_o$	Position vector of the observation point
ROI	Region of interest

r_s	Sampling radius
s	Scale factor
S	Scattering surface
S_A	Sensitivity of the metallic alloy used as a conductor
SAE	Society of Automotive Engineers
SAW	Submerged arc welding
SEM	Scanning electron microscopy
SG	Strain gage
sgn I	sign[$I(1) - I(2)$] for the Carré algorithm
sig	Sign function
SLM	Spatial light modulator
SNR	Signal-to-noise ratio
s_{OPD}	Optical path difference
SSD	Sum of squared deviations
T	Shear stress
t_1, t_2	Time for the first and second interferogram acquisition
$\mathbf{T}_i$	Translation vector
u	Component of the displacement field along the x direction
$(u_1, v_1, 1)$, $(u_2, v_2, 1)$	Image coordinates for both cameras
UOE	U-shape, O-shape, and expansion (pipe-fabrication process)
u_r	Radial component of the in-plane displacement
USB	Universal serial bus
u_t	Amount of uniform rigid-body translation
V	Fringe visibility or contrast
VDIC	Volumetric digital image correlation
V_f	Correlation fringe visibility or contrast
V_r	Radial phase variation around a pixel
w	Component of the displacement of the object surface along the z direction
$w(\mathbf{x})$	Weighting function
$\mathbf{x}(x, y)$	Coordinates on the observation plane
(x, y, z)	Cartesian coordinates
$(x_{c1}, y_{c1}, z_{c1}, 1)$, $(x_{c2}, y_{c2}, z_{c2}, 1)$	Homogenous coordinates corresponding to point Q in camera 1 and camera 2, respectively
$(x_w, y_w, z_w, 1)$	Homogeneous coordinates in the world coordinate system
y	Distance from the neutral line
z	Distance between the screen where the scattered light is gathered and the object
z_i	Distance between the aperture and the imaging plane
ZNSSD	Zero-normalized sum of squared differences
z_o	Distance from the object to the aperture
ZSSD	Zero-mean sum of squared differences

α	Angle that defines the translation direction
α_P, α_Q, α_T	Factors to control of the amount of regularization
α_t	Relative phase shift between acquired interferograms
γ	Illumination angle
Υ	Wrapping operator
γ_1, γ_2	Illumination angles for an in-plane interferometer
γ_{ij}	Shear strains being $i = x, y,$ or z and $j = x, y,$ or z
Δ	Change in the parameter
$\Delta\mathbf{d}$	Displacement difference
Δl	Change of the length
δ_{NL}	Angle of the neutral line
ΔOPC	Optical path change generated by the PZT displacement
ΔPZT	Displacement of the piezoelectric transducer
$\Delta\mathbf{r}$	Displacements of the scattering surface
Δs_{OPD}	Optical path difference
δx	Lateral shift in shearography
$\delta_{\sigma max}$	Angular position of the maximum stress axis
$\Delta\varphi$	Variation of the phase of the speckle in the object beam produced by the displacements of the diffuser
$\Delta\phi$	Variation in the phase difference
$\Delta\phi(m,n)$	Wrapped phase to be determined
$\Delta\phi_w(n,m)$	Measured wrapped phase
ε_1, ε_2	Principal strains
ε_1, ε_2, ε_3	Measured strains by gages 1, 2, and 3 (see Fig. 6.2)
ε_i	Normal strains, being $i = x,\ y,$ or z
$\zeta(\mathbf{x}, \mathbf{p})$	Subset function
η	Principal angle (for mechanical stresses)
λ	Wavelength of the illumination source
ν	Poisson ratio
ξ	Diffraction angle for the m-order
$\xi(x, y)$	Surface height at (x, y)
ρ	Specific resistance of a uniform conductor
σ	Normal stress
σ_1, σ_2	Principal stresses
σ_B	Bending stress
σ_C	Stress along the circumferential direction
σ_L	Stress along the longitudinal direction
$\sigma_L(x,y)$	Longitudinal stress component measured in each angular point
τ	Shearing stress
τ	Time on the observation plane
φ	Phase of the speckle
ϕ	Relative phase between the interfering beams
φ_1, φ_2	Phases of the interfering wavefronts

ϕ_i^E	Phase value for the i^{th} pixel on the external circle
ϕ_i^I	Phase of i^{th} pixel on the internal circle
φ_s	Random component of the phase of the speckle
ϕ_w	Wrapped phase
χ	Angle of the conical mirror
$\chi(\mathbf{p})$	Cost function
ψ	Deterministic component of the phase of the speckle
ψ_i	Initial optical phase
ψ_o	Object phase
$\Omega(\mathbf{r})$	Complex amplitude at each point in a speckle pattern
ω_i	Complex amplitude of the incident light in (x, y)