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Episcopic coaxial illumination device for the simultaneous recording of the speckle signature in the spectrum and in the image of scattering reflective surfaces

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ABSTRACT

Inspection of optically rough surfaces in search of defects or other surface features with deterministic reflectance distributions is a subject well suited to optical techniques. We present a device with episcopic coaxial illumination, specifically developed for such kind of inspection tasks, which simultaneously renders both a coherent image and the spatial spectrum of a portion of the surface, precisely defined by the illuminating laser spot. It is based on the well-known single-lens coherent image processing system, with beamsplitters added to insert the illuminating laser beam and to allow simultaneous access to the Fourier transform and the image planes. The device allows inspecting the speckle signature of surface features in both planes, thus allowing different defect recognition approaches. By selecting the size of the illuminated area of the object or the lens aperture, different speckle sizes can be obtained. If the speckle size is made large enough, identification of individual features can be made on the basis of their particular speckle signatures. Some envisaged applications are the characterization of defects or structures in rough surfaces, the evaluation of speckle statistics in precisely defined zones of surfaces or the identification of authentication marks.

Keywords: reflective scattering surface, optical Fourier transform, speckle signature, authentication.

1. INTRODUCTION

When a defect is present in a coherently illuminated area of an optically rough reflective surface, the scattered light distribution encodes information about the defect and also about the roughness of the surrounding surface. Since the invention of laser, many attempts have been made to extract surface roughness and defect features by exploiting different optical configurations, usually contrived to render the spectrum of the scattered radiation\textsuperscript{1-8}. In most cases, speckle is present in the whole space downstream from the scatterer, and it sometimes constitutes a kind of noise which must be filtered, but other times speckle is precisely the desired signal. For example, authentication speckle-based schemes are nowadays subject of research\textsuperscript{9}, taking advantage of the strong dependence of the scattered optical field on the particular microscopic features of the illuminated surface.

We present a device which simultaneously renders a coherent image and the energy spectrum of a small portion of the surface of reflective objects. The intended application is to perform inspections for characterizing defects, authentication tasks or even the analysis of surfaces through the scattered fields, following a parametric approach as an alternative to the profiling techniques. In our knowledge, the proposed illumination-observation configuration was not yet reported for such applications and it may constitute an interesting option when small portions of the surface must be precisely illuminated, and a certain control of the speckle size is desirable.

2. OPTICAL SYSTEM ARCHITECTURE

The architecture of the device is depicted in Fig. 1. It corresponds to the single-lens coherent image processing system (Ref. 10, p. 477), with the addition of two non-polarizing cube beamsplitters: the first one to coaxially introduce the episcopic illumination laser beam, and the second one to allow simultaneous access to the Fourier transform plane and to the image plane. For a collimated input beam, the curvature center $C$ of the wavefront reaching the object coincides

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approximately with the lens focal point $F$, but $C$ can be displaced at will by changing the input beam curvature.

3. MODEL FOR THE SPECTRUM ANALYZER AND THE IMAGING PROCESS

3.1 Spectrum analyzer

We follow the classical Fourier Optics model considering a harmonic field $V_0(r,t) = e^{-i\omega t}$, where $V_0(r)$ is the complex amplitude. The distances (Figs. 1 and 2) are named as $z_{\text{ol}} = z_L - z_o$, $z_{\text{cl}} = z_L - z'_{\text{c}}$, etc. Under the assumptions:

(H1) Fresnel diffraction conditions apply to the propagation between planes $z_o \rightarrow z_L$ and $z_L \rightarrow z_s$; (H2) quadratic-phase approximation applies to the incident spherical wave at the plane $z_o$; (H3) incident wavefront on the object has uniform modulus, and (H4a) distance $z_{\text{ol}}$ is sufficiently small that the effect of the lens aperture can be described by its geometric backprojection onto the object plane, the field amplitude $V_s$ at the plane $z_s$, conjugate of $z'_{\text{c}}$, is (Ref. 10, p. 418)

$$V_s(x_s,y_s) = V_0(z_{\text{cl}}) \exp\left(\frac{ikz_{\text{ol}}}{z'_{\text{cl}}}\right) \exp\left[\frac{ik(x_s^2 + y_s^2)}{2z_{ls}}\right] \left[1 + \frac{z_{\text{ol}}}{z_{ls}} \frac{z_{ls}}{z_{ls}'} \right]$$

(1)
where \( V_o^- \) is the complex amplitude of the field just before reaching the object, \( k = 2\pi/\lambda \) the wavenumber, \( B_L \) a lens transmission coefficient that accounts for the optical thickness of the lens at its center and any losses, \( p_L \) the lens aperture function, and \( R_o \) the complex amplitude reflection coefficient of the object, which comprises the effect of different factors including the object pupil function (which can also specify a limited illumination field), the illumination and observation directions, the surface microtopography —i.e., the height \( h(x_o, y_o) \) of the surface points with respect to a reference plane—, multiple scattering, and shadowing. In a first approach, under normal incidence and observation, the following expression applies in many cases of practical interest:

\[
R_o(x_o, y_o) = \text{Constant} \times \exp\left[2khi_b(x_o, y_o)\right]
\]  

(2)

If, instead of (H4a), we suppose that (H4b) lens aperture is large enough to collect all the light diffracted by the object, then \( p_L(x, y) = 1 \) and (1) becomes (Ref. 10, p. 412)

\[
V_i(x, y) = V_0^- \frac{z'_{cl}}{z'_{co}} \exp(ikz_{cl})B_L \frac{\exp(ikz_{ls})}{i\lambda z_{ls}} \exp\left[\frac{ik(x_o^2 + y_o^2)}{2z_{ls}}\left(1 - \frac{z'_{cl}z_{cl}}{z'_{co}z_{ls}}\right)\right] R_o\left(\frac{z'_{cl}x}{\lambda z_{co}}, \frac{z'_{cl}y}{\lambda z_{co}}\right)
\]

(3)

where the tilde (\( \sim \)) stands for Fourier transform. So, the optical field at the plane \( z_s \) is, excluding a quadratic phase term, proportional to the spectrum, \( \tilde{R}_o(\nu_x, \nu_y) \), of \( R_o(x_o, y_o) \). This spectrum would coincide with the angular spectrum of the wavefront reflected from the object if a collimated illumination would be employed, and the spatial frequencies would be then (in the paraxial approximation) \( \nu_x = \theta_x/\lambda, \quad \nu_y = \theta_y/\lambda \), where \( \theta_x, \theta_y \) are the angles between the propagation direction of a plane-wave component and the planes \( YZ, XZ \) respectively. However, in our case, as a spherical incident wavefront is employed, the spatial frequencies \( (\nu_x, \nu_y) \) are related to the deflection angles with respect to the incident rays coming from the virtual source \( C' \), which form angles \( \theta_{OX}, \theta_{OY} \) with the planes \( YZ, XZ \). Therefore, in the paraxial approximation,

\[
\nu_x = \frac{z'_{cl}}{\lambda z_{co}} x - \frac{\theta_x}{\lambda}, \quad \nu_y = \frac{z'_{cl}}{\lambda z_{co}} y - \frac{\theta_y}{\lambda}
\]

(4)

The ray tracing construction of Fig. 2 illustrates how all the rays deflected an angle \( \lambda \nu \) [for instance, \( \lambda \nu_{av}(D_o/2) \)] with respect to the incident ray at a generic object point \( P_o(\rho_o) \) [i.e., \( P_o(D_o/2) \) or \( P_o(0) \)] impinge in a same point \([x_o, y_o]\) with \( \rho_o = (x_o^2 + y_o^2)^{1/2} \) the radial coordinate of \( P_o(\rho_o) \). From the figure, the existence of vignetting of the spectrum is clear, due to the effects of the object finite size and the diverging illumination. We deduced the maximum, \( \nu_{av}(\rho_o) \), and minimum, \( \nu_{av}(\rho_o) \), values of the maximum spatial frequency that can be collected by the aperture stop from a generic point \( P_o(\rho_o) \) of the object:

\[
\nu_{av}(\rho_o) = \frac{D_L}{2\lambda z_{cl}} \left[ 2\rho_o + \frac{z_{cl}}{z_{co}} \right], \quad \nu_{av}(\rho_o) = \frac{D_L}{2\lambda z_{cl}} \left[ 1 - 2\rho_o - \frac{z_{cl}}{z_{co}} \right]
\]

(5)

From (5), a criterion to minimize the vignetting of the spectrum is to make small both the object size–aperture diameter ratio \( D_o/D_L \) and the distances ratio \( z_{cl}/z_{co} \). The value of \( D_o \) is given by

\[
D_o = \frac{z_{co}}{z_{cl}} \text{min}(D_o, D_L)
\]

(6)

### 3.2 Imaging process

Under the assumptions: (H5) quadratic-phase approximation at the lens plane \( z_l \) for a spherical wave emanating from a point \((x_o, y_o)\) at the object plane; (H6) diffraction-limited lens; (H7) Fresnel diffraction conditions apply to propagation between planes \( z_l \rightarrow z_s \), and (H8) object size \( D_o \) smaller than \( D_L/4 \), the coherent image formation can be described as a convolution (Ref. 12, p. 113):

\[
V_i(x, y) = \text{Constant} \times \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} V_{og}^*(x, y) h_{oi}(x - x, y - y) \, dx \, dy
\]

(7)

with
\[ V_{\text{sc}}(x,y) = \frac{1}{|m|} V_0^\dagger \left( \frac{x}{m} \cdot \frac{y}{m} \right), \quad m = -\frac{z_{li}}{z_{ol}}, \quad h_{al}(x,y) = \int p_L(\alpha,\beta) \exp \left[ -\frac{ik}{z_{li}} (\alpha x + \beta y) \right] d\alpha d\beta \] (8)

where \( V_{\text{sc}} \) is the scattered field amplitude just above the object, \( m \) the magnification and \( h_{al}(x,y) \) the impulse response.

3.3 Speckle size

The lateral \( \varepsilon_{\rho i} \) and longitudinal \( \varepsilon_{zi} \) speckle sizes in the image plane \( z_i \) can be deduced from the correlation of the speckle intensities (Ref. 11, p. 79-84). Taking the criterion of the first minimum in the correlation, the speckle size is

\[ \varepsilon_{\rho i} = 1.22 \frac{z_{li}}{D_L}, \quad \varepsilon_{zi} = 8 \lambda \left( \frac{z_{li}}{D_L} \right)^2 \] (9)

On the other hand, although the spectrum of wavefronts reflected from rough surfaces is a common subject, it is not easy to find an estimation of the speckle size in the spectrum when it is obtained in other locations than the focal plane of the transforming lens. A feasible expression found in the literature \(^{13}\) does not agree with our results (see subsection 4.2).

![Figure 3](image-url)

Figure 3. (a) Series of images of a same portion of a Ronchi ruling with spatial frequency 11.81 mm\(^{-1}\), recorded with the illumination stop full open \((D_u = 12 \text{ mm})\), but with different aperture stop diameters \(D_L\). (b) Same than (a) with more laser power, for enhancing low light-level regions. (c) Energy spectra, each one corresponding to the scene in the same column, obtained as the irradiance at the Fourier transform plane. Actual scene size (a) and (b): 0.84\( \times \)0.84 mm\(^2\); Frequency plane size (c): 288\( \times \)288 mm\(^{-2}\).

4. RESULTS

4.1 Calibration

In order to calibrate the system, a precisely manufactured object with a well-known and sufficiently broad spectrum was employed. Specifically, we selected a Ronchi ruling made on glass with spatial frequency 300 line pairs per inch (11.81 mm\(^{-1}\)). Images and spectra for different aperture stop diameters are presented in Figure 3. From them, we measured the image magnification \( m = -7.87 \) (full size of the scene 1.12\( \times \)0.84 mm\(^2\)), and the spatial frequency scale in the spectrum, \( \nu_x/\nu_y = 59.7 \text{ mm}^{-1}/\text{mm} \) (full size of the frequency plane 386\( \times \)288 mm\(^2\)). Both measured values are compatible (within 4\%) with the values of the same quantities calculated from the distances directly measured in the prototype.
Correcting these distances with the calibration data, we finally obtained the values $z_{cl} = 50.0$ mm, $z'_{co} = 6.3$ mm, $z_{cl} = 56.3$ mm, $z_{L} = 443$ mm, $z'_{cl} = 62.6$ mm, and $z_{L} = 253$ mm. The input beam is the collimated output of a SM fiber optic coupled diode laser of wavelength $\lambda = 658$ nm. It has a gaussian profile with diameter $D_b = 5.2$ mm at $e^{-2}$ relative intensity. From Figs. 3 and 4, it is clear that the range of measurable spatial frequencies, $\nu_M(\rho_o)$, is roughly proportional to $D_L$ and only
increases marginally when $D_o$ increases. This result is congruent with (5) and (6) and also the theoretical values $ν_M(0)$ calculated with (5) are in agreement with the experimental ones, measured as half the size of the irradiance distributions in the spectra obtained with $D_u = 1$ mm, Fig. 4f.

### 4.2 Lateral speckle size

From the data of Fig. 4, we confirmed the theoretical value (9) for the lateral speckle size in the image. As the theory predicts, this size increases when reducing the aperture stop size $D_L$ and does not depend on the size $D_o$ of the illuminated area of the object. On the other hand, the lateral speckle size in the spectrum (Fig. 4) does not depend on $D_L$ (as long as the variations of $D_L$ do not affect the value of $D_o$) and increases when reducing $D_o$. This behavior does not correspond to the one predicted in Ref. 13 and further work is necessary to clarify the question.

### 5. CONCLUSIONS

We presented a variant of the single-lens coherent image processing system, specifically contrived to perform inspection and identification tasks of opaque reflective surfaces. The employment of coherent, precisely shaped, episcopic illumination allows simultaneously obtaining both the image of a well defined portion of the object surface and the spectrum of the complex reflection coefficient distribution of this portion. The employment of a single lens is advantageous in terms of minimizing the number of optical surfaces that can contribute to coherent noise (parasitic reflections, dust). The simple and compact architecture of the system allows its use for field operation.

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