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REMOTE SENSING OF SURFACE STRUCTURES

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Abstract: The current technical set-up of speckle interferometry is based on temporal phase-shifting with a single CCD camera, which requires a vibration-isolated environment. In order to apply the phase-shifting technique to an industrial environment, without any vibration isolation, four phase-shifted speckle images are simultaneously acquired by means of four cameras. In order to achieve this aim we use four parallel speckle interferometers. The appropriate phase differences between the beams are realized by variable path differences employing movable prisms. This new laboratory set-up demonstrates the feasibility and the applicability of long-range surface structure, surface deformation and surface profile measurements. The change of surface structure, caused e. g. by erosion, influences the fringe contrast of the interference fringes and their visibility of the phase-shifting method. An additional modelling of the quadruple speckle interferometer using a ray tracing simulation program demonstrates the dependence of the fringe contrast on surface structure modifications in the nanometer scale. The ray tracing method takes into account the effects of polarization, diffraction and interference. Measurement results verify the detectability of eroded surface areas.

Keywords: speckle interferometry, spatial phase shifting, multichannel set-up, simulation, ray tracing, erosion

1 INTRODUCTION

Recent progress in photonic measurements is based on the development of miniature lasers, digital cameras and advanced image acquisition systems. Moreover, sophisticated optical set-ups enable the measurement of an increasing number of parameters of technical objects. An increasingly powerful measurement technology emerges from optical engineering [1].

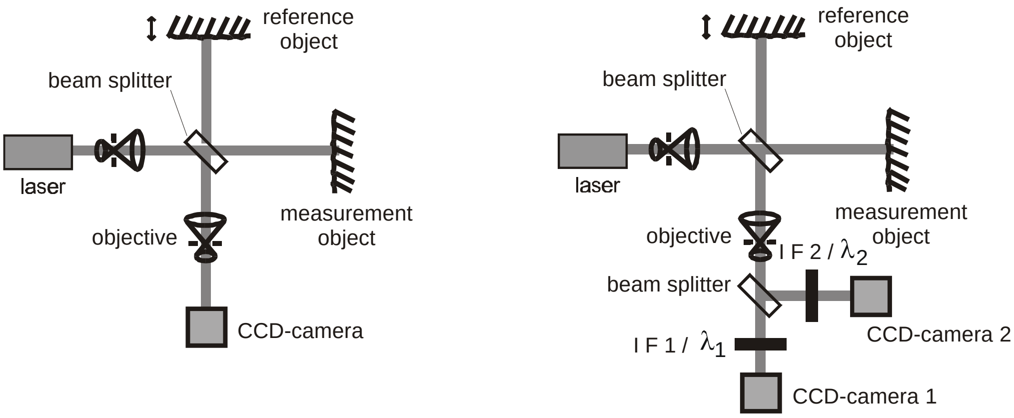
Speckle interferometry is of major importance for the measurement of technical surfaces, i.e. surfaces having a surface roughness in the order of the applied optical wavelength [2, 3]. Illuminating a rough surface with a beam of coherent light – a laser beam – results in a typical speckle pattern containing relevant surface information of the statistical phase variation of the detected image. In order to retrieve, e.g. the surface deformation, the measurement object of interest represents a reflecting surface in an interferometer set-up, while the phase of a reference beam has to be shifted [4, 5, 6]. This procedure can be performed at a fixed wavelength or at two or more wavelengths simultaneously. Detectable surface deformations range from some 100 nm to several cm [7, 8, 9, 10].

A drawback of conventional photonic measurement systems based on speckle interferometry is the requirement of the successive detection of different images at the different phase-shifts of the respective reference beams. For most of the preferred phase shifting algorithms used for image analysis, four successive images per deformation state and/or illumination wavelength have to be acquired. During the acquisition of these four successive images the optical set-up has to be vibration-damped, i.e. the surface to be measured must not at all move with respect to the optical sensor head. It is desirable for the application of speckle interferometry in technical, "rough" environments to be able to acquire the necessary images simultaneously in a "one shot" measurement. Simultaneous image acquisition of phase-shifted speckle images enables the detection of moving surfaces without the necessity of vibration-isolated optical set-ups.

Further benefits of this so-called "Quadruple Phase-Shifting Speckle Interferometry" (QPSI) technique concerning the remote sensing of surface structures will be outlined in the lecture.

2 PHASE-SHIFTING SPECKLE INTERFEROMETRY

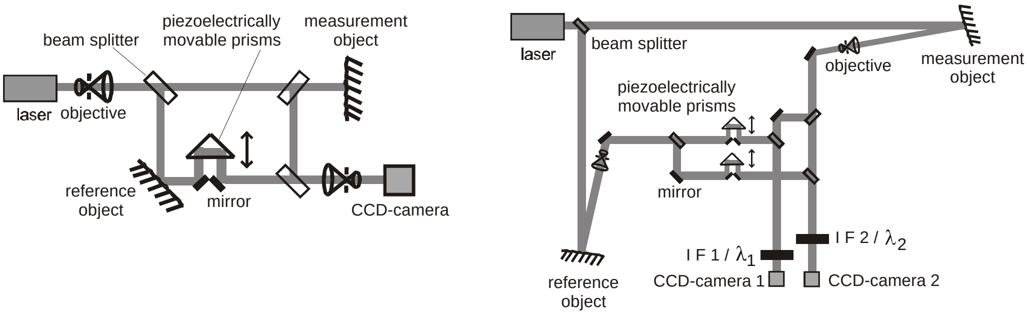
In speckle interferometry typically one reference beam is superposed by a measurement beam in an interferometer. The two interferometer set-ups of Fig. 1 are based on the conventional Michelson interferometer. Two cameras (Fig. 1b) are used for the simultaneous detection of two images at different wavelengths (λ_1, λ_2) filtered out by interference filters IF1 and IF2.



a) Michelson interferometer with one camera

b) Michelson interferometer with two cameras for the simultaneous measurement of two images

Figure 1. Michelson interferometer-setups



a) Mach-Zehnder interferometer

b) Two parallel Mach-Zehnder interferometers

Figure 2. One and two parallel Mach-Zehnder interferometers

Phase shifting of the reference beam is performed by means of a piezoelectrically positioned reference surface.

If separate reference beams with independently shiftable phases are required, the Mach-Zehnder interferometers of Fig. 2 are to be preferred. Fig. 2a shows a conventional Mach-Zehnder interferometer, whereas Fig. 2b represents a double interferometer, i.e. two parallel Mach-Zehnder interferometers. Here, phase shifting of the reference path(s) is performed by means of piezoelectrically movable prism(s).

The intensities I of each camera pixel (x,y) are expressed by the term

$$I(x,y) = I_0(x,y) \cdot \{1 + \beta(x,y) \cdot \cos[\phi(x,y) - \alpha(x,y)]\} \quad (1)$$

with the basic intensity I_0, the fringe visibility β, the pixel phase ϕ and a piezoelectrically introduced phase shift α being equal for all pixels. A local phase change results from an out-of-plane displacement of a surface element. A subtraction of two images taken at two different surface conditions generates fringes in the difference image. The fringes may be interpreted as a contour line plot of the surface height modifications.

Using two different laser wavelengths for the illumination of the two images, a synthetic wavelength is produced in the difference image

$$\Lambda = \frac{\lambda_1 \cdot \lambda_2}{2|\lambda_1 - \lambda_2| \cdot \cos\Theta} \tag{2}$$

with the illumination angle Θ. The simultaneous detection of two images taken at two different laser wavelengths can be achieved by the use of two cameras and appropriate interference filters in the detection path of the respective interferometer set-ups, as shown in Figs. 1b and 2b.
The technique of „phase shifting“ is based on a known, externally introduced phase shift α in the reference path of the respective interferometer. Commonly employed phase-shifting algorithms, e.g. the Carré algorithm [11] require four successive images each shifted by 90^0 corresponding to a displacement of e.g. $\lambda/8$ of the reference mirror in a Michelson interferometer (Fig. 1). A major disadvantage of the method using successively acquired images (temporal phase shifting) at different phases is the measurement time and the sensitivity to vibration. For this reason the commonly used *temporal* phase shifting technique as described above is replaced by a new *spatial* phase shifting technique based on a four-camera system.

The advantage of the recently developed set-up presented here is the simultaneous detection of the phase shifted images which are, for example, necessary to execute, e.g. the Carré algorithm. As shown in Fig. 3, the set-up comprises four parallel Mach-Zehnder-type interferometers with four CCD cameras. The four reference paths are shifted by 90^0 with respect to each other by means of three piezoelectrically movable prisms. The set-up is designed for long range measurements, i.e. the measurement distance is up to several meters.

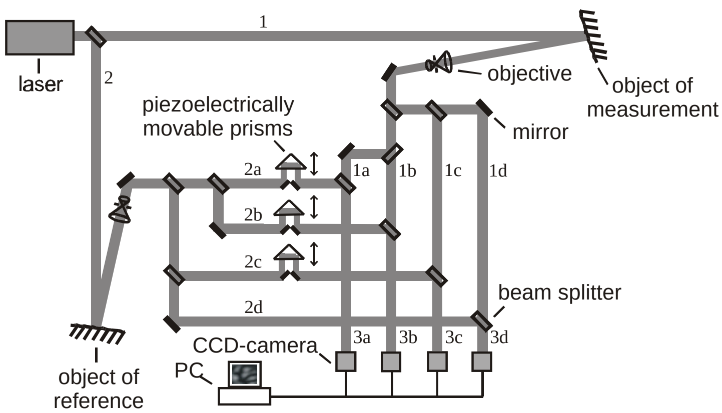


Figure 3. Principal setup of the quadruple phase-shifting speckle interferometer

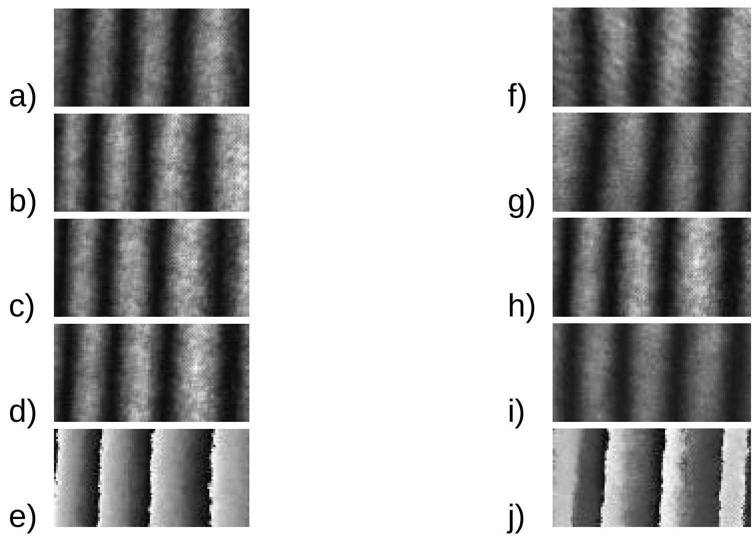


Figure 4. a) to d) Interferogram of path 3a, e) phase-shifting pattern of paths 3a, f) to i) interferogram of paths 3a to 3d, j) phase-shifting pattern of paths 3a to 3d

For maximum visibility the four interferometers have to be accurately adjusted with respect to the equal path lengths of the respective object beams and reference beams.

Fig. 4 depicts the detected interference fringes obtained at different phase positions, when the measurement object is replaced by a mirror and the objective is not used. The comparison of the images Fig. 4 e) and j) demonstrates the feasibility of the quadruple phase shifting method (right column, f) to i) as compared to the conventional temporal phase-shifting method (left column, a) to d)).

A demonstration of the speckle interferometer is shown in Fig. 5 where the images a) to c) correspond to a temporal phase-shifting using three cameras. Fig. 5 d) is a corresponding image obtained from the spatial phase shifting by means of four cameras.

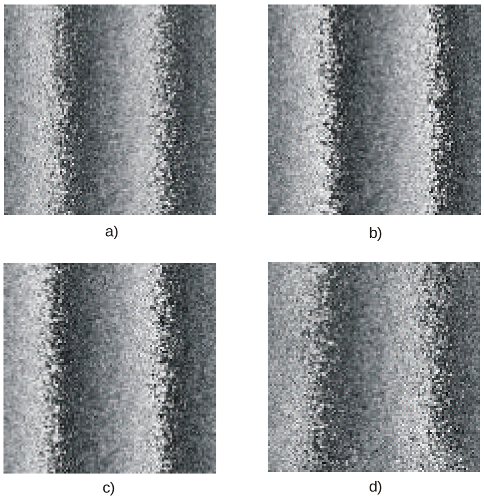


Figure 5. a) to c) temporal phase shifting of cameras 1 to 3, d) spatial phase shifting with 4 cameras

3 EROSION AND FRINGE CONTRAST

An optical simulation based on ray tracing exhibits clearly, that the fringe contrast decreases with increasing surface erosion [7, 5]. Therefore, we simulate an interference pattern with the surface being devided into five portions. In these portions we find the surface to be eroded in different quantities, starting from the first portion with a maximum erosion depth of zero nm, the second has 50 nm, the third has 100 nm, the fourth has 150 nm, and the fifth has 200 nm. The surface is illuminated at a wavelength of 488 nm. Fig. 6 exhibits such an image. We discover a clear reduction of the contrast of interference fringes. As the erosion reaches the order of the wavelength of illumination, the fringes disappear.

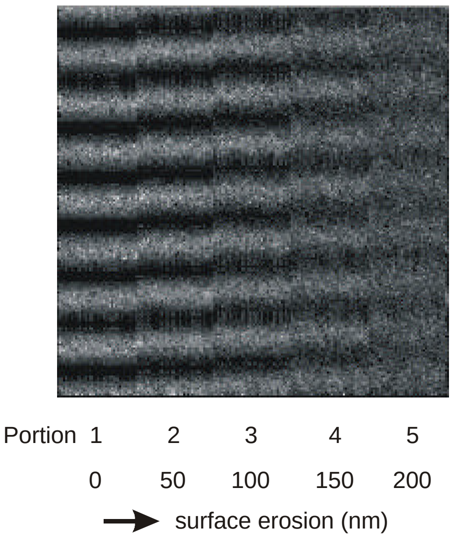


Figure 6. Interference fringe pattern of a surface eroded in 5 portions (vertical stripes) in different quantities ranging from 0 to 200 nm

During the simulation, we check the relation between the erosion and the fringe contrast for an erosion from zero to one half of the wavelength of the illumination light. The result is a curve showing the contrast depending on the depth of the erosion [12]. The theoretical fringe visibility γ at the wavelength λ, the erosion q and the angle of illumination Θ is given by the term

$$\langle q \rangle = \frac{\lambda\sqrt{1/\gamma - 1}}{2\pi\cos\Theta} \qquad (3)$$

Fig. 7 shows such a curve with all important parameters being listed. The simulation shows the same result as the simulation of the speckle contrast. The curve is equivalent to the one anticipated by the theory.

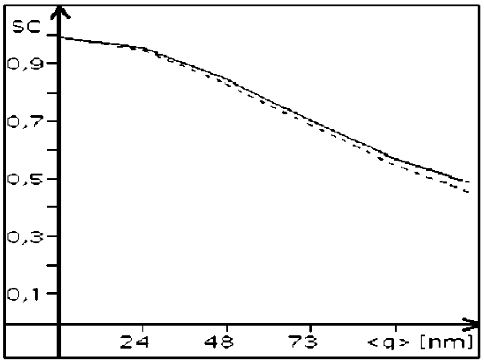


Figure 7. Erosion and fringe contrast, q = erosion, SC = fringe contrast, solid curve = calculated, broken curve = theory, illuminating wavelength = 488 nm, angle of illumination = 45^0

4 CONCLUSION

QPSI offers unique possibilities for the on-line detection of surfaces of technical objects. The simultaneous detection of four separate phase-shifted images using four parallel speckle interferometers results in short measurement times, corresponding approximately to the camera exposure time, and enables novel optical set-ups, e.g. compact sensor heads, without the necessity for a vibration-isolated environment.

REFERENCES

[1] Consortini Anna, *TRENDS IN Optics,* Academic Press, ISBN 0-12-186030-2, San Diego, London, New York, Boston, Sydney, Toronto, 1996.
[2] Dainty J.C., *Laser speckle and related phenomena,* Springer-Verlag, 2. Auflage, Berlin, Heidelberg, 1984.
[3] Ruprecht M., *Ferndiagnostik technischer Oberflächen mittels Laser-Speckle-Verfahren*, Shaker Verlag, ISBN 3-8265-4540-0, Aachen, 1998.
[4] Creath, K., *Temporal phase measurement methods*, Robinson D.W., Reid G.T., Interferogram Analysis, Institute of Physics Publishing, London, 1993, S. 94-140.
[5] Berger E., von der Linden W., Dose V., Jakobi M., Koch A.W., *Reconstruction of surfaces from phase-shifting speckle interferometry: Bayesian approach,* Applied Optics, Vol. 38, Nr. 23, 1999.
[6] Van Haasteren A.J.P., *Real-time phase stepped speckle interferometry*, Dissertation, Technische Universität Delft, 1994.
[7] Jakobi M., Evanschitzky P., Koch A.W., *Erosionsmessung an rauhen Oberflächen mittels Streifenkontrast in der Speckle-Interferometrie*, Technisches Messen, Vol. 66, Nr. 4, 1999, S. 163.
[8] Schnars U., Jüptner W., *Principles of direct holography for interferometry*, Fringe 93, Proc. of the 2nd Int. Workshop on Automatic Processing of Fringe Patterns, Bremen, 1993, S. 115.
[9] Seebacher S., Osten W., Jüptner W., *Measuring shape and deformation of small objects using digital holography*, SPIE, Vol. 3479, 1998, S. 104.
[10] Pedrini G., Fröning P., Tiziani H.J., Gusev M.E., *Pulsed digital holography for high-speed contouring that uses a two-wavelength method*, Applied Optics, Vol. 38, Nr. 16, 1999, S. 3460.
[11] Koch A. W., Ruprecht M. W., Toedter O., Häusler G., *Optische Meßtechnik an technischen Oberflächen,* expert verlag, Renningen-Malmsheim, 1998.
[12] Dreiden G. V., Semenova I. V., *Correlation holographic interferometry applied for studies of laser-induced erosion*, Optics Communications 118 (1995) 21-24.