10th IMEKO TC7 International Symposium
June 30–July 2, 2004, Saint-Petersburg, Russia

APPLYING SPECKLE-INTERFEROMETRY TO THE SHAPE MEASUREMENT OF MOVING OBJECTS

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Abstract – Speckle-interferometry is a very interesting group of measurement methods based on coherent light dissipation properties. There are a lot of applications of this effect, but the most interesting one is shape-measurement. It is astonishing that a nearly random structure of speckle image can contain information about the contour of the object illuminated by coherent light. The method is well-known but it is not so popular because of great disadvantage: method needs very good stability of the measurement object and instrument. So this technique was applied only in laboratory for a long time.
In this article we want to present special algorithms and setups which permit applying speckle-interferometry out of the lab – in industrial conditions.

Keywords: shape measurement, speckle-interferometry, two-cameras setup.

1. SPECKLE-INTERFEROMETRY

Speckle-interferometry is a modern and very fast developing method for measuring several surface parameters. The main ideas and principles of this technique were based in 70th years of 20th century, but nowadays, thanks to fast computers and modern image acquisition devices, it is possible to talk about real gap in this scientific field.

Speckle-interferometry is based on the speckle-effect (peculiarity of the coherent light reflection on optical rough surfaces), which could be used for the measurement of such parameters like surface roughness, erosion, surface displacement and other. But may be the most interesting speckle effect application is shape measurement of the optical rough surface, where usual optical methods do not work.

Subjective speckle image (SSI) – image of the optical rough surface in coherent light made by optical system with its own aperture and focus distance [1] – looks like system of randomly distributed light dots (see fig.1). But this “random” system contents information about the surface shape. The process of the SSI forming shows that every point in the image plane is formed by the summary of elementary waves reflected from a corresponding part of the surface. The area of this part depends on the illuminating light wavelength and on the parameters of the optical system. So it is possible to say that the resulting phase at one point in the image plane contains the average optical path length between this point and a corresponding area on the surface.

A speckle-image as every image is spatial distribution of intensities, but not phases. So, to get information about phases from the speckle-image we have to use special methods. There is only one method to measure the phase of the optical wave: interferometry. If registration plane is illuminated by object- and reference beam, then we can get information about the phase of the object beam by one of the interference parameter changing:

$$I = I_o + I_r + 2\sqrt{I_o \cdot I_r}\cos(\varphi_o - \varphi_r) \qquad (1)$$

Eq. 1 is interference formula, where I – is intensity distribution in speckle interferogram, I_r, I_o, φ_r, φ_o – intensity and phase distribution of the reference and object beams. By changing the phase of the reference beam φ_r on 90 degrees using well-known optical methods it is possible to get different speckle-interferograms I_1, I_2, I_3, I_4. After it, using Carré:

$$\varphi_o = \arctan\left(\frac{\sqrt{(3(I_2 - I_3) - (I_1 - I_4))}}{I_1 + I_2 + I_4 - 3I_3} \times \atop \times \sqrt{((I_2 - I_3) + (I_1 - I_4))} \right) \qquad (2)$$

or Harriharan-Schwider:

$$\varphi_o = \arctan\frac{3I_2 - (I_1 + I_3 + I_4)}{(I_1 + I_3 + I_4) - 3I_3} \qquad (3)$$

algorithms, it is possible to calculate phase distribution of the object beam, which contents information about surface contour [3].

But if the surface roughness exceeds a quarter of the light-wavelength, the calculated phase of each detector point is in another 2π-range. The formula of the phase distribution in object beam could be presented so:

$$\varphi_o = \frac{4\pi F(x,y)}{\lambda_1} + \Psi_{\lambda_1}, \qquad (4)$$

where $F(x,y)$ - the surface shape, λ_1 - wavelength of the illuminating beam, Ψ_{λ_1} - so-called speckle-noise randomly distributed between 0 and 2π. In order to reduce the range of ambiguity the two-wavelengths method is used. The essence of this method is shown in equation (5). The difference of object beams phase distributions formed b the same surface illuminated with different wavelengths λ_1 and λ_2 is the phase distribution of the object beam formed by the same surface illuminated with "artificial" beam with wavelength Λ.

$$\varphi_{\lambda_1} - \varphi_{\lambda_2} = \frac{4\pi F(x,y)}{\lambda_1} - \frac{4\pi F(x,y)}{\lambda_2} + \\ + \underbrace{\Psi_{\lambda_1} - \Psi_{\lambda_2}}_{\lim\limits_{(\lambda_1-\lambda_2)\to 0} \to 0} = 2\pi F(x,y)\cdot\frac{2(\lambda_2-\lambda_1)}{\lambda_1\lambda_2} \qquad (5)$$

So the algorithm of two wavelength speckle-interferometry could be shown on the example of a real contour measurement of woman's profile on the back of an old italic 200 lire coin:

2. TWO-CAMERAS SETUP

The first idea of the two-wavelength speckle-interferometry method realisation is based on hypothetical admission (which, nevertheless, was confirmed by practice), that the phase of the SSI does no change greatly in some region limited by borders connected with the mean size of the speckles:

$$\sigma_s = 1.44\frac{a\lambda}{D}, \qquad (6)$$

where σ_s – mean size of the speckles, – aperture size, a – distance between lens centre and image plane.

It means that on the SSI there are a lot of regions where the phase is nearly the same. It allows us to use spatial phase-shifting.

Method which we had used before is called temporal phase-shifting, because of taking of I_1, I_2, I_3, I_4 is separated in time, and for phase calculating we are using the same points of different speckle-interferograms. If it is possible to say that the phase of the SSI in points *(x,y), (x+1,y), (x+2,y),* and *(x+3,y),* is nearly the same, than it is possible to produce phase-shifting between adjacent points (for example by producing angle between object and reference beams).

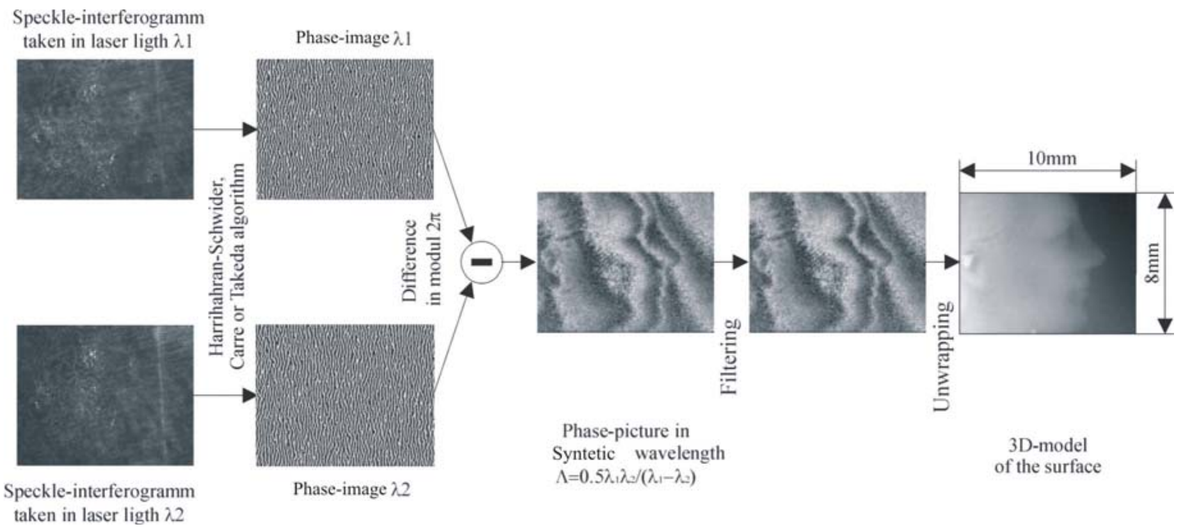


Figure 1. Algorithm of the two-wavelength speckle-interferometry.

The problem of this method is that for one measurement we have to take 8 speckle-interferograms of one surface (I_{11}, I_{12}, I_{13}, I_{14} in wavelength λ_1 and I_{21}, I_{22}, I_{23}, I_{24} in wavelength λ_2). If the object moves or changes between any of these 8 registrations, measurement will be destroyed by decorrelation. It means that this method could work only on special vibration damping tables, where object and optical system of the speckle interferometer are completely stable.

We have put ourselves the task to solve this problem using experience of previous scientists and our own investigations.

It allows us to reduce the number of registered images from 8 to 2. Of course, this method has disadvantages. Spatial phase-shift adds its own component to resulting phase, but this component is consistent and could be compensated. Another disadvantage is that spatial phase-shifting produces not such accurate measurement results as temporal phase shifting, but we have to pay for measurement speed with something [4].

So we have reduced the number of registered images from 8 to 2. But still object must be stable between these two shots. And here we want to present a two-cameras speckle-interferometer [5] which permits to record these images simultaneously:

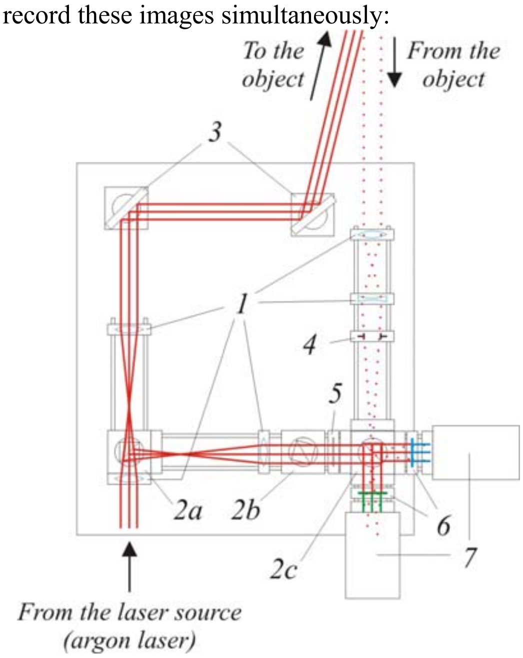


Fig. 2. Two-cameras speckle-interferometer based on interference filters.

In this setup multiwave argon laser is used. Coherent laser beam consists of different coherent wavelengths, including 496.5nm and 501.7nm, is divided on illuminating and reference beam be beam-splitter 2a. Illuminating beam is expanded by an optical system and redirected by mirrors 3. After scattering by the measured surface illuminating beam transpose to object beam and returns to the objective of the speckle-interferometer. Here SSI is formed. Reference beam with the help of optical system obtains the same radius of equiphase lines as the object beam and is turned slightly in order to produce a spatial phase-shift with the beam-splitter 2b. Afterwards the light is guided to beam-splitter 2c where it is divided into two beams and led to two spatially separated cameras 7. The object beam is divided by beam-splitter 2c too. Interference filters are situated in front of the cameras. These filters pass the wavelength 496.5nm for one camera and wavelength 501.7nm to the other one. Speckle-interferogram of each wavelength is formed on chips of cameras. This interferograms are taken simultaneously by PC with special frame grabber and after all mathematical calculations it produces a phase image of the measured surface like an artificial beam with a synthetic wavelength of 49.7µm.

Experimental results show that this setup can work without any damping (in vibration conditions) and measure the contour of an optical rough continuous surfaces with diameter up to 20 mm and height differences up to 1,5mm, placed on distance up to 1,5m at an accuracy about 10-15%. Resolution in Z direction is 256 steps on every 50µm and up to 500 points in X direction, but resolution depends mostly on the employed CCD-camera.

The great disadvantage of this setup is low efficiency of illumination. Measurement surface dissipation, partly loosing in beam-splitters and low coefficient of filters which connected with the small difference of the used wavelengths results in loosing about 95% of illumination power. It reduces working distance, measuring area and signal-noise ratio.

Using of very expensive gas laser and low illumination efficiency coefficient of this setup forced us to offer a structure based on semiconductor lasers and polarisation filters:

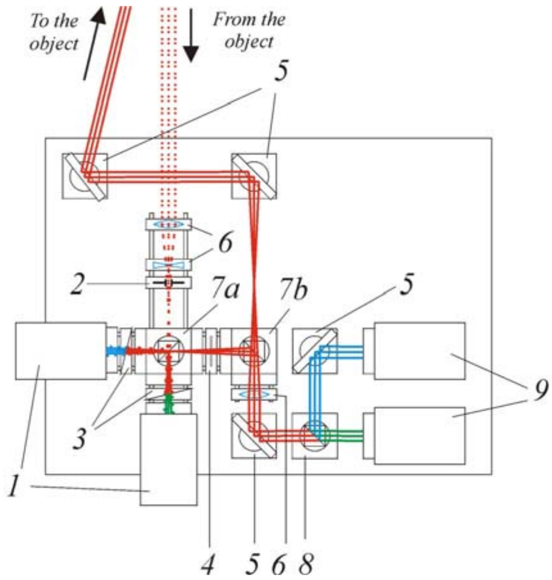


Fig. 3. Two-cameras speckle-interferometer based on polarisation filters.

Semiconductor lasers could not be multiwavelength (with enough stability), but employment of two different laser source allows to produce two different laser beams with different wavelength and an orthogonal polarisation. The superposition of these two separated beams is realised by mirror and polarisation beam splitter. Summary beam can be separated to two cameras with polarisators which has a maximum passing coefficient for chosen polarisation and nearly zero for orthogonal one.

This setup has nearly the same characteristics as the previous one, its accuracy is a little better – 7%, but it has two disadvantages. The first one is semiconductor lasers are not so stable as gas laser and need special algorithm of stabilisation. The second one is that it is really hard to direct two laser beams in one direction. A little angle between spreading direction of these two beams produces additional methodical error.

3. MATHEMATICAL METHODS OF THE SMEARED IMAGE RESTORATION

Unfortunately the two cameras setups do not solve the problem of object moving completely. With growing of the object's speed it is necessary to decrease the exposure time of cameras (to "freeze" object's movement), but this decreasing has its limit. Sooner or later there will not be enough laser power to register any signal on such a short exposition. Experiments with moving objects have shown that maximum speed of the object when it is possible to get stable phase picture of the object with error not more than 10% is decreasing with exposure time increasing on every aperture diameter:

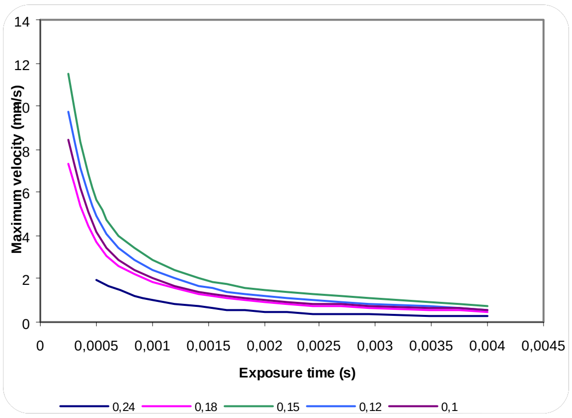
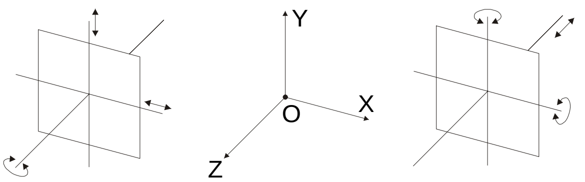


Fig. 4 Maximum speed depending on exposure time.

Of course it is possible to say that we find the limit of applying two-cameras speckle-interferometers to shape measurement of moving objects. But in fact it possible to increase maximum velocity of the object by applying special mathematical algorithms to the object motion smeared speckle-interferograms. Motion smeared images (smeared by object's movement while exposure time) is well developed field of image processing and a lot of restoration algorithms are worked out.

First of all let's classify object movements:



In plane movement | Z – to the speckle-interferometer | Out of plane movement

Fig. 5 Object's movement classification.

Out of plane movement produces complicated point spread function (PSF) especially for speckle structures. PSF of in plane movement is much easier and it is possible to use motion smeared images restoration algorithms for speckle-smeared interferograms. But there are several problems in realisation of such kind of restoration.

In situation when object moves during exposure time only the object beam moves while the reference beam keeps stable. It leads to some limitations in restoration applying. Takeda in [7] showed that spectrum of speckle-interferogram is complicated function which is shown in equation (7):

$$\begin{aligned} &F\{I(x,y)\} = I_R \cdot \delta(f_x,f_y) + F\{I_O(x,y)\} + \\ &+\sqrt{I_R}F\left\{\sqrt{I_O(x,y)}\right\} * F\left\{e^{-j(\varphi_O(x,y))}\cdot e^{-j\delta}\right\} + , \\ &+\sqrt{I_R}F\left\{\sqrt{I_O(x,y)}\right\} * F\left\{e^{j(\varphi_O(x,y))}\cdot e^{j\delta}\right\} \end{aligned} \quad (7)$$

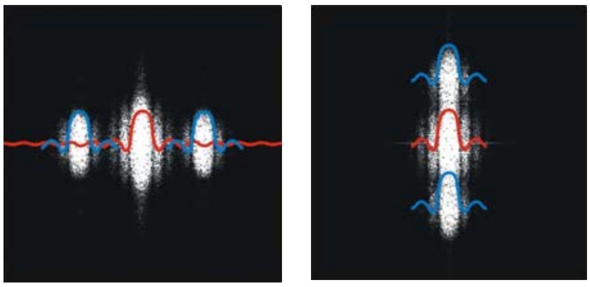
where $F\{I_o(x,y)\}$ – Fourier spectrum of speckle-image given in eq. (8) [7]:

$$\begin{aligned} &F\{I_O(x,y)\} = \langle I\rangle^2 \{\delta(f_x,f_y) + \\ &+\left(\frac{\lambda D}{a}\right)^2 \frac{4}{\pi}\left[arc\cos\left(\frac{\lambda D}{a}\rho\right) - \left(\frac{\lambda D}{a}\rho\right)\sqrt{1-\left(\frac{\lambda D}{a}\rho\right)^2}\right]\}, \\ &\rho = \sqrt{f_x^2 + f_y^2} \end{aligned} \quad (8)$$

It is possible to show mathematically that spectrum of the motion smeared speckle interferogram is:

$$\begin{aligned} &F\{I(x,y)\} = I_R \cdot \delta(f_x,f_y) + F\{I_O(x,y)*(PSF(x,y))\} + \\ &+2\sqrt{I_R}F\left\{\sqrt{I_O(x,y)*(PSF(x,y))}\right\} * F\left\{e^{-j(\varphi_O(x,y)*(PSF(x,y)))}\cdot e^{-j\delta}\right\} + \\ &+2\sqrt{I_R}F\left\{\sqrt{I_O(x,y)*(PSF(x,y))}\right\} * F\left\{e^{j(\varphi_O(x,y)*(PSF(x,y)))}\cdot e^{j\delta}\right\} \end{aligned} \quad (9)$$

It shows that possibility of restoration depends on the direction between moving and spatial-phase shift (SPS). It is more understandable to show it graphically:



Moving and SPS directions are parallel. | Moving and SPS directions are orthogonal.

Fig. 6. Spectrums of the motion smeared speckle-interferograms.

On fig.6 it is clearly shown that unsmearing algorithms are applicable only when moving and SPS directions are orthogonal.

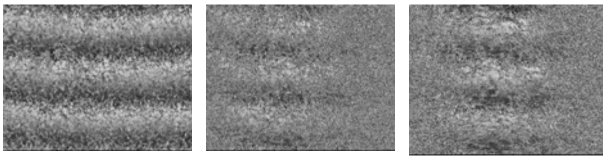
There are a lot of unsmearing algorithms: blind deconvolution, regularisation, Wiener deconvolution and others. But the best results we have got using Tikhonov regularization [8]:

$$w(x,y) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\frac{K(-\omega)\cdot G(\omega,y)}{|K(\omega)|^2 + \alpha\cdot\omega^2}e^{-j\omega x}d\omega, \quad (9)$$

$$K(\omega) = \int_{-\infty}^{\infty} PSF(x) \cdot e^{j\omega x} d\omega,$$

$$G(\omega, y) = \int_{-\infty}^{\infty} g(x, y) \cdot e^{j\omega x} d\omega,$$

where *w(x,y)* – restored image, *g(x,y)* – motion smeared image, *α* – regularization parameter, which is more than zero but less than one.



Phase-image of the stable object | Phase-image of the object moving with the velocity of 50 mm/s | Phase-image calculated with restored speckle-interferogramms

Fig. 7. Restoration with Tikhonov regularisation example.

Restoration which is shown on fig. 7 is not perfect, it forces us to remember another problem – "speckle-boiling". It means that speckles are not only smearing when object is moving during exposure time, but also changing their form. It is related with an angle between illuminating and reflected beam. Because of this angle speckles changes their structure, depending on the observing position. So another requirement of unsmearing algorithms applying is equality of this angle to zero (what is possible only in simulation) or perpendicularity of the illumination-reflection angle to the object's moving direction.

The main disadvantage of all unsmearing algorithms is that one has to know PSF, it means in the easiest variant speed and direction of movement. These parameters are unknown in the most part of cases.

4. CONCLUSION

The results of our investigation are two types of two-camera speckle-interferometers: the first one based on the gas laser and interference filters and the second one based on the semiconductor lasers and polarisation filters. These setups can work without any damping (in vibration conditions) and measure shape of optically rough continuous surfaces with diameter up to 20 mm and height difference up to 1,5mm, placed on distance up to 1,5m with accuracy about 10-15%. Resolution in Z direction is 256 steps on every 50µm and up to 500 points in X direction and Y direction. The maximum speed of the object relatively to the instrument is 10 mm/sec.

If this relative speed is more than 10 mm/sec then it is possible to use unsmearing algorithms based on deconvolution process but in this case it is necessary to carry out two conditions:

- angle between illuminating and reflected light must be orthogonal to movement direction;
- movement direction must be orthogonal to spatial phase shifting direction.

In practice these conditions is not easy to fulfil and mathematical possibility of motion smeared reconstruction is interesting only as a theoretical foundation.

To increase the maximum speed of the measurement object in two-cameras speckle-interferometry technique it is better to use the shortest exposure time of cameras in combination with the most powerful lasers. For example pulsed lasers synchronised with cameras.

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