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Improving activity visualization in dynamic speckle testing of paint drying by evaluation of a temporal correlation radius

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We propose an approach for improving visualization of activity map obtained as an output of pointwise dynamic laser speckle analysis. The map reflects the speed of change of the speckle pattern formed on the surface of the tested object and thus provides information about the speed of processes leading to these change. The approach is based on pointwise calculation of the normalized temporal correlation function and further determination of the correlation radius. In case of negative exponential dependence of the correlation function on the time lag between the recorded speckle patterns, the obtained description of activity is quantitative. The proposed visualization enhancement of the activity map has been verified by processing raw data from a paint drying experiment.

Keywords: dynamic speckle, paint drying, pointwise processing, correlation function

INTRODUCTION

Dynamic laser speckle metrology provides a highly sensitive tool for non-destructive testing of paint drying [1]. Evaporation process during the drying leads to microscopic changes of the sample surface that create "boiling" speckle pattern on the sample under coherent illumination. This pattern carries information about the dynamics of the undergoing processes. Dynamic speckle testing includes sequential acquisition of correlated speckle patterns and their pointwise statistical processing [2,3]. The output of the measurement is a two-dimensional map which gives the distribution of a certain statistical parameter chosen to differentiate between the regions of lower or higher activity on the sample surface. The expectations are to obtain a detailed map with a good contrast to ensure high sensitivity, but processing of raw data yields a strongly fluctuating distribution of the parameter estimate that renders difficult visualization of activity. Furthermore, the chosen parameter usually maps non-linearly activity time scales and this makes possible only qualitative evaluation.

In this work we propose to enhance activity visualization by using as a statistical parameter the temporal correlation radius of intensity fluctuations. As a first task we determined the form of the temporal correlation function of the fluctuations, $R(\tau)$, where τ was the time lag, for the paint drying experiment. We checked the applicability of the widely used exponential model [4], $R(\tau)=\sigma^2\exp(-\tau/\tau_{corr})$, where σ^2 is the variance and τ_{corr} is the correlation radius, to describe intensity fluctuations in this case. As a second task, we verified quality of the activity map built as a distribution of the ratio between the correlation radius and the time lag and proved the contrast improvement.

PAINT DRYING EXPERIMENT

The experiment with paint drying was carried out with a specially designed circular metal object with two hollow regions of the same depth – a central circular section and an annular region – and two flat annular regions. A transparent polyester paint was used to cover the object to form a flat layer on its surface. Thus the circular and annular hollow regions contained larger quantity of paint than the other two annular regions. As a result, the speed of paint drying was different on the object surface. The object was illuminated with a He-Ne laser, and dynamic speckle patterns were recorded by a CMOS camera with a pixel interval Δ = 7 μm. The camera optical axis was normal to the object

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surface. The set-up was positioned on a vibration-insulated table. The 8-bit encoded speckle patterns were acquired at an interval $\Delta t = 250$ ms. The size of the processed images was $N_x \times N_y = 780 \times 582$ pixels.

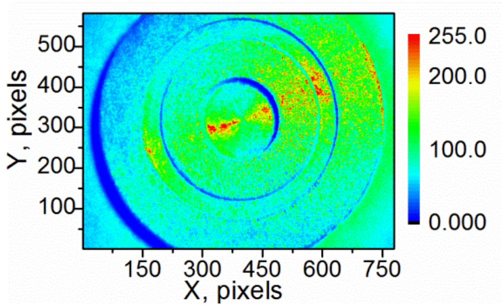

Fig. 1. Speckle pattern formed on the surface of a circular metal object covered with polyester paint; the pattern is presented as a contour map of the recorded intensity.

A typical speckle pattern is shown in Fig. 1 as a contour map. It is seen that the speckle pattern is characterized with non-uniform intensity distribution across the object, most probably due to non-uniform reflectance. The regions of different activity are not recognizable without statistical processing. We processed *N* = 128 images. The acquired raw data allowed for pointwise processing which means that the entries corresponding to a given pixel $(i,k), i = 1,2...N_x, k = 1,2...N_y$ form a temporal sequence of intensity values, $I_{ik,n}, n = 1,2...N$ of length *N* and enable evaluation of the chosen statistical parameter at this pixel by averaging over the whole sequence. The result of the pointwise processing is a two-dimensional distribution of size $N_x \times N_y$ of the obtained parameter values.

RESULTS

Fig. 2 depicts the two-dimensional (2D) distribution of the variance estimate of intensity fluctuations. The variance estimate at a pixel (i,k) is found from the formula

$$\hat{\upsilon}(i,k) = \frac{1}{N}\sum_{n=1}^{N}\left(I_{ik,n} - \bar{I}_{ik}\right)^2; \bar{I}_{ik} = \frac{1}{N}\sum_{n=1}^{N} I_{ik,n} \qquad (1)$$

where $\bar{I}_{ik}$ is the mean intensity at pixel (i,k). Due to the fixed length of the formed temporal sequences, the map of the variance estimate shows different behaviour in the hollow regions and on the flat surfaces of the test object. Due to non-uniform intensity distribution in the speckle patterns (Fig. 1), the variance distribution reflects incorrectly the developing activity on the object surface as a result of paint evaporation. The variance estimate must have practically the same value in the hollow regions; the same should be true for the flat regions. However, we see substantial variance variation in these regions. We built also the 2D map of the speckle contrast as a ratio of the square root of the variance estimate and the mean value; the map is shown in Fig. 3. The contrast is not very high and its variation across the object does not provide correct description of activity.

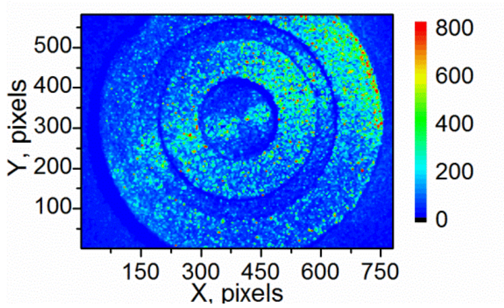

Fig. 2. Contour map of the variance estimate that reveals regions of different activity.

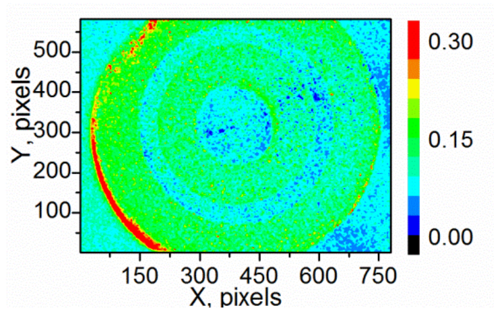

Fig. 3. Contour map of the pointwise contrast estimate.

In case of non-uniform illumination and varying reflectivity across the object surface one should apply normalized processing. Recently we introduced pointwise estimation of the normalized temporal correlation function [5] according the formula

$$\hat{R}_{norm}(i,k,m) = \frac{1}{N-m}\frac{1}{\hat{\upsilon}(i,k)}\sum_{n=1}^{N}\left(I_{ik,n} - \bar{I}_{ik}\right)\left(I_{ik,n+m} - \bar{I}_{ik}\right) \qquad (2)$$

where the index "*m*" corresponds to the time lag $\tau = m\Delta t, m = 1,2..M$ between the compared speckle images. The maximum value of the normalized function is 1. The 2D map of $\hat{R}$ at *m* = 5 is depicted in Fig. 4. The map shows much higher activity in the leftmost part of the object. Probably this is due to less quantity of paint there. The map reveals the regions of different activity but for this particular time lag the contrast is not satisfactory.

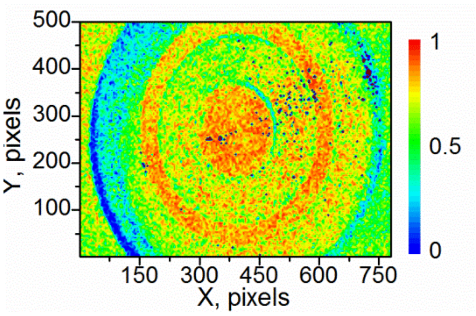

Fig. 4. Contour map of the normalized temporal correlation function at a time lag $\tau = 5\Delta t$.

The temporal correlation function provides information about the time scales of the undergoing activity. The width of this function determined at some level gives the correlation radius of the observed process. The problem is that the correlation function maps non-linearly the dependence on the time lag. This results in decreased contrast of activity visualization based on the normalized correlation function. The results of processing the raw data obtained by us for different objects [6,7] give a negative exponential dependence on the time lag, $R_{norm}(\tau) = \sigma^2 \exp(-\tau/\tau_{corr})$, as a close description to the experimentally estimated curves. To illustrate this statement, we calculated $\hat{R}(i,k,\tau)$ inside the spatial window of 50×50 pixels in the region of constant activity on the object surface starting from the pixel (325,90). The average value of the obtained estimates is shown as a function of the time lag in Fig.5. The correlation radius is determined at level 1/*e*. Figure 6 gives the parameter $\Omega(\tau) = -\ln\{\hat{R}_{norm}(\tau)\}$ as a function of the time lag. We see practically linear dependence on τ. This result can be used for improving activity map quality by transforming $\hat{R}_{norm}(\tau)$ to $\Omega(\tau)$. In the case of negative exponential dependence on τ of the normalized correlation function it is possible to build the 2D map of the estimate of the correlation radius across the object:

$$\hat{\tau}_{corr} = \frac{m\Delta t}{\Omega(m\Delta t)} \qquad (3)$$

In principle, it is enough to find $\Omega(\tau)$ for a given time lag. We used Eq.(3) at $m = 5$ and obtained the correlation radius distribution presented in Fig. 7. The map gives variation of the correlation radius across the object in seconds. Besides the fact that the map in Fig.7 provides better visualization of activity than the map in Fig.4, it also allows for its quantitative evaluation. The value of 6 s obtained from Fig. 5 corresponds well to the mean value in the spatial window of 50 by 50 pixels with its first pixel located at (325,90).

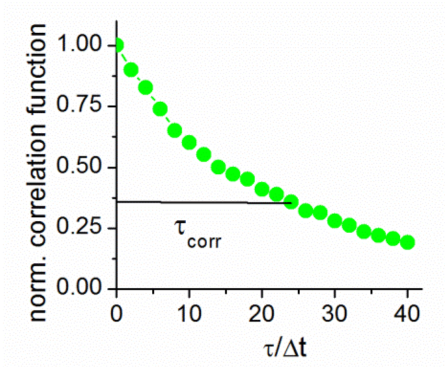

Fig. 5. Normalized temporal correlation function (the abscissa gives the ratio between the time lag and the acquisition interval $\Delta t = 250$ ms).

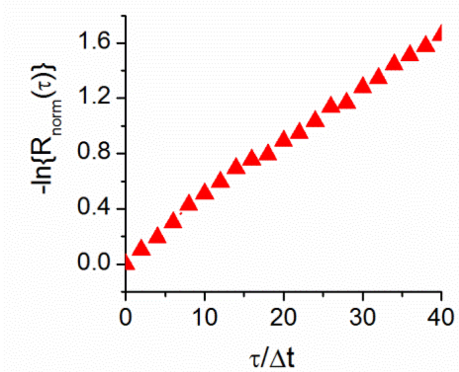

Fig. 6. Linear dependence of the logarithm of the normalized correlation function on the time lag (the abscissa gives the ratio between the time lag and the acquisition interval $\Delta t = 250$ ms).

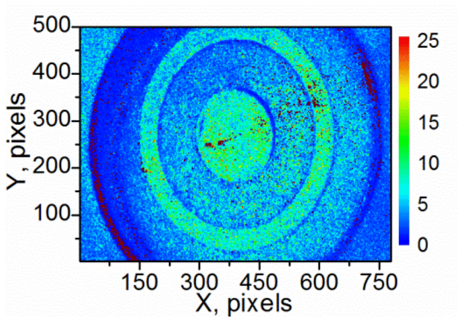

Fig. 7. Contour map of the normalized temporal correlation function at a time lag $\tau = 5\Delta t$; the time scale is given in seconds.

CONCLUSIONS

Based on processing of experimental data, we proposed an approach for enhancing visualization of regions of slower or faster changes on a surface of a diffusely reflecting object that are relied to undergoing processes of physical or biological nature inside it. The approach included pointwise calculation of the normalized temporal correlation function from a recorded sequence of speckle patterns formed on the object surface under laser illumination and determination of the 2D contour map of the correlation radius by accepting a negative exponential model for the correlation function of intensity fluctuations. The approach was verified by processing a paint drying experiment at which the correlation function at a given point corresponded to the accepted model. Then it is possible to describe activity quantitatively. Nevertheless, even when the accepted model for the logarithm of the correlation function is not strictly linear, it is expected to achieve activity map visualization enhancement.

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ПОДОБРЯВАНЕ НА ВИЗУАЛИЗИРАНЕТО НА АКТИВНОСТТА ЧРЕЗ ОЦЕНЯВАНЕ НА РАДИУСА НА КОРЕЛАЦИЯ ПРИ ТЕСТВАНЕ НА СЪХНЕНЕ НА БОЯ С ДИНАМИЧЕН СПЕКЪЛ

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(Резюме)

В работата се предлага подход за подобряване на визуализирането на картата на активността, която се получава като изходен резултат при поточковия динамичен спекъл анализ. Картата показва промяната в спекъл картината, формирана върху повърхността на тествания обект и осигуряваща по този начин информация за скоростта на процесите, предизвикали тази промяна. Подходът се базира върху поточково пресмятане на нормираната времева корелационна функция, последвано от определяне на радиуса на корелация. В случая на отрицателна експоненциална зависимост на корелационната функция от времевия лаг между записаните спекъл картини полученото описание на активността е количествено. Предложеното подобряване на визуализирането на картата на активността е проверено чрез обработка на експериментални данни от експеримент със съхнене на боя.