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Letters

Monitoring of Paint Drying Process by Digital Speckle Correlation

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The state of drying paint is monitored from the dynamic behaviors of the speckle pattern arising from laser illumination of the region inspected. Temporal variation of the peak height of the cross-correlation function between successive frames taken with a fixed interval is plotted until the peak maintains a stationary maximum value. We used a speckle pattern in the diffraction field for monitoring of a single region and that in the image field for simultaneous monitoring of various regions. Both the normal and the phase-only algorithms were compared for cross-correlation computation. The former showed more distinct variation of peak height.

Key words: digital speckle correlation, paint drying process, noncontact

The noncontact monitoring of painted surfaces that cannot be touched is often needed in industries and daily individual lives. Recently a method detecting the reflectivity of THz electromagnetic waves has been proposed.[1)] This method requires a special source and is not suited for simple and quick testing. In this article we propose a new technique using detection of the dynamic change of speckle patterns that appear when the surface is illuminated by a laser beam. A speckle pattern shows random movement that indicates change of microscopic surface structures and disappears when they cease to move after drying. Dynamic behaviors of speckle have been investigated for deterministic movement of a rough surface on the basis of cross-correlation of the patterns. When subjected to homogenous deformation to be decomposed into translation, rotation, and strain, speckle patterns show displacement and decorrelation, i.e., a shift and a fall-off of the cross-correlation peak.[2)] The speckle displacement has been utilized for measurement of surface deformation by speckle photography and digital speckle correlation.[3)] Changes of object illumination, that is, changes of the incident angle and/or wavelength also cause displacement and decorrelation of speckle. The speckle displacement is proportional to the changes of incident angle and wavelength, while the rate of decorrelation accompanying the changes depends on the surface roughness.[4)] Speckle decorrelation caused by microscopic changes of a surface subject to fatigue testing was detected by projecting a speckle pattern on a so-called shadow filter recording the original pattern and by measuring the total transmitted light.[5)] Speckle decorrelation during the drying process of a paint was also reported, however, without explanation of the optical setup used.[6)] In this article we digitally detect speckle decorrelation caused by random movement of scatterers during the drying process of paints. The mobility of the scatterers indicates the drying process; hence, if the surface is dry, there will be no speckle movement and the decorrelation will stop. Although the dynamic behavior of speckle can also be evaluated from the contrast of time-averaged speckle patterns, the present method can be applied to monitor temporal variation in more detail.

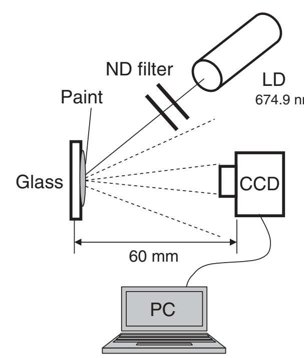

Fig. 1. Setup of digital speckle correlation in the diffraction field.

Figure 1 shows the optical setup to observe speckles arising from a painted glass plate in the diffraction field. A beam of 1 mm in diameter from a laser diode (LD) with wavelength 674.5 nm and output power of 0.5 mW is incident on a glass sheet freshly painted. A charge-coupled device (CCD) is positioned at a distance of 60 mm from it. The acquired pattern changes rapidly during the drying process frame after frame. We stored the frame into a personal computer successively at an interval of 1 s. For calculating the cross-correlation of speckle patterns in successive frames we used two algorithms. The first one is the normal cross-correlation that is numerically calculated on the basis of the relationship

$$C_{12}(X,Y) = \iint I_1(X',Y')I_2(X'+X,Y'+Y)\,dX'\,dY' = \mathcal{F}^{-1}[\hat{I}_1(\xi,\eta)\hat{I}_2{}^*(\xi,\eta)], \quad (1)$$

where the Fourier transform and its inverse are defined as

$$\hat{f}(\xi,\eta) = \mathcal{F}[f(x,y)] = \iint f(x,y)\exp[i2\pi(\xi x+\eta y)]\,dx\,dy \quad (2)$$

and

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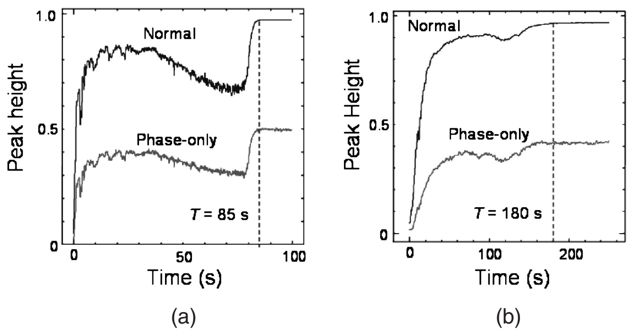

Fig. 2. Temporal variations of height of correlation peak.

$$f(x,y) = \mathcal{F}^{-1}[f(\xi,\eta)] = \iint f(\xi,\eta)\exp[-i2\pi(x\xi + y\eta)]\,d\xi\,d\eta. \quad (3)$$

We also calculated the phase-only correlation defined by

$$C_{12}(X,Y) = \mathcal{F}^{-1}\left[\frac{\hat{I}_1(\xi,\eta)}{|\hat{I}_1(\xi,\eta)|}\frac{\hat{I}_2{}^*(\xi,\eta)}{|\hat{I}_2(\xi,\eta)|}\right] \quad (4)$$

that uses only the Fourier phase. This algorithm is not affected by variations of the mean intensity and a real time device is available that carries this calculation in 30 ms.[5)]

First we acquired the speckle patterns arising from poster color and nail polish. Image acquisition started from 10 s after painting at an interval of 100 ms with an exposure time of 30 ms. After acquisition of 100 frames we calculated both the normal and the phase-only correlations between successive frames and obtained the graphs of the height and position of the correlation peak. We found that the peak position was always located at zero which means there was no translation of speckle. This is because of lack of a systematic motion of the drying surface. Although no speckle translation can also occur in the case of object translation and rotation[3)] as called speckle boiling, it is obviously not the case here. The peak height variations represented in Fig. 2(a) for a poster color and 2(b) for a nail polish show complicated behaviors but finally reach a maximum value that indicates the stationary dried state of the surface. The time duration up to the stationary maximum is the same for both algorithms; 86 s for the poster color and 180 s for the nail polish. Though before saturation of the peak height some stationary state can be observed, the maximum stationary values indicate the final state of perfect drying.

We next investigated the dependence of the peak height variation on the sampling interval as shown in Fig. 3 where the cross-correlations between the successive patterns (a), every second pattern (b), every third pattern (c), and every fourth pattern (d). We see that intermediate peaks vary but that the final stationary states appear after the same duration of time. We also calculated the variation of speckle contrast that is defined by

$$C = \frac{\sqrt{\langle [I(X,Y) - \langle I\rangle]^2\rangle}}{\langle I\rangle}, \quad (5)$$

where $\langle\cdot\rangle$ denotes the spatial averaging. This is displayed in

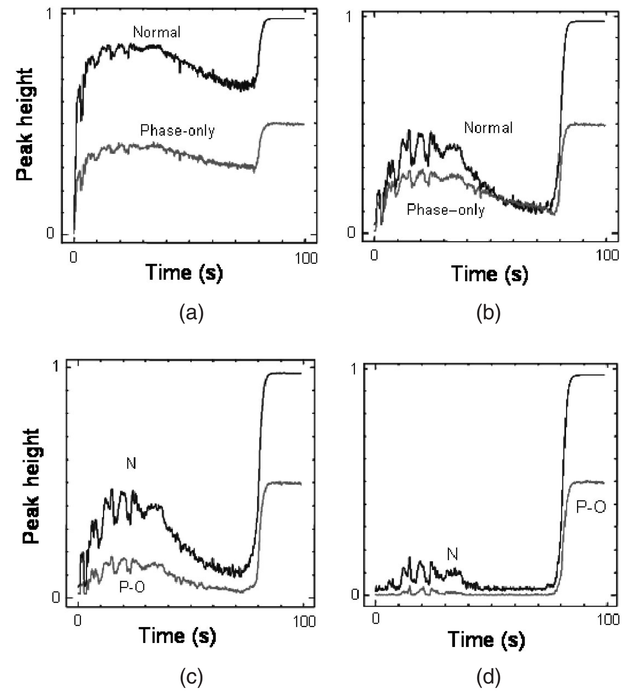

Fig. 3. Dependence of the correlation peak height for a poster color on sampling intervals. (a) Every frame, (b) every two frame, (c) every three frame, and (d) every four frame.

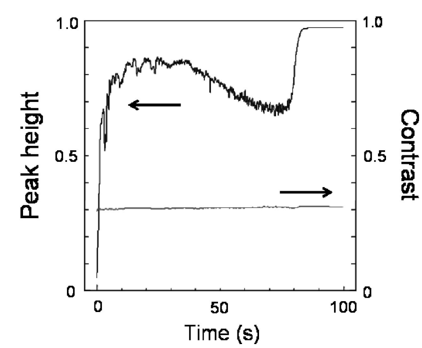

Fig. 4. Comparison between the peak height of normal cross-correlation and the pattern contrast.

Fig. 4 together with the variation of the normal correlation peak height for the poster color. We notice that the contrast remains the same during the entire process and that the exposure time is short enough to freeze the pattern movement. The lower contrast value than unity that is expected for the well-developed speckle is mainly due to a finite resolution of the CCD.

To compare the processes taking place in different regions we employed the imaging system shown in Fig. 5. We divided the whole image into four subimages each of which consisted of 256×256 pixels and was correlated separately. Thus we could compare the regions painted in different manners. Figure 6 shows the variations with different strokes of painting and different materials, poster color and nail polish. It is seen that the poster color dries more quickly than the nail polish and that two strokes of painting result in even slower drying. We could monitor not only the natural