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Monitoring and evaluation of drying of paint by using phase-shifting digital holography

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Abstract. We propose a novel method for monitoring the drying process of a painted surface by using phase-shifting digital holography. In comparison with previous methods using speckle patterns, the proposed method can afford an intensity image for directly monitoring and local variations of drying without an imaging lens. It can also be used for surfaces of complex shapes. In addition, quantitative analysis utilizing a cross-correlation function and phase change derived from the reconstructed complex amplitude is performed and the drying time of paint for different areas and temperature is evaluated. The technique is also applied to monitoring the drying process of a complex surface of a lightbulb. [DOI: 10.1117/1.3284783]

Subject terms: phase-shifting digital holography; cross-correlation; paint drying.

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1 Introduction

The painting of industrial components and products is important for gloss, rust prevention, waterproofing, durability, etc. Many industrial processes involve a coating of components with thin layers of paint. To maintain the quality of components, the quality of painting should be carefully controlled by monitoring the painting process. Drying is also a part of the painting process and hence knowledge of the paint drying process has practical importance. For in-process monitoring, noncontact evaluation of the paint drying process is highly desirable.

Several methods have been proposed to monitor the drying process of painting.[1–5] Recently, a noncontact method for paint monitoring using reflection of tetrahertz electromagnetic waves has been proposed.[1,2] The proposed system could detect a paint thickness. The method, however, requires a special source and is not suitable for quick observation. Dynamic speckle interferometry has been applied to monitor a drying process of several types of paint.[3,4] We also proposed a method which uses the peak height of the cross-correlation function between successive frames of laser speckle patterns observed in the reflected field of a painted surface.[5] It was possible to monitor nonuniform drying by employing an imaging system and comparing the variations in different regions in the preceding method. In practical applications, however, the specimen may not be planar and local variation of drying rate might also be required.

In this paper, we propose a novel method in which the light reflected from the specimen is recorded successively by phase-shifting digital holography[6–8] at an interval depending on drying process and the reconstructed complex amplitude of the image are cross-correlated. In the holographic method, it is also possible to visualize the local variation from images of phase change and the temporal tendency from the cross-correlation of reconstructed intensities between adjacent frames.

2 Principle of Paint Monitoring

The experimental setup is illustrated in Fig. 1. A painted surface of an aluminum plate is illuminated with an expanded beam emitted from a laser diode with a 658-nm wavelength. Paint of a commercial synthetic resin type for a car body was applied to the aluminum plate with a small paintbrush. The color of the paint was silver. The temperature of the aluminum plate was controlled to be constant using a thermoelectric cooler (TEC) and its control circuit. The reflected or scattered beam from the painted surface was interfered with a reference beam reflected from a piezoelectric transducer (PZT) mirror. After applying a phase shift of $\pi/2$ to the reference beam by a PZT mirror, a phase-shifted in-line hologram was captured by a charge-coupled device (CCD) of 512×512 pixels with 8-bit gray levels. The size of a pixel of the CCD is $12.87 \times 12.92\ \mu m^2$. From four phase-shifted holograms we derived the complex amplitude $U_0(x,y)$ at the CCD surface,[6]

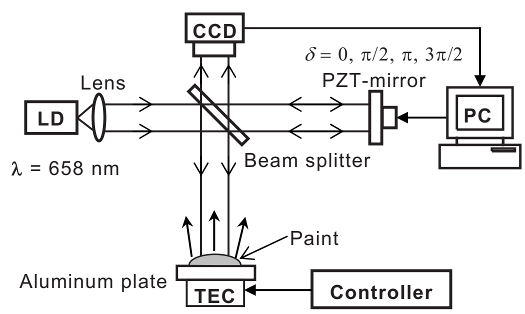
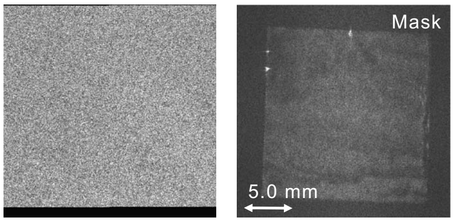


Fig. 1 Experimental setup: LD, laser diode; CCD, charge-coupled device; PC, personal computer; and TEC, thermoelectric cooler.



(a) (b)

Fig. 2 Images of (a) the hologram and (b) the reconstructed intensity images of a painted surface.

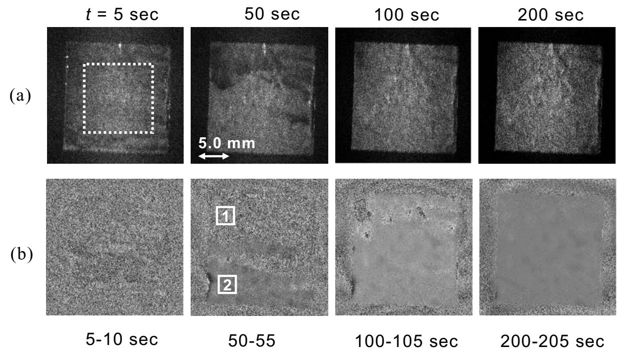


Fig. 3 Reconstructed intensity and phase difference images of the aluminum surface painted with silver paint varied with time: (a) intensity image and (b) phase difference image between adjacent frames.

which was then Fresnel transformed to reconstruct the complex amplitude at the object plane $U(X,Y;t)$ for the instance of hologram recording t:

$$U(X,Y;t) = \exp\left[\frac{i\pi}{\lambda Z}(X^2+Y^2)\right]\int\int U_0(x,y)\exp\left[\frac{i\pi}{\lambda Z}(x^2 + y^2)\right]\exp\left[-\frac{i2\pi}{\lambda Z}(xX+yY)\right]\mathrm{d}x\,\mathrm{d}y, \tag{1}$$

where Z is the reconstruction distance. The total time for the hologram recording was less than 1 s. The reconstruction of the holograms was performed with a single fast Fourier transform (FFT) method.

Figure 2 shows the hologram and reconstructed intensity images of the aluminum plate painted with the silver paint. The recording distance between the CCD surface and the painted surface was 430 mm. A black paper sheet having an aperture of $18\times 18\ \mathrm{mm}^2$ was used for a mask to avoid the aliasing effect. For monitoring a drying process, the recording of the four phase-shifted holograms was repeated with an interval $T=5$ s. The measurements were conducted in a closed room to reduce an influence of air flow. The temperature of the aluminum plate was held to 25 °C during the measurement. As seen in Fig. 2(b), the reconstructed image intensity displayed uniform speckle structure. The undulation seen in the image is due to a local variation of the paint thickness.

3 Experimental Results and Discussion

To investigate the change of image depending on the drying status, the intensity images at various lapses were obtained and are shown in Fig. 3(a). We also took the difference of phase between successive frames and display the results in Fig. 3(b). In Fig. 3(b), after 50 s, they began to display an island structure of a constant brightness surrounded by a uniform speckle pattern showing a local activity. In the area of the island structure, a slight phase change occurs due to the dried state of the paint. The area of the island structure expands as time passes. After 200 s, the distribution of phase difference becomes uniform to infer uniform dryness. In Fig. 3(a), the intensity images also showed a local activity similar to those seen in the phase difference images in Fig. 3(b). In the beginning state of the drying process, the intensity of reflected or scattered light shows a high local activity because the painted surface varies hard in microscopic scale. On the other hand, when the paint is completely dry, the painted surface becomes stable and the intensity distribution of reflected or scattered light no longer shows any temporal variation. Therefore, if the reflected and/or scattered light is recorded successively by digital holography, the drying process can be monitored and evaluated by using a cross-correlation and phase difference between successive images.

To investigate the variation of intensity images quantitatively, we calculated the cross-correlation function $C(X,Y)$ between successive intensities at two instances t_j+T and t_j:

$$C(X,Y) = \int\int I_{tj}(X',Y')I_{tj+T}(X'+X,Y'+Y)\mathrm{d}X'\,\mathrm{d}Y' = F^{-1}[\hat{I}_{tj}(\xi,\eta)\hat{I}^*_{tj+T}(\xi,\eta)], \tag{2}$$

where T is the recording interval. The Fourier transform of $f(x,y)$ and its inverse are defined as

$$\hat{f}(\xi,\eta) = F[f(x,y)] = \int\int f(x,y)\exp[i2\pi(\xi x+\eta y)]\mathrm{d}x\,\mathrm{d}y, \tag{3}$$

and

$$f(x,y) = F^{-1}[f(\xi,\eta)] = \int\int f(\xi,\eta)\exp[-i2\pi(x\xi + y\eta)]\mathrm{d}\xi\,\mathrm{d}\eta. \tag{4}$$

We also calculated the standard deviation σ of phase difference distributions of $\arg[U(X,Y;t_j)U^*(X,Y;t_j+T)]$ and plotted these results as a function of time. The phase of reflected light is supposed to be more sensitive to the microscopic variation of a painted surface than the intensity. The area in the dotted square shown in Fig. 3(a) whose size of 256×256 pixels $(11\times 11\ \mathrm{mm}^2)$ was used to calculate the cross-correlation and standard deviation.

To investigate the local variation of drying state, the peak value of cross-correlation C_p and standard deviation σ of phase difference in both areas 1 and 2 shown as a square in Fig. 3(b) were calculated. The size of both areas 1 and 2 was 64×64 pixels. The temporal variations of peak height of cross-correlation C_p and value of standard deviation σ are shown in Figs. 4(a) and 4(b), respectively. To suppress

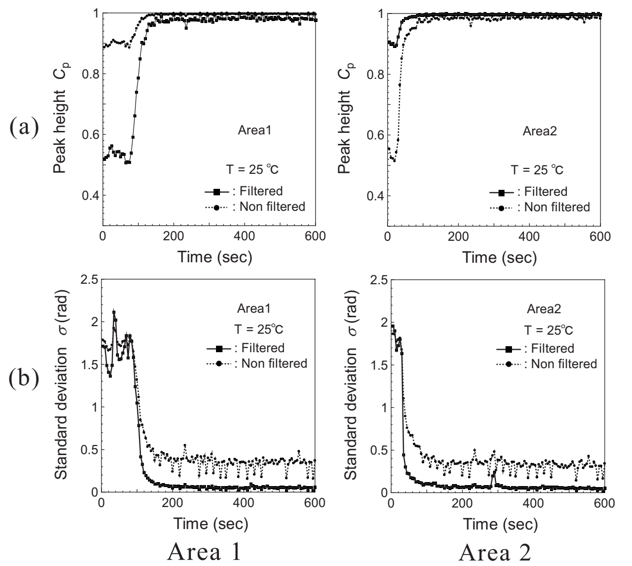


Fig. 4 Time dependence of (a) peak value of cross-correlation function C_p and (b) standard deviation of phase difference σ in the different areas of 1 and 2 in Fig. 3.

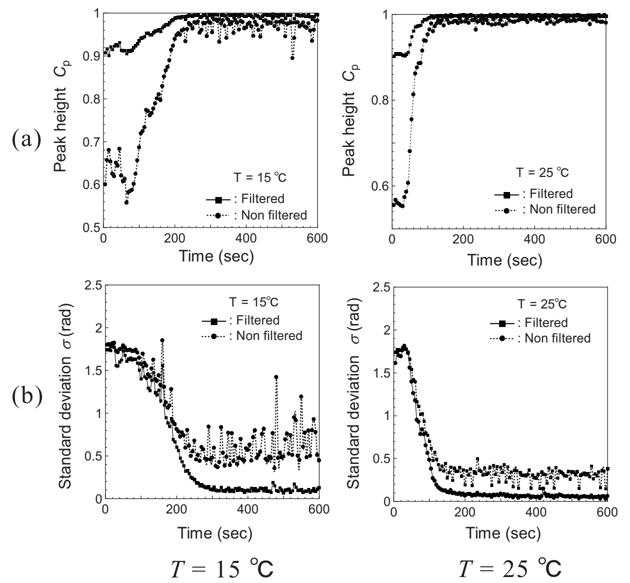


Fig. 5 Temperature dependence of variation in the values of (a) cross-correlation C_p and (b) standard deviation of phase difference σ.

the noise caused by air flow and/or vibration, the reconstructed intensity was subjected to a moving average with a 3×3 matrix before calculating the cross-correlation function. In addition, the value of the phase difference was also obtained by averaging the conjugate product $U(X,Y;t_j)U^{*}(X,Y;t_j+T)$ over a moving 3×3 matrix. These values of C_p and σ obtained after the averaging process were also plotted in Fig. 4 as a filtered value. By virtue of the averaging process, the values of both C_p and σ vary smoothly and show no often seen rapid change in Fig. 4(b). In both Figs. 4(a) and 4(b), the values of both C_p and σ remain practically constant for about 30 or 80 s in both areas. The drying state in such a period is mainly due to evaporation of solvent in the paint.[3] Therefore, the amplitude and phase of the object wave are mainly affected by decreasing the content of solvent in the paint, and the relatively high surface activity continues for a while. After the period of solvent evaporation, the surface activity decreases and then the values of C_p and σ approach a constant. As seen in Fig. 4, the values of both C_p and σ in area 2 approach a constant more quickly than those in area 1. This means that area 2 is drying more quickly than area 1, and the results correspond to those seen in Fig. 3. It is shown that the local variation of drying state can be evaluated with the proposed method. It can be considered that the time when the values of C_p and σ became constant is the drying time. From the results, it is evaluated that drying time of the paint is about 200 s for area 1 and about 150 s for area 2.

Next, to study a temperature dependence of the drying process, the measurement was conducted under different temperatures of the aluminum plate of 15 and 25 °C, respectively. The drying process also depends on the humidity of the environment. Since it is difficult to control the humidity and temperature simultaneously without any special equipment, we concentrated on the study of the temperature dependence of the drying process in the experiment. The results are shown in Fig. 5. It is clearly seen from the changes of both C_p and σ that the temperature of the plate considerably affects the drying process of the paint. By using the reconstructed amplitude and phase, it is shown that both a local variation and temperature dependence of the paint drying process can be monitored.

The technique was also applied to monitoring the drying process of a complex 3-D surface. We used a small lightbulb whose surface was painted with the same silver paint described in the previous experiment. The total height of the lightbulb was 20.0 mm. The recording distance for the lightbulb was 410 mm. The measurement was conducted at a room temperature of 23.6 °C. Figure 6 shows the reconstructed intensity image painted with the silver paint. For clarity, the image was subjected to moving averaging with 3×3 matrix.

Two areas shown as a square of 64×64 pixels in Fig. 6 were analyzed with the same procedure as for the previous experiment and the results are shown in Fig. 7. As seen in Fig. 7, the drying time of area 1 (the head of the lightbulb) becomes much shorter than that of area 2 (a thread surface of the lightbulb). Since the paint in the thread surface

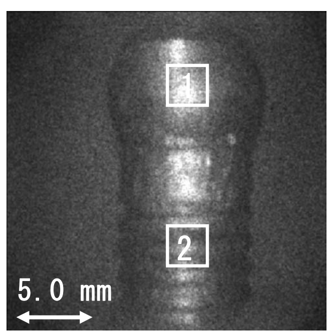


Fig. 6 Reconstructed intensity image of the lightbulb.

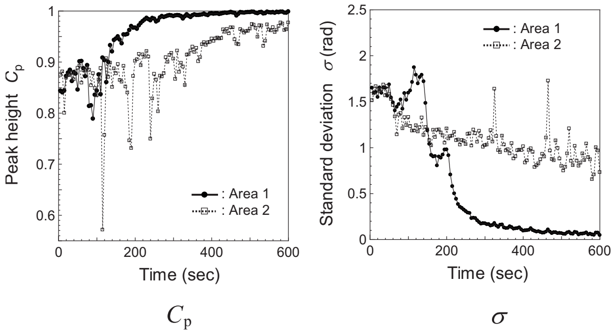


Fig. 7 Time dependence of peak value of cross-correlation function C_p and standard deviation of phase difference σ in the different areas 1 and 2 in Fig. 6.

flowed into the valley of the thread, the thickness of the paint in area 2 increased and the drying time became longer. The results seem to be reasonable and the local variation of the paint drying process in the complex surface of a lightbulb can be detected with the proposed method.

4 Conclusions

We proposed a novel method for monitoring the drying process of a painted surface by using phase-shifting digital holography. By using the reconstructed amplitude and phase of the object wave reflected from the painted surface, the surface activity of paint can be monitored with a noncontact method. The drying state of the paint surface can be detected quantitatively. In comparison with previous methods using speckle patterns, the proposed method can afford an intensity image for directly monitoring local variations of drying without an imaging lens. It can also be used for surfaces of complex shapes such as a lightbulb. In addition, quantitative analysis utilizing a cross-correlation function and the phase change derived from the reconstructed complex amplitude is possible. The proposed method can be applied to industrial applications if environmental disturbances such as vibration and air flow are adequately suppressed.

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