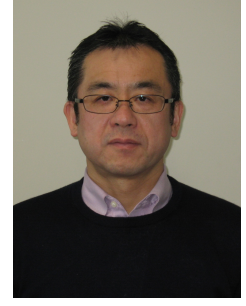


MULTIMODAL METROLOGY USING DIGITAL HOLOGRAPHY FOR INDUSTRIAL APPLICATION: MULTISPECTRAL SHAPE MEASUREMENT AND DEFECT DETECTION TECHNIQUES

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Digital holography has been widely applied to measure three-dimensional surface profiles and various properties of industrial products. In digital holographic techniques, visualization and numerical analysis of surface profiles can be simultaneously obtained from numerically reconstructed holograms. Multiwavelength digital holography is particularly suited for these measurements. This paper discusses a multiscale technique based on multiwavelength digital holography for inner-surface-profile measurements of straight pipes¹ and its multimodal extension achieved by integrating with lock-in thermography². To broaden the multiplexing capability of digital holography, we also introduce a spatiotemporal multiplexing approach into digital holographic interferometry to achieve simultaneous multiscale and multimodal measurements³.

For multiwavelength investigation, multiwavelength digital holography was developed using three lasers as shown in Fig. 1. To investigate an inner wall of a straight pipe, a cone shaped mirror was set in the pipe and scanned along its axis using a stepping motor. For imaging the inner wall, the reconstructed intensity images corresponding to three lasers with wavelengths of λ_1 , λ_3 and λ_4 were merged to generate a color image as shown in Fig. 2(a). Furthermore, the wavelength λ of a red laser diode (LD) was tuned by changing the injection current to LD and two sets of four phase-shifting holograms for wavelength λ_1 and λ_2 were recorded to conduct two wavelength method. By two wavelength method, surface profile Δh of the inner wall of the pipe can be obtained using the phase difference $\Delta\phi$ between the reconstructed phases for both λ_1 and λ_2 as $\Delta h = \Lambda/2 = \lambda_1\lambda_2/(2|\lambda_1-\lambda_2|)$. The surface profile of the inner wall can be seen in Fig. 2(b). Here, Λ is a synthetic wavelength artificially generated using λ_1 and λ_2 . If additional lasers or wavelength tunable lasers are introduced into the DH system, multispectrum imaging and multiscale measurements can be realized.

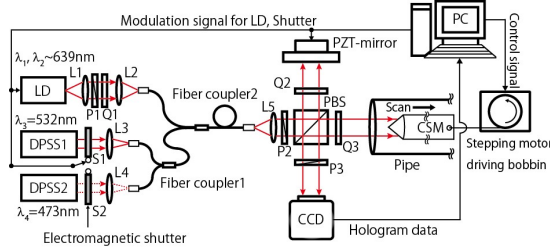
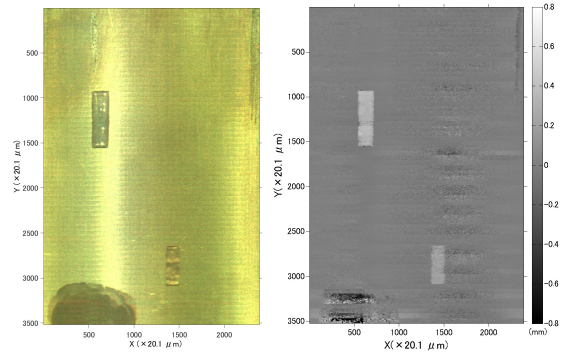


Fig. 1. Setup for a pipe inspection system.

For multimodal investigation using different wavelengths in DH, lock-in thermography was conducted simultaneously with time-series digital holographic interferometry, as shown in Fig. 3. In the setup, digital holograms and thermal infrared images were recorded sequentially at constant time intervals and used for lock-in analysis to detect defects in electronic devices. For the lock-in analysis, an amplitude-modulated signal with a known frequency was applied to a commercial solar-battery film containing artificially fabricated defects. The IR camera detected infrared radiation with wavelengths ranging from 8 to 13 μm emitted by defects in the film. Fig. 4 shows the results obtained with both LIT and DH. Fig. 4(a) shows the hot spots associated with defects detected by LIT, while Fig. 4(b) shows the deformation of the film evaluated



(a) Color image. (b) Surface profile.

Fig. 2. Color and profile images of the inner wall of a brass pipe.

by DH. These results were obtained with an input signal of 3.0 V_{pp} and 0.1 Hz. As seen in both images, the maximum deformation of 80 nm occurs at the hot spot with the highest temperature variation. The information could be used to assess the condition of the solar-battery film.

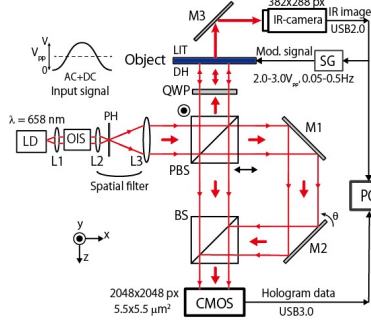
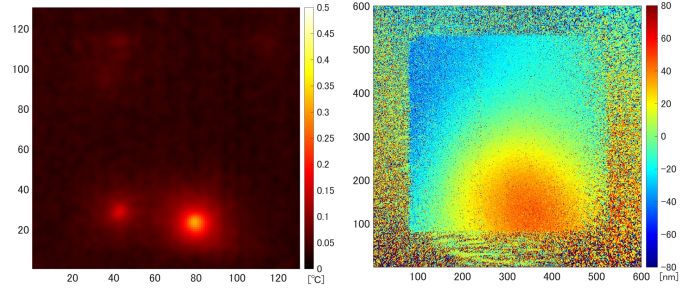


Fig. 3. LIT+DH system.



(a) Defects (LIT). (b) Deformation (DH).

Fig. 4. Results obtained for 3.0Vpp-0.1Hz input.

As discussed above, multispectral and multimodal digital holography can be applied to a wide range of industrial applications. To this end, the information-recording capacity of DH for multiple data streams should be enhanced. In conventional DH, multiplexing of recorded information is typically limited to either spatial-frequency-band multiplexing constrained by the camera pixel size, or temporal multiplexing. Here, we propose a novel off-axis frequency-modulation continuous-wave DH, in which the spatiotemporal frequency domain enables recording of multiple holograms. Since the frequency of LDs is modulated with different saw-tooth functions as shown in Fig. 5, the interference signal detected at CMOS camera varies with a beat frequency f_b depending on the optical path difference between reference and object light waves. Furthermore, by tilting the object angle with different orientations, holograms can be multiply recorded in spatial frequency domain (f_x, f_y).

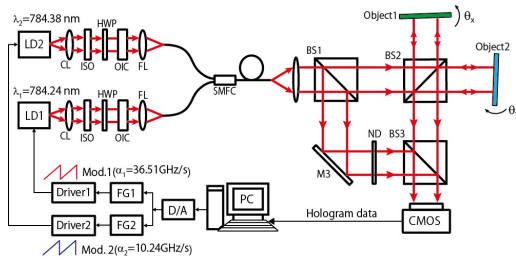
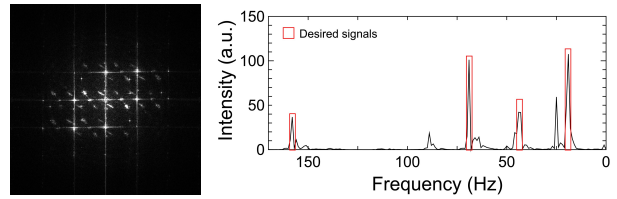


Fig. 5. Off-axis FMCW-DH system.



(a) f_x, f_y domain.

(c) Beat spectrum f .

Fig. 6. Spatiotemporal multiplexing.

As shown in Fig. 6, holograms include the multiple information recorded for both two wavelength and two objects. The information was recorded in both spatial frequency as shown in Fig.6(a) and temporal frequency as shown in Fig. 6(b) domains. Therefore, it is successfully demonstrated to record multiple information using both spatial and temporal frequency domains.

As described above, digital holography can be used to develop measurement techniques that meet a wide range of industrial requirements by utilizing diverse light sources and recording devices. Furthermore, it allows for the expansion of recorded information, and its usefulness is expected to further broaden through integration with emerging technologies such as Artificial Intelligence.

Acknowledgements

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