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Abstract. High-resolution deformation measurement method, which requires only two speckle patterns in electronic speckle pattern interferometry, is proposed by using fringe analysis based on specklegram. In fringe analysis using the proposed optical system, a pair of real- and imaginary-part components concerning the deformation information is extracted from one speckle pattern by Fourier transform in the same manner as the off-axis digital holography processing. A specklegram is calculated as a fringe image by multiplying the components of the real and imaginary part of speckle patterns in order to perform a high-resolution deformation analysis. Then, the phase map concerning deformation is detected from the specklegram, and the influence of speckle noise is also reduced by shifting the component on frequency domain. Furthermore, the amplitude of the intensity distribution of speckle pattern is normalized in order to reduce the influence by speckle noise much more. It is confirmed that the accuracy of the deformation measurement is efficiently improved by the proposed noise reduction methods. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.OE.53.3.034107](https://doi.org/10.1117/1.OE.53.3.034107)]

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1 Introduction

When a coherent light like a laser beam is emitted to a rough surface, the scattering light from the rough surface interferes in a complex manner. Then, speckle patterns can be observed as the phenomenon of such interference.¹⁻³ Generally, the phase information as the intensity distribution of the scattering light from the surface of the measured object is recorded in the speckle pattern. Usually, the deformation measurement of the object with rough surfaces has been performed by using this information.¹⁻⁵

In the 1960s, speckle interferometry based on this phenomenon was developed. The technology was frequently employed in the field of vibration analysis. Furthermore, electronic speckle pattern interferometry was also developed by introducing TV-camera technology into the speckle interferometry.¹⁻⁵ In the latter half of the 1980s, fringe scanning technology¹ was introduced to speckle interferometry. Then, the resolution power of speckle interferometry was improved to $\sim 1/100$ of wavelength of light source.^{4,6} In the 1990s, deformation measurement based on temporal carrier technology using high-speed cameras was reported.^{7,8} Successively, a high-resolution power measurement method based on the temporal carrier technology was also developed by extending this technology as two-dimensional (2-D) analysis using virtual speckle patterns.⁹

Recently, the demand of such a dynamic and high-resolution measurement in industrial fields has increased. In particular, the measurement of an object with rough surfaces is required. Some new measurement methods using speckle interferometry are proposed.¹⁰ Special optical systems are

also developed for high-speed measurement.¹⁰ However, the shape and the location of speckles that hold the phase information of deformation usually change in a complex manner in the case of a large deformation in the process of deformation.¹⁻³ This feature of speckle is a big problem in deformation measurement with large deformation. Furthermore, when the deformation speed increases more, a much higher-speed camera is required for performing the deformation measurement by ordinary methods,¹ which must use many sheets of speckle patterns for the analysis. In order to avoid such problems, a new method that can analyze phenomena by the minimum number of sheets of speckle patterns and that does not use any higher-speed camera has been required.¹¹⁻¹⁵ Generally, there are two kinds of analysis methods.¹¹ One is the method that would directly analyze speckle patterns.^{16,17} The other one is the method that analyzes the specklegram produced from speckle patterns. In this method, a high-resolution fringe analysis can be performed by using the skilled filtering technology in fringe analyzing process.^{9,10} Then, one sheet of specklegram is calculated by using two sheets of speckle patterns grabbed before and after the deformation.⁶ That is, at least two speckle patterns are required for producing one sheet of specklegram. However, it has been difficult to perform a high-resolution deformation measurement with only one sheet of specklegram by ordinary fringe analysis method.

In this paper, the basic feature of speckle is discussed on the process of producing speckles, and the new feature of speckle pattern concerning the spatial information that has never been discussed before is introduced to the fringe analysis process in speckle interferometry. Finally, the new deformation measurement method is proposed by using the new

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feature of the speckle patterns without using any high-speed camera. At the same time, a new optical system is set up for employing such a feature. In the new method, only two sheets of speckle patterns grabbed before and after a deformation are used for the deformation analysis by employing 2-D filtering technologies.^{6,18,19}

In this paper, two novel noise reduction methods are proposed without using any filtering technologies. The measurement accuracy of the new method is first improved by shifting the information concerning the deformation on the frequency domain. Second, the influence by a fluctuation of intensity of speckle that is spatial noise in speckle intensity is again reduced by normalizing the amplitude of intensity of speckle patterns. In this paper, two kinds of improvements of fringe analysis by this shifting and the normalization of the amplitude of speckle intensity distribution are discussed.

In the experiments for confirming the validity of the principle, the out-of-plane deformation measurement is performed by using only two speckle patterns grabbed before and after deformation by the proposed method. It is confirmed that a high-resolution deformation measurement by the new method can be realized by using the filtering technology. It is shown that the object that includes the convex or concave phase distribution can also be measured by this method.

2 Three Kinds of Information Distribution in Speckle Pattern Grabbed by New Optical System

In this paper, the optical system as shown in Fig. 1 is set up. The pixel size of camera is $2.2 \mu\text{m}$. In this optical system, the reference beam is given as a flat wave. That is, a reference beam is not influenced by observing-lens system of the optical system by setting a bypass of the reference beam. The spatial information is given in each speckle by using the flat wave reference beam, and the frequency of the spatial information recorded in speckle can be controlled by adjusting the yawing angle of mirror-2 in the optical system. The speckle patterns [see Figs. 2(a) and 2(b)] before and after deformation are grabbed by the optical system. A specklegram is generally calculated as a fringe image concerning the deformation of the measured object.^{6,9,10,18} Then, the measured deformation, which is treated in this paper, is illustrated as the specklegram shown in Fig. 2(c), and the deformation is an out-of-plane deformation.

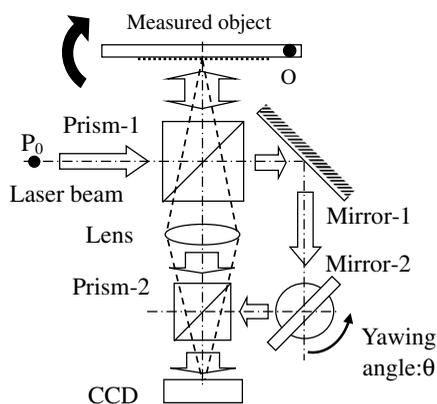


Fig. 1 Optical system.

In the fringe analysis in this paper, there are some features of interest. For example, seemingly, the speckle patterns as observed in Figs. 2(a) and 2(b) grabbed under this operation are not different from the ordinary speckle pattern. However, when a part of the speckle pattern is magnified, it is confirmed that there are small circular grains that are overlapping with each other as shown in Fig. 2(d). These grains are some speckles. Furthermore, we find that there are vertical interference fringes in the speckle pattern. Then, the existing area of these interference fringes is restricted to the inside of each speckle. The pitch of the fringes is almost the same as the pitch of fringes in the adjacent speckle. However, these fringes are not connected between each speckle. There is also a special feature in this speckle pattern. That is, when the speckle pattern is transformed to the frequency domain from the spatial domain by Fourier transform, the speckle pattern has a special information distribution in frequency domain as shown in Fig. 3(a). A binary image of the information distribution in frequency domain shown in Fig. 3(a) is illustrated in Fig. 3(b) in order to impress visually the distribution of information. The information distribution is constructed by three components as shown in Fig. 3(b) shown in previous reports.²⁰ However, it has already been reported that the information concerning the deformation was included only in the special signal distribution that was shaped as a circle as shown in Fig. 3(b).²⁰ At the same time, it is also known that this phenomenon is the same situation as off-axis digital holography.²¹

As shown in Fig. 2(d), because the direction of the fringes in speckles is vertical, the position of the central frequency of the circle information is located horizontally and symmetrically at both sides of bias position in Fig. 3(b). In this case, the intensity distribution of speckle pattern, $I_0(x, y)$, can be described as Eq. (1).^{6,18}

$$I_0(x, y) = a(x, y) + b(x, y) \cos[2\pi f_0 x + \phi(x, y)], \quad (1)$$

where f_0 is the central frequency of the information that is shaped as a circle in frequency domain. Here, $a(x, y)$ is bias component, $b(x, y)$ is amplitude, and $\phi(x, y)$ is an initial phase information that includes random component.

As shown above, there are some features in the speckle patterns that are grabbed by the optical system shown in Fig. 1. In this paper, a novel deformation measurement method is proposed by using these new phenomena of speckle interferometry.

3 Deformation Measurement by Using only Two Speckle Patterns with Fourier Transform

3.1 Fringe Analysis by Using only Two Speckle Patterns

There are two kinds of analyzing processes for deformation measurement method using speckle fringes analysis. They are difference of phase method and phase of difference method.¹¹ The former is the method that would directly analyze speckle patterns.¹¹⁻¹⁷ The total deformation information is given from the difference between the phase maps of each speckle pattern. The idea of this analysis method is generally the same as the off-axis digital holography technology.²¹ However, the method cannot be hoped for a high-resolution fringe analysis because the complicated signal with some speckle noise has to be treated directly in the processing.¹¹⁻¹⁷ On

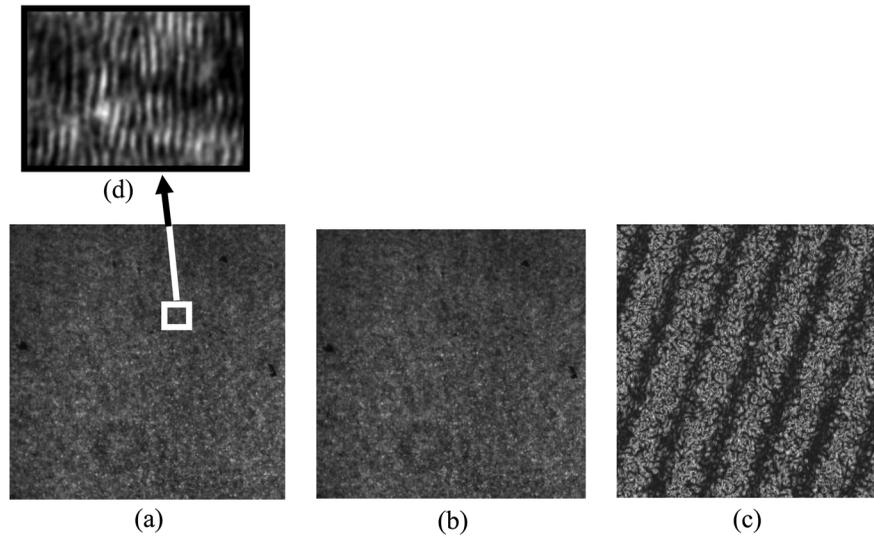


Fig. 2 Speckle patterns and specklegram. (a) Speckle pattern before deformation. (b) Speckle pattern after deformation. (c) Specklegram by speckle patterns before and after deformation. (d) Fringes in speckle.

the other hand, a high-resolution fringe analysis can be performed by using the skilled filtering technology for fringe analyzing process in the latter method.^{9,10} In this paper, the latter method, which can perform a high-resolution analysis by using filtering technology,^{18,19} is employed.

Here, it is assumed that the intensity of speckle patterns (S_0, S_1) before and after the deformation are generally given as shown in Eqs. (1) and (2), respectively.

$$I_1(x, y) = a(x, y) + b(x, y) \cos[2\pi f_0 x + \phi(x, y) + \Delta\phi(x, y)], \quad (2)$$

where $\Delta\phi(x, y)$ is phase changing value by the deformation of an object.

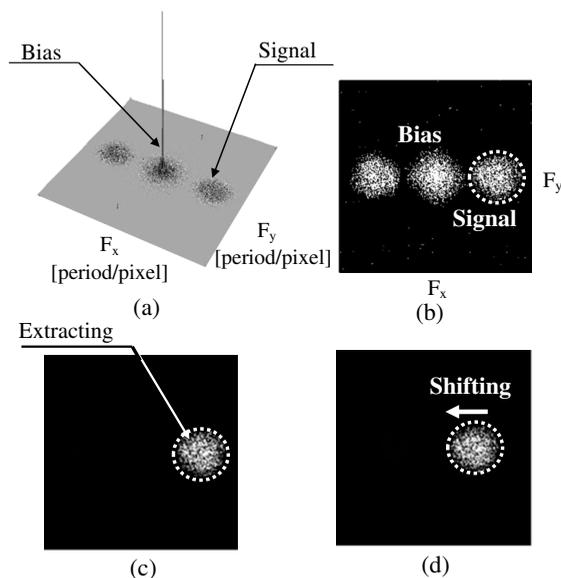


Fig. 3 Speckle pattern before deformation in frequency domain. (a) Speckle pattern in frequency domain. (b) Speckle pattern in frequency domain. (c) Signal component. (d) Shifted signal component.

Then, the intensity distribution of the specklegram is generally given as Eq. (3) by using square operation of difference between speckle patterns grabbed before and after the deformation.⁶

$$\begin{aligned} I_{sg}(x, y) &= [I_0(x, y) - I_1(x, y)]^2 \\ &= b(x, y)^2 + b(x, y)^2 / 2 \times \cos 2[2\pi f_0 x + \phi(x, y)] \\ &\quad + b(x, y)^2 / 2 \times \cos 2[2\pi f_0 x + \phi(x, y) + \Delta\phi(x, y)] \\ &\quad - b(x, y)^2 \cos[4\pi f_0 x + 2\phi(x, y) + \Delta\phi(x, y)] \\ &\quad - b(x, y)^2 \cos \Delta\phi(x, y), \end{aligned} \quad (3)$$

In Eq. (3), the first term is a bias component. The fifth term is fringe image information. It is thought that the other terms are noise components because all of them include random noise component, $\phi(x, y)$. Therefore, it is important that only fringe image information is extracted as a specklegram in the operation.

On the other hand, the intensity of speckle pattern as shown in Eq. (1) is also given as $I_0(x, y)$ by Eq. (4) as shown by Takeda.²²

$$I_0(x, y) = a(x, y) + c(x, y) \exp(2\pi i f_0 x) + c(x, y) * \exp(-2\pi i f_0 x), \quad (4)$$

where $c(x, y) = (1/2)b(x, y) \exp[i\phi(x, y)]$; symbol “*” is described as a complex conjugate. The spatial frequency for x direction is shown as f_0 . Now, when the intensity distribution shown in Eq. (4) is transferred to frequency domain by Fourier transform, Eq. (4) is transferred as Eq. (5).²²

$$F[I(f, y)] = A(f, y) + C(f - f_0, y) + C * (f + f_0, y), \quad (5)$$

Furthermore, only $C(f - f_0, y)$ is extracted by filtering as shown in Fig. 3(c) from Fig. 3(b) in frequency domain, and the extracted information is transferred to spatial domain by inverse Fourier transform. A pair of the real and imaginary part of the information is given by $c(x, y) \exp(2\pi i f_0 x)$,

shown in Eq. (6) as the same manner of Fourier method by Takeda.²²

$$\begin{aligned} I_{0R}(x, y) &= \text{Re}[c(x, y) \exp(2\pi i f_0 x)] \\ &= \text{Re}\{(1/2)b(x, y) \exp[2\pi i f_0 x + i\phi(x, y)]\} \\ &= (1/2)b(x, y) \cos[2\pi f_0 x + \phi(x, y)], \end{aligned} \quad (6)$$

$$\begin{aligned} I_{0I}(x, y) &= \text{Im}[c(x, y) \exp(2\pi i f_0 x)] \\ &= \text{Im}\{(1/2)b(x, y) \exp[2\pi i f_0 x + i\phi(x, y)]\} \\ &= (1/2)b(x, y) \sin[2\pi f_0 x + \phi(x, y)]. \end{aligned} \quad (7)$$

By the above operations, the information of speckle patterns that is shaped as the circle in frequency domain is separated as the sine and cosine components. Then, the separated signal includes no bias component signal.

In a manner similar to the above operations, the sine and cosine signals of the speckle pattern after the deformation are given as Eq. (8) without any bias component.

$$I_{1R}(x, y) = (1/2)b(x, y) \cos[2\pi f_0 x + \phi(x, y) + \Delta\phi(x, y)] \quad (8)$$

$$I_{1I}(x, y) = (1/2)b(x, y) \sin[2\pi f_0 x + \phi(x, y) + \Delta\phi(x, y)]. \quad (9)$$

Furthermore, if the ordinary square operation of the difference between speckle patterns grabbed before and after the deformation as shown in Eqs. (6) and (8) would be performed as the calculation for producing a specklegram under ordinary method, the new bias component occurs again in the specklegram as shown in Eq. (3). Therefore, in this paper, the multiplication operations as shown in Eqs. (10) and (11) using a pair of Eqs. (6) and (8) and a pair of Eqs. (6) and (9), respectively, are performed instead of using square operation as ordinary method in order to produce specklegram. As the results, the intensity distribution of specklegram can be given as Eqs. (10) and (11).

$$\begin{aligned} SG_1(x, y) &= (1/2)b(x, y) \cos[2\pi f_0 x + \phi(x, y)] \\ &\quad \times (1/2)b(x, y) \cos[2\pi f_0 x + \phi(x, y) + \Delta\phi(x, y)] \\ &= (1/8)b(x, y)^2 \{ \cos[4\pi f_0 x + 2\phi(x, y) + \Delta\phi(x, y)] \\ &\quad + \cos\Delta\phi(x, y) \} \end{aligned} \quad (10)$$

$$\begin{aligned} SG_2(x, y) &= (1/2)b(x, y) \cos[2\pi f_0 x + \phi(x, y)] \\ &\quad \times (1/2)b(x, y) \sin[2\pi f_0 x + \phi(x, y) + \Delta\phi(x, y)] \\ &= (1/8)b(x, y)^2 \{ \sin[4\pi f_0 x + 2\phi(x, y) + \Delta\phi(x, y)] \\ &\quad - \sin\Delta\phi(x, y) \}. \end{aligned} \quad (11)$$

In Eqs. (10) and (11), the cosine and sine components of the information concerning the deformation are calculated. Furthermore, intensity distributions shown in Eqs. (10) and (11) are filtered in order to obtain specklegrams concerning the cosine and the sine components as Filtered[SG₁] and Filtered[SG₂], respectively. In this filtering processing, 2-D

band pass width is decided by an operator. Finally, a phase map of the deformation can be detected from specklegram shown in Fig. 4(a) as Fig. 4(c) using Eq. (13). This is the basic fringe analysis method that is proposed in this paper. This processing for detecting a phase map of the deformation of the object has been already proposed in many papers.^{19,22}

$$\Delta\phi(x, y) = \arctan(-\text{Filtered}[SG_2]/\text{Filtered}[SG_1]). \quad (12)$$

In the case of the phase map shown in Fig. 4(c), the standard deviation of the difference between the actual deformation by a piezoelectric transducer (PZT) and the measured result by this method is 0.114 rad. Clearly, there is locally an undulation in the phase map because there is a lot of 1/f noise as speckle noise around the foot of the signal shown in Fig. 4(b).

3.2 Noise Reduction for Improvement of Measuring Accuracy in Basic Fringe Analysis

A phase map is given in Fig. 4(c) by the basic fringe analysis using Eq. (12) from speckle pattern shown in Fig. 4(a). However, it is confirmed that there is a noise source as 1/f noise around the foot of the fringe signal shown in Fig. 4(a). If the noise source is removed, it can be thought that the measurement accuracy would be improved much more. In this paper, two noise reduction methods are proposed: (1) by shifting the signal on frequency domain and (2) by normalizing the amplitude of the signal.

3.2.1 Improvement by shifting the signal on frequency domain

When the intensity distribution shown in Eq. (4) is transferred to frequency domain by Fourier transform, Eq. (4) can be written as Eq. (5). Furthermore, when the result by Fourier transform is shifted by changing the frequency domain as shown in Fig. 3(d), the shifted result is given by Eq. (13). Then, the shifting frequency value is f_s .

$$\begin{aligned} \mathbf{F}[I(f, y)] &= A(f, y) + C(f - f_0 - f_s, y) + C \\ &\quad * (f + f_0 + f_s, y). \end{aligned} \quad (13)$$

In this case, only speckle pattern before the deformation is shifted by subtracting f_2 on frequency domain. Then, the specklegram as shown in Eq. (10) is given as Eq. (14).

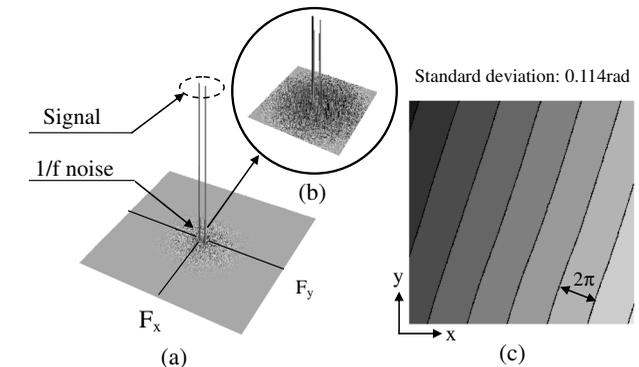


Fig. 4 Result of fringe analysis by basic method. (a) Fringe signal. (b) Noise. (c) Phase map from Fig. 4(a).

$$\begin{aligned}
SG_s(x, y) &= (1/2)b(x, y) \cos[2\pi(f_0 - f_s)x + \phi(x, y)] \\
&\quad \times (1/2)b(x, y) \cos[2\pi f_0 x + \phi(x, y) + \Delta\phi(x, y)] \\
&= (1/8)b(x, y)^2 \{ \cos[(4\pi f_0 - 2\pi f_s)x + 2\phi(x, y) \\
&\quad + \Delta\phi(x, y)] + \cos[2\pi f_s x + \Delta\phi(x, y)] \}. \quad (14)
\end{aligned}$$

When the frequency of the component is shifted on frequency domain, in comparison with the result by not shifting on frequency domain, it is confirmed that the distribution of 1/f noise decreases as shown in Fig. 5(b) from Fig. 4(b). Generally, the 1/f noise around the foot of each signal overlaps as shown in Fig. 4(a) in the case of no shift because the signals of conjugation by Fourier transform are too near in frequency domain. However, 1/f noise shown in Fig. 5(a) is not superimposed by shifting frequency, f_s . The signals are separated from such a noise source in frequency domain. As a result, S/N ratio of signal is improved by shifting the signal on frequency domain. That is, the influence of the noise on S/N ratio is reduced to about half by the cancellation of the overlap. It is confirmed that this effect would result in higher-resolution power than the method without shift. Also, this information that is shifted is analyzed by spatial fringe analysis method⁶ in the processing for calculating phase map. The spatial fringe analysis method that is used in this paper is based on the Moiré phenomenon.^{6,18} Therefore, the measurement accuracy is much efficiently improved by the averaging effect based on the feature of Moiré phenomenon against 1/f noise.

3.2.2 Improvement by normalizing the amplitude of signal

The influence of 1/f noise can be reduced by the normalization of the amplitude of intensity distribution. The intensity distributions shown in Eqs. (6) and (8) also include a noise source concerning a fluctuation (1/f noise) in the amplitude $b(x, y)$. In this paper, the amplitude of intensity distribution as shown in Eq. (6) is estimated by using the operation shown in Eq. (16). Then, the influence of the noise source concerning 1/f noise is also reduced by using the estimated amplitude as shown in Eq. (16). Then, the amplitude of the speckle pattern can be defined as shown in Eq. (17).

$$b'_0(x, y) = \sqrt{I(x, y)^2 + I(x, y)^2}, \quad (15)$$

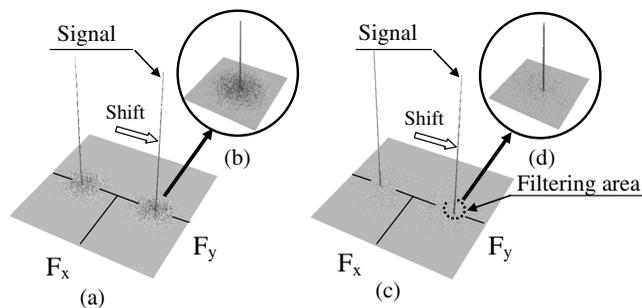


Fig. 5 Specklegram with carrier information. (a) Shifted fringe signal. (b) Noise. (c) Shifted and normalization fringe signal. (d) Noise.

$$I_{sp}(x, y) = I_{0R}(x, y)/b'_0(x, y). \quad (16)$$

Furthermore, the specklegram as shown in Eq. (15) can be described as Eq. (17) by using this normalization process.

$$\begin{aligned}
SG(x, y) &= \cos[2\pi(f - f)x + \phi(x, y)] \\
&\quad \times \cos[2\pi f x + \phi(x, y) + \Delta\phi(x, y)] \\
&= 1/2 \{ \cos[(4\pi f - 2\pi f)x + 2\phi(x, y) + \Delta\phi(x, y)] \\
&\quad + \cos[2\pi f x + \Delta\phi(x, y)] \}. \quad (17)
\end{aligned}$$

As a result, the influence of 1/f noise is reduced much more by the normalization of the amplitude of intensity distribution as shown in Fig. 5(d).

3.3 Detection of Phase Map of Deformation

In the calculating process of phase map, the shifted and normalized signal component is extracted by the 2-D band-pass filter as shown in Fig. 5(c). The fringe image with the carrier information is given by the filtering operation.^{18,19} Then, the phase map is given as shown in Fig. 6(a) by using spatial fringe analysis method.^{6,18} In the case of the result that is analyzed from Fig. 5(c), the standard deviation of the difference between the actual deformation given by the PZT and the measured result by this method is 0.013 rad. It is a very high-resolution measurement result.

The result of the shifted signal that is operated by no normalization of amplitude is shown in Fig. 6(b). The standard deviation of the difference between the actual deformation given by the PZT and the measured result that is given from Fig. 5(a) by this method is 0.048 rad.

By comparison with the result of the case of no shift and no normalization shown in Fig. 4(c), the measuring accuracy by the proposed operation for noise reduction in this paper is clearly improved as shown in Fig. 6(a). It is confirmed that the measurement accuracy by the new method is higher than 1/200 wavelength because this optical system is constructed as a double path interferometry. As a result, it can be confirmed that the proposed method for reducing the influence of some noise source is useful at the point of improving the measurement accuracy of speckle interferometry.

The wrapped phase map detected by difference of phase method¹¹⁻¹⁷ is obtained in Fig. 7(a) by analyzing the same data shown in Figs. 2(a) and 2(b). In this method, each phase map before and after deformation of the object is

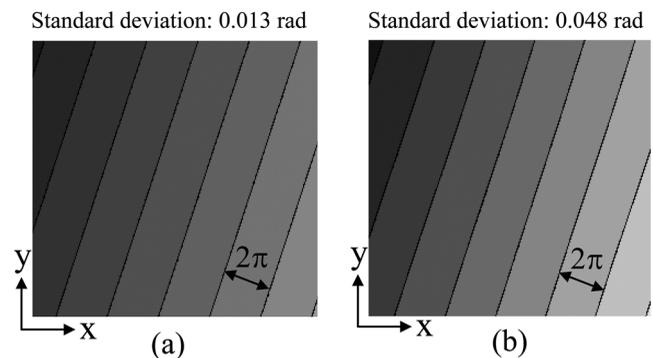


Fig. 6 Detected phase maps under noise reduction. (a) Phase map from Fig. 5(c). (b) Phase map from Fig. 5(a).

detected from each speckle pattern. Then, the total wrapped phase map as shown in Fig. 7(a) is calculated by subtracting between these phase maps of speckle patterns. This analyzing idea is fundamentally the same as the processing of digital holography.²¹ Though the phase distribution concerning the deformation is observed in this phase map, it is too noisy to unwrap the wrapped total phase map shown in Fig. 7(a). In this case, the speckle size is set as 15 μm in order to separate the bias and the signal components in frequency domain as shown in Fig. 3(a). So, there are a lot of noises in low-frequency area. The phase map detected by difference of phase method includes a lot of low-frequency noise. Only area of wrapped phase map, which can be analyzed smoothly, is shown in Fig. 7(a). In Fig. 7(b), the wrapped phase map concerning the center area of the unwrapped phase map shown in Fig. 6(a) is shown. The area shown in Fig. 7(b) corresponds to the area of Fig. 7(a). It is confirmed that the wrapped phase map shown in Fig. 7(b) is smoother than the result shown in Fig. 7(a). From these results, it is confirmed that fringe analysis method based on phase of difference method is useful for noise reduction in speckle interferometry. It should also be noted that speckle interferometry is the method for detecting deformation measurement. The purpose of speckle interferometry is different from digital holography. Though both speckle interferometry and digital holography are technologies based on the same phenomena, we should think that there must be the optimum fringe analysis method depending on the purpose of measurement. That is, the idea based on difference of phase method is useful in digital holography; however, it can be confirmed that the fringe analysis based on phase of difference method is also useful in speckle interferometry for detecting the deformation.

3.4 Measurement Result for Concave Phase Distribution

In the previous section, a deformation by the rotation of flat plate was measured for the investigation of the measurement accuracy of the new method. In this section, the measured object is the deformation of a beam by a force shown in Fig. 8(a). That is, the measurement possibility of the measurement object that includes the convex or concave phase distribution is checked in this experiment.

The measured results are shown in Fig. 8. The unwrapped phase map shown in Fig. 8(e) can also be detected by performing the same fringe analysis operation used in Fig. 6(a)

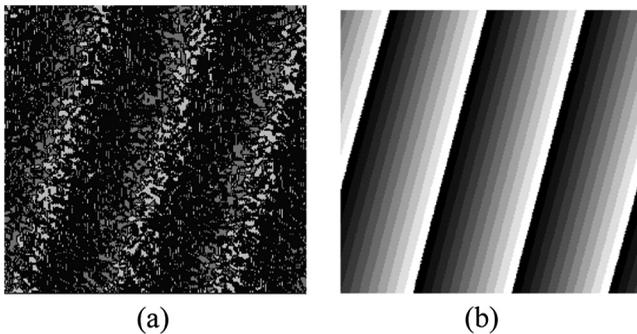


Fig. 7 Comparison of wrapped phase maps by difference of phase method and phase of difference method. (a) Difference of phase method. (b) Phase of difference method.

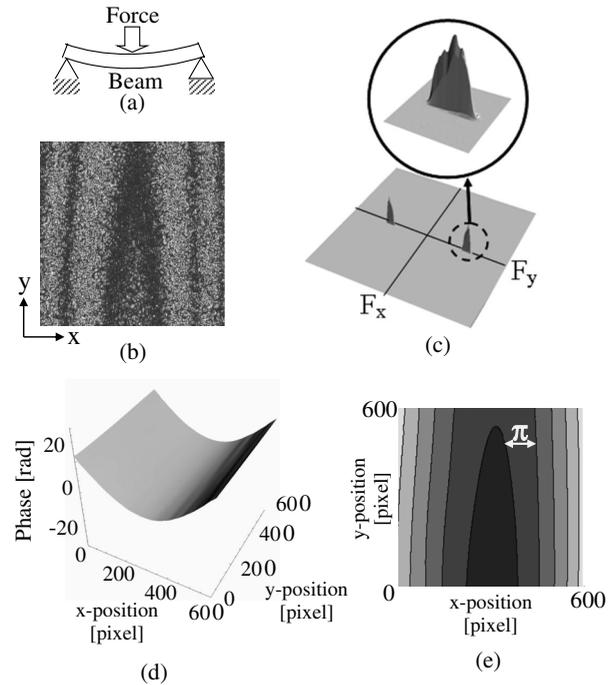


Fig. 8 Measured results. (a) Measured object. (b) Specklegram. (c) Shifted fringe image information in frequency domain. (d) Phase map. (e) Contour phase map (one step: π rad).

as the case of the deformation of the rotation of the plate. From these results, it is confirmed that this method can analyze the object that includes the concave phase distribution. In this paper, it is confirmed that the new speckle interferometry can analyze the measured object with not only the monotone phase distribution, but also the concave phase distribution by using only two speckle patterns before and after the deformation of the object.

4 Conclusion

The measured phenomena that change rapidly have to be grabbed by a high-speed camera, for example, in the measurement of the destruction of an object, and so on. Generally, a lot of speckle patterns must be physically grabbed for analyzing such phenomena in high resolution. However, it is usually difficult to catch such phenomena without using a special high-speed camera. Furthermore, there must be a physical limitation of the crank speed of high-speed camera. Therefore, a measurement method without using a lot of speckle patterns in the analysis of a high-speed event has been strongly required.

In this paper, the method by the new feature of speckle pattern concerning the fringe analysis based on Fourier transform was discussed so that dynamic events can be measured without any special high-speed camera. The optical system was set up for using the new feature of speckle interferometer. The phase map of the deformation of the object was detected by using fringe signals with a high S/N ratio under phase of difference method, which can fulfill higher accuracy measurement than difference of the phase method. Namely, it was confirmed that the fringe analysis based on phase of difference method was the useful fringe analysis processing in speckle interferometry.

Furthermore, in the proposed processing, the influence by $1/f$ noise source was reduced by shifting and normalizing the amplitude of speckle intensity distribution in order to obtain fringe images with high S/N ratio. Then, the high-resolution analysis of the speckle interferometry was improved efficiently.

As a result, a new speckle interferometry that would be able to measure a high-speed deformation by using only two speckle patterns grabbed before and after the deformation was proposed by using the new feature of speckle pattern. It is confirmed that the new speckle interferometry can analyze the measured object with not only the monotone phase distribution but also the concave phase distribution by using only two speckle patterns before and after the deformation of the object in some experiments.

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