Dynamic ESPI (DESPI) and Hilbert transform method for deformation analysis of MEMS and very small object

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ABSTRACT

In this study a Dynamic Electronic Speckle Pattern Interferometry (ESPI) method was applied to investigate deformation field of small industrial elements. In the proposed phase analysis method, the interference signal is considered in time domain and the phase was analyzed by Hilbert transform method. Two experiments were performed, with in-plane and out-of-plane sensitive systems in order to make a complete characterization of the deformation field in three dimension. First, experiments were carried out for the measurements of thermal expansion of a joint material (ceramic-copper-stainless steel). The deformation field showed clearly the difference between the thermal expansions of the stainless steel and ceramic. The thin copper layer can also be clearly distinguished in the deformation distribution. Next, experiments were performed for a scratch-drive device of MEMS. Movement of the element of the device was accurately measured while the device is operating.

Keywords: Electronic Speckle Pattern Interferometry, Phase analysis, Deformation, Hilbert transform, MEMS

1. INTRODUCTION

The Electronic Speckle Pattern Interferometry (ESPI) is an optical interferometric technique appropriate for measurements of mechanical characteristics of objects with diffusely scattering surfaces [1-3]. Although the technique originated in the 1970s, its rapid development started in the late 1980s, owing to the improvement of the electronic devices, such as CCD cameras and computers, together with the introduction of the phase shifting methods [3]. The variable that provides information about the deformation of the object under study and that can be measured by ESPI is the phase derived from the interference signal. In order to determine the phase, there exist numerous methods. They can be classified as phase shifting methods (in space and time domain) and Fourier transform method with spatial carrier. The temporal phase shifting methods can provide measurements with high precision; however, they are mostly appropriate for static and quasi-static phenomena, since the object should be stationary during the acquisition of at least three consecutive frames [3,4]. In the spatial phase shifting method the phase shift is separated out in space and recorded either on one frame that contains several images with different phase shift, or is recorded simultaneously on several cameras that are separated in space. This makes the optical systems more complicated and expensive. As a result, the method becomes more sensitive to environmental conditions such as vibration and air turbulence. The Fourier transform method is widely used in fringe analysis in conventional interferometry. However, in ESPI it suffers significantly from the speckle noise. As a result the measurement accuracy is reduced, as well as the spatial resolution, compared to phase shifting methods. One other disadvantage of the spatial phase shifting and Fourier transform method is that the unwrapping procedure is performed in space domain. If there are discontinuities in the wrapped phase values, the unwrapping procedure becomes very difficult to perform automatically.

To address the problems with the existing phase analysis methods outlined above, and to extend the ESPI to dynamic phenomena analysis, in recent years, several methods have been reported that allow the phase analysis for dynamic phenomena [5-8]. In these methods the interference signal is considered in temporal domain, instead of spatial domain. If the temporal development of the interference intensity at every pixel is considered, a fairly good signal that is free from speckle noise can be obtained. This will simplify the calculation procedure, and improve the measurement range of the data, as well as the accuracy of the method.

The purpose of this paper is to report the application of Dynamic ESPI (DESPI) with Hilbert transform (HT) method for phase analysis to investigate the deformation field of small industrial object, e.g., a joint material and a Micro-Elector-Mechanical-System (MEMS). The joint materials are used widely in mechanical constructions. They are subjected to different mechanical stresses, including thermal loading. The studies of thermal expansion of joint materials especially over very restricted area around the boundary of the materials are therefore of great interest in
experimental mechanics. We carried out two experiments with in-plane and out-of-plane sensitive systems in order to study the 3D deformation field due to thermal expansion.

We used MEMS to demonstrate the effectiveness of our technique in investigating dynamic deformation as MEMS device is getting increasing attention in the field of optical communication as a promising switching device and micro-mechanical engineering, etc. One instance of optical MEMS, which is already in market, is the device used in digital video projector. In those applications of the MEMS device, the accuracy of the movement is the most important factor. Therefore, demand to establish new techniques that can inspect the movement of very small optical elements has been on the rise.

2. METHOD

The main idea and the detail of the temporal Hilbert transform method have been already presented in our previous study[8]. Here, we are going to outline only the main points. Let us consider a typical optical system to measure the in-plane deformation of the object illustrated in Fig.1. Detail description for the experiment will appear in section 3.1. The interference speckle images obtained in dynamic ESPI (DESPI) can be represented by

\[ I(x, y, t_i) = I_0(x, y, t_i) + I_m(x, y, t_i) \cos \{ \phi(x, y, t_i) \} \quad i = 1, 2, 3, \ldots \]

where \( t_i \) is the time the \( i \)-th frame of speckle interference pattern is taken, \( I_0(x, y, t_i) \) and \( I_m(x, y, t_i) \) are the bias and the modulation intensities, respectively. This expression for interference speckle image holds generally in the other type of optical system. \( \phi(x, y, t_i) = \theta(x, y, t_i) + \phi(x, y, t_i) \) is the signal phase, where \( \theta(x, y, t_i) \) is the random phase of the speckle field, which varies rapidly in space domain and very slowly in time domain. Therefore, the rapid change of speckle phase in space causes very large noise, and it makes the phase analysis very complicated or degrade the accuracy of the derived phase. In the proposed method, phase analysis is carried out in temporal domain. The advantage of the shift from spatial to temporal domain, where the phase analysis is performed, is clearly understood from the temporal signal that is fairly free from the noise. A typical temporal signal is shown in Fig.2.

\[ \phi(x, y, t_i) \]

is the phase due to the object deformation, which is the main value of interest in ESPI, since it provides information of object under testing such as deformation, strain, vibration etc. \( \phi(x, y, t_i) \) usually varies very slowly in space domain and might vary rapidly in time domain. If we consider the time domain, we can regard each point independently in space. We can associate interference signal at each point with a complex wave function \( \psi(t) = u(t) + iv(t) \) where the imaginary part is the HT of the real part. The HT of \( u(t) \) is defined by

\[ v(t) = \text{HT}[u(t)] = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{u(t')}{t'-t} dt' \]
HT\{u(t)\} is a linear functional of \( u(t) \) and is equivalent to the filtering that gives phase shift by \( \pi/2 \). By taking the arctangent function of the ratio between the imaginary and real parts of the complex wave function we, can determine the phase \( \Phi(x, y, t) \) of the interference signal. In order to calculate the Hilbert transform, we used MATLAB Signal processing toolbox [9-10] for FIR filters design. The ideal Hilbert transformer is characterized by a frequency response

\[
H_{HT}(e^{i\omega}) = \begin{cases} 
1, & -\pi < \omega < 0 \\
-i, & 0 < \omega < \pi 
\end{cases}
\]

The impulse response \( h_{HT}[n] \) of the Hilbert transformer is obtained by computing the inverse discrete-time Fourier transform and is given by

\[
h_{HT}[n] = \begin{cases} 
0 & \text{for } n \text{ even} \\
\frac{2}{\pi} \frac{1}{n} & \text{for } n \text{ odd}
\end{cases}
\]

3. EXPERIMENTAL SET-UP AND RESULTS

The object of this study was a joint material of ceramic and stainless steel with a thin copper layer inserted by brazing. The thermal expansion coefficients of the three materials are: \( 3 \times 10^{-6}/K \) for ceramic, \( 17.7 \times 10^{-6}/K \) for copper, and \( 15 \times 10^{-6}/K \) for stainless steel. The considerable difference in the thermal expansion coefficients between the ceramic and the stainless steel will lead to accumulation of stress in the boundary between the two materials, if the specimen is to be heated. In order to examine the thermal expansion of the joint material, two different experiments, measurements of in- and out-of-plane displacement of an object, were carried out. The optical systems are shown in Fig. 3 and Fig. 1. In both experiments a high-speed Photoron FASTCAM-PCI camera was used. After the data had been acquired, the phase analysis using HT was performed in the following stages. In the first stage, a three-dimensional matrix \( \mathbf{M}(x, y, t) \) is created by successively taking frames of interference signal. In the second stage, the bias intensity is estimated and removed from the interference pattern for each pixel and matrix \( \mathbf{M}'(x, y, t) \) is created. Following, a HT is performed for the matrix \( \mathbf{M}'(x, y, t) \) in temporal domain and the wrapped phase value is determined. If the deformation field has discontinuities, as for example the appearance of a crack, the unwrapping in space domain will become difficult. The unwrapping procedure in time domain does not suffer these kinds discontinuities problems, since the signal is considered separately for every pixel. In addition, the direction of unwrapping is straightforward. The unwrapped phase values are recorded as two-dimensional images, which represent the space development of the deformation. Because some pixels have low modulation intensity, the phase in these pixels could not be determined correctly. These pixels give spiky noise in the final results. To remove this noise, a median filter is applied in space domain.

3.1. In-plane measurements

The optical system to measure the in-plane deformation of the object is illustrated in Fig.3. A semi-conductor laser of the wavelength 680 nm was used as a coherent light source. The injection current was set to 103 mA. The beam is collimated to illuminate the sample and the mirror at angle of 45°. Half of the light beam illuminates directly the object. The other half of the light beam is reflected from the mirror and illuminates the object at a - 45° angle. The sensitivity vector lies in x-y plane parallel to the x direction. The high-speed CCD camera was arranged perpendicularly to the surface of the specimen, and the speckle patterns were taken at the acquisition rate of 60 fps. The f/# of the camera lens...
was adjusted to 16 to give an optimal correlation fringe contrast. The resolution of 512 by 240 pixels with size 15 µm was used. In order to determine the sign of the thermal expansion, a temporal carrier was introduced by moving the mirror by PZT. The observation area of the object was 3.5mm x 8mm. The thickness of the copper layer between the stainless steel and ceramic plates is 0.35 mm. The object was placed on the Peltier device to induce temperature change. The overall increase in the temperature was from 25°C to 55°C. The in-plane measurements in x and y direction of the object were carried out separately. After the data acquisition a three dimensional matrix with the raw data was constructed. The HT filter window size was chosen to include on average 5 periods of the cosine function – 59 points in time domain. The same size of the averaging window was adopted. Fig. 4 shows the deformation field of the object in parallel to the boundary of the joint material. The object was initially heated and then the temperature was gradually reduced. It can clearly be distinguished the position of the ceramic and the stainless steel. While the ceramic shrunk slightly, the stainless steel shrunk considerably. In Fig. 4 one side along the object was taken as a reference zero deformation. Figure 5 demonstrates the deformation in y direction, i.e., perpendicular to the boundary. The deformation of the stainless steel is significant compared to the ceramic. In a cross section of the deformation field along the specimen shown in Fig. 6, a local peak (indicated by arrow) followed by a negative slope in the deformation profile can be seen. This part represents the copper layer between the stainless steel and the ceramic. These results are in accordance with our previous measurements obtained by using statistical interferometry [11].

3.2. Out of plane measurements

The optical set-up for out-of-plane measurement is illustrated in Fig. 1. This is a Michelson type interferometer with diffusive surface employed for the generation of the reference speckle pattern. A semiconductor laser of wavelength 680 nm was used as a light source. The injection current was set to 103 mA. The sensitivity vector is normal to the plane of the object. The speckle fields from the reference object and the specimen interfere in the plane of the CCD camera. In this experiment, the same camera in section 3.1 was used. The f/ of the camera lens was set to 11. The frames were taken continuously with acquisition rate of the camera 30 fps. The observation area of the object was 3.5 mm x 8 mm. The conditions for the thermal heating of the specimen were the same as in the in-plane measurements. Figure 7 gives

Fig. 4 Deformation field of the joint material in parallel to the boundary at 10 seconds after the initial heating of the specimen, when the longer side of the object was placed parallel to the reference surface

Fig. 5 Deformation field for the in-plane system at 10 seconds after the initial heating of the object, when the longer side of the object was placed perpendicular to the reference

Fig. 6 Cross-section along the specimen for y direction deformation measurements
2D deformation field for out-of-plane measurement system at 17 second after the initial heating of the specimen. Similar to the in-plane measurements a jump-like deformation field was observed. Also the copper layer can clearly be distinguished.

3.3 Displacement measurement of MEMS
In the next experiment, MEMS of scratch-drive device that is designed to carry a micro object on it was observed. Figure 8 shows the photograph of the device. The device consists of an array of a small plate of size 70µm x 140µm as shown in Fig. 9. When a voltage is applied to the device, the movable element is attracted toward the base plate owing to the electrostatic force. As a result, other end of the element moves upward, and drives a small object mounted on the device to the right side (see the illustration of one element in Fig.9).

In the experimental system, the optical system is basically same with that in the experiment of out-of-plane displacement in the section 3.2. However, the light source was replaced with LD of wavelength \( \lambda = 405\text{nm} \) since much smaller structure has to be resolved in the current experiment. Equivalently, this change of the light source reduce the speckle size because the speckle size is proportional to the wavelength of the light used and equal to the resolution of the imaging system. The observation system was also improved to sufficiently magnify the object using an objective lens with relatively longer working distance of 64mm and magnifications x50 to x400.

The observed deformation field of the five elements of the device under the applied voltage 14V is shown in Fig.10. Figure 11 shows that the displacement of the central element under sinusoidal driving signal with the amplitude 0-14V. It can be seen that the maximum displacement of the central element is 300nm at its end. Moreover, it was found that two elements at right and left ends of the array moves in a different manner from the others. Obviously, this behavior of the movement is an unexpected one, and may be caused by the deformation of the beam where 8 elements are lifted. Because originally, the device was designed to work with ten times higher applied voltage, the experiment might be carried out under a rather transient condition of the object.

4. CONCLUSIONS
In this paper, we applied ESPI for studies of thermal expansion of a joint material and inspection of dynamic movement of a scratch-drive device of MEMS. The phase analysis method based on Hilbert transform (HT) method is performed over
the temporal interference signal. We examined the influence of the bias and modulation intensities on the calculated phase values. The variations in the bias intensity contribute mostly to the errors in the phase values. To reduce the influence of the bias intensity variations it was removed prior to performing the HT operation. The obtained deformation field showed clearly the difference between the thermal expansions of the stainless steel and ceramic of the joint material. The thin copper layer can also be clearly distinguished as a jump-like change in the deformation field, where most of the stress will be accumulated. It was also confirmed that the present method is useful for the inspection of the MEMS device. It was revealed that unexpected movement was taking place under a transient condition of the device.

Acknowledgements
This work was partly supported by a Grant-in-Aid for Development of Science Research (B)(13555193) of the Japanese Ministry of Science and Education. We thank Dr. Yoshio Arai for kind discussions about the joint material, which he supplied. Authors also thank Dr. Hane at Tohoku Univ. for providing a sample device of MEMS.

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