

Study of thermal expansion in a joint material by optical Hilbert transform method for phase analysis based on orthogonal linear polarization phase shifting

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We study thermal expansion in a joint material (ceramic-copper-steel) by optical interferometry with spatial phase shifting. The method for quantitative phase analysis is based on optical Hilbert transform (HT) method. It uses both temporal and spatial interference signal, where HT is carried out optically by separation of orthogonal components of polarized light via Wollaston prism. The phase is obtained from the cosine and sine interference patterns that are recorded simultaneously in one frame. Volume data representing the temporal development of 2D deformation field were obtained. The accuracy of the method was estimated to $\lambda/10$.

Keywords: spatial phase shifting, phase analysis, thermal expansion, joint material

INTRODUCTION

In many structural components ceramic-metal joint materials are used. Such joint materials are subjected to different mechanical stresses due to the difference in thermal expansion coefficients and elastic modules, which can lead to fracture of the material. Therefore the studies of the deformation of the joint materials under thermal loading are of great interest in experimental mechanics. Optical interferometry as a method that provides high spatial and temporal resolution is an ideal one for *in-situ* measurement of dynamic events [1]. To obtain the deformation field, in optical interferometry it is necessary to analyze the phase distribution. Currently there exist numerous methods that mainly include Fourier transform for fringe demodulation, phase shifting and Wavelet transforms [2]. For dynamic event analysis of special interest are the spatial phase shifting methods, because the phase shift is carried out in one frame. Recently, several methods for spatial phase shifting have been proposed [1-11] that can be used for studying both static and dynamic events. Generally they use either diffractive element or a polarizing element to perform the spatial phase shifting, where in one frame two, three or four phase shifted images are recorded. In

all these methods, however, some additional technique is required to estimate the bias intensity. Moreover, the unwrapping of the phase is performed in space domain, which is not always a trivial task, especially in speckle metrology and in circularly distributed fringe patterns, for example. In this study we propose a method that combines both time and space domain to obtain the phase distribution and does not require capturing of additional reference images. To obtain the bias intensity we use temporal averaging of the interference signal. The unwrapping of the phase is also performed in time domain, which makes the method entirely automatic and straightforward. The spatial phase shifting is carried out with Wollaston prism where the orthogonal components of polarized light are separated spatially and recorded in one frame. Since in one frame we capture both sine and cosine functions, we call this optical Hilbert transform. We implemented the method for studying temporal development of deformation field in joint material (ceramic-copper-stainless steel) due to thermal expansion.

EXPERIMENTAL

In the experiment, a Michelson interferometer was constructed with light source SHG-YAG laser at wavelength of 532 nm. The schematic of the setup is shown on Fig. 1. Linearly polarized light from the laser passes through a quarter-wave plate

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(QWP) and is converted into circularly polarized light. The light beam is equally split into a reference and a sample beams by a non-polarizing beam splitter (NPBS). The circularly polarized light is incident to the sample. A polarizer at +45° with respect to the horizontal direction is introduced in the reference arm that converts the circularly polarized light into linearly polarized one.

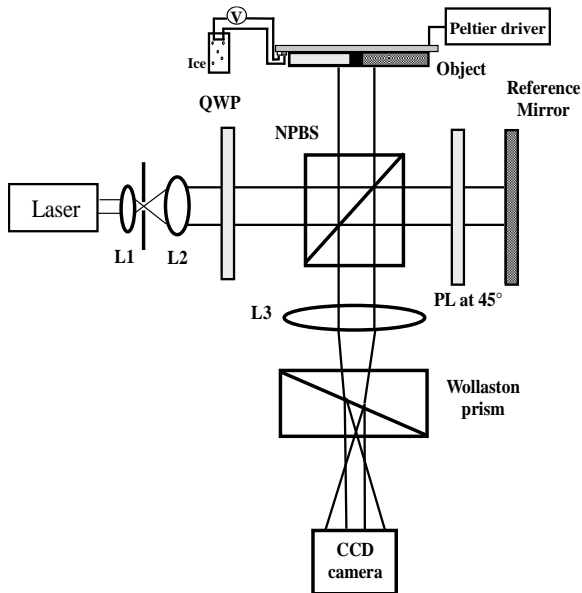


Fig. 1. Michelson type interferometer for spatial phase shifting. L1-L3 lenses; PL – polarizer; NPBS – Non polarizing beam splitter; QWP – quarter wave plate.

The reference and sample beams are recombined at the NPBS where there is a $\pi/2$ phase difference between the horizontal and the vertical component. The two orthogonal components, which represent the sine and cosine interference patterns, are spatially separated by Wollaston prism. They are captured in one single frame with CCD camera (Sony XCL-U1000) with resolution of 1200x1600 pixels and acquisition rate of 15 frames/s. Fig. 2 illustrates one frame of spatially shifted sine and cosine fringe patterns. The imaged part of the specimen is 3 mm by 6 mm.



Fig. 2. Spatially shifted patterns, imaged on the CCD camera plane.

The mathematical expressions for interference patten have been previous presented in our work

[12]. They were obtained using Jones matrices formalism. Here we present only the expressions for the sine (Eq. 1) and cosine (Eq. 2) functions, and the estimated phase (Eq. 3):

$$I_{si}(x, y, t) = I_{bias}(x, y) + I_m(x, y) \sin\left(\Delta\varphi(x, y, t) - \frac{\pi}{4}\right) \quad (1)$$

$$I_{co}(x, y, t) = I_{bias}(x, y) - I_m(x, y) \cos\left(\Delta\varphi(x, y, t) - \frac{\pi}{4}\right) \quad (2)$$

where $I_{bias}(x, y)$, $I_m(x, y)$ and $\Delta\varphi(x, y, t)$ are the bias intensity, modulation intensity and the phase difference between the reference and object fields, respectively. The bias intensity and the modulation intensities in general do not vary considerably in time, especially in short time span, which allows us to obtain them by applying some signal processing method in time domain. In our experiment the sine $I_{si}(x, y, t)$ and cosine $I_{cos}(x, y, t)$ fringe patterns are captured continuously and we can obtain $I_{bias}(x, y)$ by averaging the frames in time over the whole acquisition interval. The obtained $I_{bias}(x, y)$ image is binarized and then used to determine the identical points on each sine and cosine patterns. This procedure is critical to the correct calculation of the phase value. The translation vector of sine image towards cosine is determined by using the autocorrelation function of the binarized image and used to adjust positions of sine and cosine images. After subtracting the bias intensity, translating the sine image to overlap the cosine image, the phase can be obtained as follow:

$$\Delta\varphi(x, y, t) - \pi/4 = \tan^{-1}\left(\frac{I_{si}(x, y, t) - I_{bias}(x, y)}{I_{bias}(x, y) - I_{co}(x, y, t)}\right) \quad (3)$$

The phase is then unwrapped in time domain, where each point is unwrapped independently, converted into deformation field and filtered in space domain with median filter to remove the spiky noise. The two-dimensional distribution of the deformation field yielded in this manner can be followed in time, since it is obtained for each point in time.

RESULTS AND DISCUSSIONS

In this experiment we use joint material Ceramic-Copper-Stainless Steel illustrated in Fig. 3.

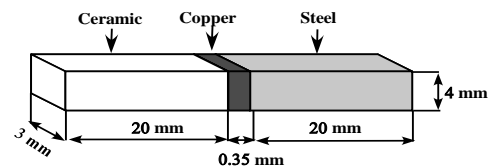


Fig. 3. Schematics of the joint material

The linear thermal expansion coefficients as follows: ceramic (Si_3N_4) - $3 \times 10^{-6}/\text{K}$; copper - $17.7 \times 10^{-6}/\text{K}$ and stainless steel - $15 \times 10^{-6}/\text{K}$.

The joint material was heated from 33 °C to 51 °C and then cooled from 60 °C to 46 °C using a Peltier device. During the heating frames were captured, until temperature reaches predetermined value. The same was performed when the sample was cooled. The temperature of the Peltier device was monitored with thermocouple. These data were used to stop the acquisition of the frames when no change in the temperature was monitored. Fig. 4 shows the temporal change in the temperature, compared with the temporal change in the deformation at one point. It demonstrates clearly that the deformation growth follows nearly the same slope as the temperature change slope.

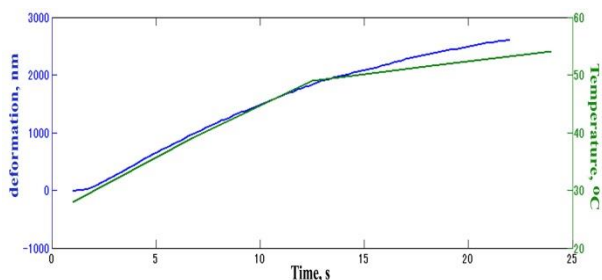


Fig. 4. Comparison between the temperature growth and the deformation growth at given point of the deformation field.

Fig. 5 shows two-dimensional distribution of the deformation field due to temperature change from 33 °C to 51 °C. The step-like change that occurs due to considerable difference in the linear thermal expansion coefficients can clearly be seen. There are several areas with remaining spikes, where the phase was not correctly determined. The incorrect determination of the phase is mainly due to incorrect overlapping of the sine and cosine images and the presence of high level of noise.

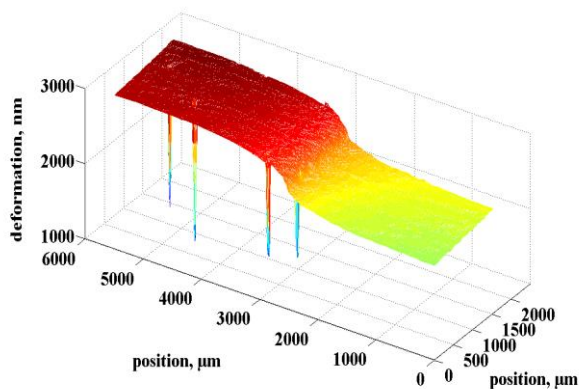


Fig. 5. Two dimensional distribution of the deformation field due to temperature change from 32 °C to 50 °C.

We examine the difference between the deformation in the steel and in the ceramics.

Theoretically it has to be 864 nm and we estimated it experimentally to be 811 nm. The deviation of $\lambda/10$ from the theoretical value accounts for the imperfection in the polarisation elements, the presence of noise, the expansion of materials along other directions, the uneven surface of Peltier device, and the incorrect superposition of the sine and cosine fringes. The method is especially sensitive to incorrect superposition and can be improved by the improving the autocorrelation algorithm.

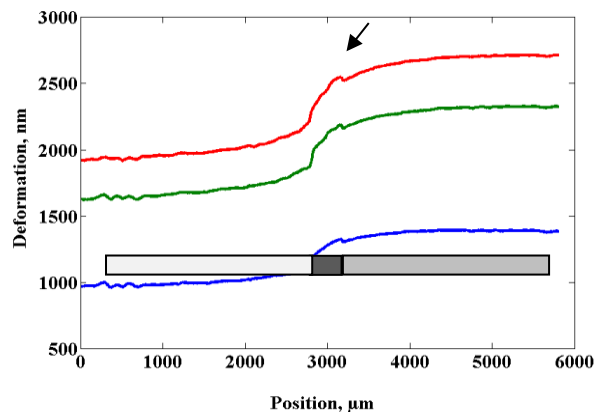


Fig. 6. Cross-sections of deformation at different moments of thermal load at 40 °C – blue line, 48 °C – green line and 51 °C – red line.

In Fig. 6 we demonstrate cross-sections along ceramic-copper-steel at different moments of thermal load (40 °C, 48 °C and 51 °C). The step-like distribution of deformation can clearly be seen. It can be noticed also a slight dent (indicated by arrow in Fig. 6) in the curve corresponding to the joint between the copper and steel and caused by the slight difference in their thermal expansion coefficients.

CONCLUSIONS

In this paper we presented spatial phase shifting method based on the separation of orthogonal components of polarized light via Wollaston prism. The phase analysis method is performed in both space and time domain. The method was applied for studying thermal expansion of joint material. We demonstrated two dimensional step-like distribution of the deformation field that is due to considerable difference in the thermal expansion coefficients of ceramic and steel. The temporal change of deformation for different thermal loads was also demonstrated. The method achieved $\lambda/10$ accuracy that can be improved further by applying a more sophisticated algorithm for superposition of sine and cosine patterns.

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ИЗСЛЕДВАНЕ НА ТЕРМИЧНО РАЗШИРЕНИЕ НА СЪСТАВЕН МАТЕРИАЛ ЧРЕЗ ОПТИЧНА ХИЛБЕРТ ТРАНСФОРМАЦИЯ ЗА АНАЛИЗ НА ФАЗАТА, ОСНОВАНА НА ФАЗОВО ОТМЕСТВАНЕ НА ОРТОГОНАЛНО ЛИНЕЙНО ПОЛЯРИЗИРАНА СВЕТЛИНА

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(Резюме)

Изследвано е термичното разширение при съставен материал (керамика-мед-стомана) с помощта на оптична интерферометрия с пространствено отместване на фазата. Методът за количествен анализ на фазата се основава на оптична Хилберт трансформация (ХТ). Той използва както времевия, така и пространствения интерференчен сигнал, където ХТ се извършва оптично чрез разделяне в пространството на ортогонално поляризираните компоненти на поляризираната светлина с помощта на призма на Уластън. Фазата е получена от cosine и sine интерференчни ивици, записани едновременно в един кадър. Получени са обемни данни, които дават времевата промяна на 2D полето на деформация. Точността на определяне на деформацията е оценена на $\lambda/10$.