MEMS MEASUREMENT BY DIGITAL HOLOGRAPHIC MICROSCOPE

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ABSTRACT

A universal digital holographic microscope to measure shape and displacement of microelement and MEMS (Micro Electro Mechanical Systems) is presented. This device is designed to exploit a measurement for MEMS with either a smooth or a rough surface. The method is based on digital laser interferometry and digital laser speckle interferometry (TV-holography) incorporated with optoelectronic devices including a diode laser, a long distance microscope (LDM), optics, a CCD camera and a high precise phase shifting technique, etc. The measuring system has a capability to measure contour, out-of-displacement/deformation, vibration of microelements. It is also possible to measure residual strain in some case. In this paper, the theory and methodology of the universal digital laser micro-interferometer are described. The usefulness of the micro-interferometer is demonstrated by examples of shape and displacement measurement for different MEMS.

Keywords: MEMS, microelements, Shape, displacement/deformation, vibration, residual stress, microscope, holography, interferometry.

1 INTRODUCTION

The fast growing industries of microelement and MEMS and the demands for greater product quality and reliability generate new challenges for measurement techniques. Optical methods enjoy the virtues of being whole-field, non-contacting and non-contaminating and are emerging as strong candidates.

Electronic Speckle Pattern Interferometry (ESPI) – also called TV-holography, is a technique to be able to measure whole field deformation for the samples with a rough surface. So far, it has been well established as a measuring tool for measuring displacement and thus strain/stress on a macroscopic level. Measurement on a microscopic level by TV-holography has been studying in recent years. This technique should also be effective in measuring deformation for microelements. However, it is suitable only for measuring samples with rough surface.

Nowadays, the applications of microelements and MEMS have spread all over the fields such as telecommunication, computer, aerospace and automobile industries. Different microelements and MEMS have been developed for special purposes. The requirement for their surface is also different, for instance, MEMS or MEMS array switch needs a smooth surface, whereas some MEMS used in sensor and actuator applications don't need a smooth surface. Therefore, it is greatly required by the industries to develop a universal micro-interferometer that is suited both for samples with smooth and rough surface.

In this paper, a universal digital holographic microscope based on a modified Michelson interferometer is described. With the micro-interferometer, a whole field out-of-plane displacement distribution both on smooth and rough surface can be quantitatively determined incorporated with the phase shifting technique. This device can be used to measure the shape or residual strain of samples with smooth surface as well.

2 MEASUREMENT PRINCIPLES

The universal digital holographic microscope is based on a modified Michelson interferometer and a developed software package for quantitatively evaluating an interferometric pattern. Fig. 1 shows the optical layout. The incoming laser beam is adapted to the corresponding field of view after through a tunable attenuator. Various types of laser can be used for
illumination; a high performance diode laser with a wavelength 650 nm and power of 30 mW which has a capability to produce a CW (for static measurement) and a stroboscopic (for dynamic measurement) is used in the device. The laser beam illuminates both an object surface to be tested and a reference surface via a beam splitter cube. The reference surface could be either a flat mirror or a scattering surface according to different purposes. The reference object is mounted on a high performance piezo translator (PZT) to provide phase shifting capability. The reference object is easily exchangeable for converting from a smooth to rough surface by means of a threaded mount. The specimen is mounted on a 6-freedom translation stage (translation in x, y, z and rotation about x, y and z axis). Various objective lenses can be chosen in order to image the specimen onto the CCD array of a CCD-camera. In this device, the Sony XC-ST70 CCD camera with a resolution of 752(H) x 582(V) pixels and the OPTEM zoom 100 series long-distance microscope (LDM) which has about 90mm working distance are adopted. Using this zoom LDM, the object as big as 5x7 mm and as small as 0.05x0.05mm can be accurately measured.

![Fig. 1. Experimental arrangement](image)

The laser beams reflected from the object and reference surface recombine after they emerge from the beam splitter. This results in an interference pattern that is recorded by the CCD camera. The recorded images are evaluated by a developed software in combination with phase shifting technique. As we know, there are three unknowns in a recorded intensity image (cf. Eq. 1.1). These are background \( I_0(x,y) \), contrast \( \gamma(x,y) \) and phase distribution \( \psi(x,y) \) which is related to the optical path difference (OPD) between the object beam and reference beam. Generally speaking, one needs at least three equations to determine the unknowns from the equation with three unknowns. The phase shifting method is a technique to quantitatively determine the phase distribution of an interference pattern by recording three (or more) intensity images corresponding to different amounts of phase shift so as to get three (or more) equations. The following shows briefly the fundamental for calculating phase distribution \( \psi(x,y) \) by recording three, four and five intensity images:

For recording three images, the phase shift is 120°. Digitizing three intensity patterns of three images provides the three equations:

\[
\begin{align*}
I_1(x,y) &= I_0(x,y) + \gamma(x,y) \cos[\psi(x,y)] \quad (1.1) \\
I_2(x,y) &= I_0(x,y) + \gamma(x,y) \cos[\psi(x,y) + 120^\circ] \quad (1.2) \\
I_3(x,y) &= I_0(x,y) + \gamma(x,y) \cos[\psi(x,y) + 240^\circ] \quad (1.3)
\end{align*}
\]

Thus the phase distribution \( \psi \) can be solved quantitatively

\[
\psi(x,y) = \arctan \frac{\sqrt{3} [I_1(x,y) - I_2(x,y)]}{2I_1(x,y) - I_2(x,y) - I_3(x,y)}
\]
The phase shifting 120° and 240° can be obtained by moving the reference object to small displacements $\lambda/6$ and $\lambda/3$, respectively.

It is simpler and faster by using a four phase-shift algorithm:

\[ I_1(x,y) = I_0(x,y) + \gamma(x,y) \cos[\phi(x,y)] \]  \hspace{1cm} (2.1)

\[ I_2(x,y) = I_0(x,y) + \gamma(x,y) \cos[\phi(x,y)+90°] \]  \hspace{1cm} (2.2)

\[ I_3(x,y) = I_0(x,y) + \gamma(x,y) \cos[\phi(x,y)+180°] \]  \hspace{1cm} (2.3)

\[ I_4(x,y) = I_0(x,y) + \gamma(x,y) \cos[\phi(x,y)+270°] \]  \hspace{1cm} (2.4)

The phase shifting 90°, 180° and 270° can be obtained by moving the reference beam to small displacements $\lambda/8$, $\lambda/4$ and $3\lambda/8$, respectively. The phase distribution is given by:

\[ \phi(x,y) = \arctan \left[ \frac{I_4(x,y) - I_2(x,y)}{I_1(x,y) - I_3(x,y)} \right] \]  \hspace{1cm} (2.5)

A five phase-shift algorithm is more precise than three and four phase shift algorithms and it has been adopted for the phase determination of the device shown in Fig. 1.\(^6\)^\(^7\) (However, the developed software has a capability to use all of three, four and five phase shift algorithms):

\[ I_1(x,y) = I_0(x,y) + \gamma(x,y) \cos[\phi(x,y)-180°] \]  \hspace{1cm} (3.1)

\[ I_2(x,y) = I_0(x,y) + \gamma(x,y) \cos[\phi(x,y)-90°] \]  \hspace{1cm} (3.2)

\[ I_3(x,y) = I_0(x,y) + \gamma(x,y) \cos[\phi(x,y)] \]  \hspace{1cm} (3.3)

\[ I_4(x,y) = I_0(x,y) + \gamma(x,y) \cos[\phi(x,y)+90°] \]  \hspace{1cm} (3.4)

\[ I_5(x,y) = I_0(x,y) + \gamma(x,y) \cos[\phi(x,y)+180°] \]  \hspace{1cm} (3.5)

The phase distribution can be solved quantitatively by:

\[ \phi(x,y) = \arctan \left[ \frac{2[I_2(x,y)-I_4(x,y)]}{-I_1(x,y)+2I_3(x,y)-I_5(x,y)} \right] \]  \hspace{1cm} (3.6)

If the tested object has a smooth surface, a mirror should be selected as the reference object. In this case, the interference pattern is usually a visible fringe pattern and the phase map [i.e. the quantitative distribution of $\phi(x,y)$] is a visible fringe pattern as well. Such kind of fringe pattern has usually information of object contour. Fig. 2a shows the phase map of such an interference pattern.

If the tested object has a rough surface, a scattering surface should be selected as the reference object. In this case, the interference pattern is a speckle pattern, the phase distribution $\phi(x,y)$ is a random pattern and thus no fringes can be observed from the interference pattern or from the phase map. Fig. 2b shows the phase map of a speckle pattern. Although there are no visible fringes in such a pattern, a difference between two speckle patterns corresponding to two object states (e.g. before and after loading) has usually information of the object deformation, which will be described in detail in the chapter 4.

(a) \hspace{5cm} (b)

Fig. 2. Phase maps of the interference patterns (a) both the specimen and reference have a reflective surface (b) both the specimen and reference have a rough surface
One of the functions of the developed system is to be able measure the contour of a smooth surface. In this case the reference object is a mirror. Assuming that: (1) the specimen surface has been adjusted to be perpendicular to the surface of the reference mirror, and (2) the optical system is perfect, i.e. the laser beam is well collimated and the surfaces of the beam splitter and the reference mirror are absolutely flat, then the calculated phase distribution \( \phi(x,y) \) in Eq. 3.6 (or in Eq. 1.4 and 2.5) is related to the surface contour “\( z(x,y) \)” of the specimen to be tested:

\[
\phi(x,y) = \frac{4 \pi}{\lambda} z(x,y) \tag{4}
\]

The above assumptions are obviously too harsh. In practice, the laser could not be an absolute collimated beam and the beam splitter as well as the reference mirror could have a surface shape error, which can induce an error to measuring results. In order to eliminate these systematic errors, an experimental calibration process has been introduced into the measuring system. At first, a mirror with highly precise flatness is put on the 6-freedom translation stage instead of the specimen. The phase distribution of this interference pattern \( \phi_0(x,y) \) is calculated. This phase distribution \( \phi_0(x,y) \) contains all of the optical systematic errors, including the collimation error, surface profile errors in beam splitter and reference mirror. Then, removing the high precise mirror and putting the specimen on the stage, the phase distribution \( \phi_1(x,y) \) of the interference pattern in this case is measured again. Subtracting \( \phi_0(x,y) \) from \( \phi_1(x,y) \), one obtains a new distribution \( \phi_c(x,y) \) which is related only to the surface contour of the specimen:

\[
\phi_c(x,y) = \phi_1(x,y) - \phi_0(x,y) \tag{5}
\]

Usually, it is required to calibrate the system again (i.e. to measure \( \phi_0(x,y) \) again) if the zoom setting of the LDM has been changed. Using this technique, a tight requirement on the laser beam and optical components is not necessary, except for the requirement of the highly accurate calibration mirror. The measuring accuracy depends now mainly the phase shifting technique. By using a high performance PZT, the measuring accuracy can reach \( \lambda/30 \) or better. Fig. 3 shows a contour measurement of two silicon posts (about 0.5×0.3 mm for each post). The live image, the phase map and the quantitative information are displayed in Fig. 3, respectively.

![Image of contour measurement of two silicon posts](image-url)
4 OUT-OF-PLANE DISPLACEMENT MEASUREMENT

Many micro-components have a smooth reflective surface, for example MEMS switches used in the telecommunications industry. The surface displacement or tilting is an important specification for the MEMS switches to change laser beams to other channels. The developed measuring system can measure such displacements easily. For a sample that has a reflective surface, the surface of the reference object should be smooth too, thus a mirror is used as reference object. The coherent light reflected from the object and reference surfaces meet at the image plane (CCD array) forming an interference pattern. Because both surfaces of the sample and reference object are smooth, the phase map of \( \phi_1(x,y) \) is a visible fringe pattern. The phase distribution \( \phi_1(x,y) \) corresponding to the first state of a specimen is quantitatively measured by using the phase shifting technique. After the specimen is loaded, e.g. by adding a voltage, heating, applying stress, etc, the phase distribution \( \phi_2(x,y) \) corresponding to the second state of the specimen is quantitative measured again in a same manner. Subtracting \( \phi_2(x,y) \) from \( \phi_1(x,y) \) gives the relative phase distribution \( \Delta \) which represents the out-of-plane displacement \( w \):

\[
\Delta = \phi_2(x,y) - \phi_1(x,y) = \frac{4\pi}{\lambda} w
\]

Fig. 4 shows an application of measuring the motion of a MEMS mirror. The difference between the phase distributions \( \phi_1(x,y) \) in Fig. 4(a) and \( \phi_2(x,y) \) in Fig. 4(b) gives the result in Fig. 4c showing the motion of the middle MEMS mirror induced by applying a voltage. The quantitative evaluation can be observed in Fig. 4d. Note that even though the mirror is slightly curved (revealed by the fringe pattern in Fig. 4a and the curved fringes in Fig. 4b), the mirror deflection appears perfectly flat (revealed by the straight fringes in Fig. 4c). This means that the motion is pure rotation, with no deformation of the mirror surface during actuation.

For measuring out-of-plane displacement on samples with rough surfaces, the only change required in the setup is to replace the reference mirror with a scattering surface. The coherent light scattered from the object and reference surfaces meet at the image plane (CCD array) forming an interference pattern, called a speckle pattern. In this case, the phase distribution of the speckle pattern is a random pattern and thus, no visible fringes can be observed (cf. Fig. 2b). Although there are no visible fringes in such a pattern, it does contain phase information of the object and a visible fringe pattern related to object deformation can be observed if two speckle patterns that correspond to two deformation states are recorded and subtracted. It has been shown\(^9\) that such an optical arrangement shown in Fig. 1 is sensitive only to the out-of-plane displacement/deformation \( w \) and the relationship between the relative phase distribution \( \Delta = \phi_2(x,y) - \phi_1(x,y) \) and the out-of-plane displacement/deformation \( w \) is exactly same as Eq. 6, i.e. \( \Delta = \phi_2(x,y) - \phi_1(x,y) = \frac{4\pi}{\lambda} w \).

Fig. 5 shows an application of the system to measure out-of-plane deformation. The sample is a 5×5 mm substrate of composite material. The phase distributions \( \phi_1(x,y) \) and \( \phi_2(x,y) \) before and after loading (Fig. 5a and 5b) are the random phase patterns and thus no fringes are visible from these images. A fringe pattern depicting a out-of-plane deformation \( w \) induced by a temperature change appears by subtracting \( \phi_1(x,y) \) from \( \phi_2(x,y) \) (Fig. 5c). The small anomalous spots indicate defects (cracks or delaminations) in the sample. Because of speckle interferometry, there are a lot of speckle noises in the phase map. The key to evaluating such a fringe pattern is to reduce the noise, the so-called “salt and pepper” noise. For this purpose, a special filter function, called as phase filter, was developed and has been used in the measuring system and a smoothed image has been obtained\(^10\) (Fig. 5d). The quantitative evaluation of the out-of-plane deformation \( w \) is shown in Fig 5e. By numeric differentiation of the evaluated data \( w \), the deformation derivative \( \partial w/\partial x \) shown in Fig.4f displays the defects more clearly.
Fig. 5. Out-of-plane deformation measurement on an object with a rough surface, (a) the phase distribution before loading: \( \phi_1(x,y) \) (b) the phase distribution after loading: \( \phi_2(x,y) \) (c) the relative phase map \( \Delta \) by subtracting \( \phi_1(x,y) \) from \( \phi_2(x,y) \) (d) smoothed image of \( \Delta \) (e) 3D display of the evaluated deformation \( \omega \) and (f) derivative of the deformation \( \partial \omega / \partial x \)

5 VIBRATION MEASUREMENT

There are many reasons to determine the natural frequencies and mode shapes of the microelements and MEMS. One reason is to assess the dynamic interaction between a component and its supporting structure. Decisions regarding subsequent dynamic analyses (i.e., transient response, frequency response, response spectrum analysis, etc.) can be based on the results of the natural frequency analysis. The important modes can be evaluated and used to select the appropriate time or frequency step for integrating the equations of motion. Similarly, the results of the natural frequencies, and mode shapes can be used in modal frequency and modal transient response analyses.

In the last decade, many industries adopted Computer-Aided-Engineering (CAE) tools to reduce the number of prototype builds and to speed up the development cycle. These analytical tools are relatively inexpensive to use and faster to implement than the costly traditional test methods as used in traditional design processes. There are, however, many variables that CAE tools cannot adequately address, such as, material properties, material anisotropy etc. Therefore, efficient physical experimental techniques are still necessary for MEMS design validation and optimization.

The developed measuring system has a capability to measure vibration of MEMS and thus to determine the resonance frequencies and the mode shapes. There is no change in setup shown in Fig. 1. However, a stroboscopic laser illumination and a controller to synchronize stroboscopic illumination and excited sample should be adopted. The measuring system is suited for measurements of both smooth and rough surface.

6 RESIDUAL STRAIN MEASUREMENT

Besides the above functions, the developed measuring system can also measure a residual stress, for example induced by high temperature processing. The technique can be applied to investigate samples with either smooth or rough surface. In this case the sample has to be removed from the stage after taking the first reference image and it must be remounted on the stage after the processing. The fundamental of the technique is to measure two phase distributions \( \phi_1(x,y) \) and \( \phi_2(x,y) \) at two states, one before and the other after the processing. Obviously, the difference \( \Delta \) between the \( \phi_1(x,y) \) and \( \phi_2(x,y) \) contains not only the deformation due the high temperature but also a rigid body tilt due to imperfect remounting. In order to eliminate the information from the rigid body tilt, an algorithm has been developed in the developed software package. As an example, Fig. 6a shows the measured result of a 2mmx2mm mirror containing a residual deformation induced by high temperature processing and a rigid body tilt caused by remounting. A line profile through the middle of Fig. 6a along the vertical direction is displayed in Fig. 6b. The angle \( \theta \) indicates the tilt and the rest is the residual deformation. Fig. 6c shows the residual deformation after having eliminated the tilt. In a general case, the software can analyze all the contour data on the surface to determine the tilt plane.
For measuring deformation of a sample which has to be removed between measurements of the first and second states, an accurate repositioning method is required. Commercially available positioning devices with an accuracy of a few microns are usually satisfactory.

7 CONCLUSIONS

A universal digital laser micro-interferometer which has capability to measure shape, displacement, vibration and residual stress of microelements and MEMS has been developed. The varied and interesting applications show that this measuring system is very flexible and useful. The two advantages of this measuring system are (1) it can be used to measure samples with either smooth or rough surface, (2) the measuring area for object size is flexible; using the OPTEM Zoom 100 LDM, the measurement area is from 50×50 µm up to 5×7 mm. By using other lenses on the CCD camera, larger objects could be measured, up to the size of beam splitter cube, e.g. 30 mm. Also, the measurement is automatic, quantitative, full field, non-contact, simple and rapid. Although the measurement system is based on coherent optical interferometry, there is no special requirement on the coherence length, because the optical path lengths of the object and reference beams are well balanced. Furthermore, the system does not have stringent requirements on the quality of the optical components and collimation quality of the laser beam, because all applications are related to a relative measurement (subtraction between two phase distributions). The developed system has a measuring sensitivity of about 30 nm and an accuracy of 50 nm.

REFERENCES