Measurement of in-plane deformations of microsystems by digital holography and speckle interferometry

Invited Paper

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The reliability of microsystem is an important issue and for their quality inspection, it is necessary to know the displacements or deformations due to the applied mechanical, thermal, or electrostatic loads. We show interferometrical techniques like digital holography and speckle interferometry can be used for the measurement of in plane deformations of microsystems with nanometric accuracy and we give a description of the measurement uncertainties.

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The increasing trends towards miniaturization in many different application fields, from optical communications to medicine, have produced in the past few years a dramatic progress in the development of micro-electro-mechanical systems (MEMS) and micro-opto-electro-mechanical systems (MOEMS)[1]. Miniature robots, micro mirrors, micro actuators, optical scanners are some examples of MEMS devices. New applications are emerging as the existing technology is applied to the miniaturization and integration of conventional devices.

The reliability of such systems is an important issue that still requires advanced research. For the quality inspection, it is necessary to know not only their geometry but also the displacements or deformations due to the mechanical, thermal, or electrostatic loads. The measurement of the deformation of micromechanical systems may be used for the calculation of strain and, along with the evaluation of applied forces, allows for obtaining stresses and consequently extraction of material parameters[2−5]. This information may in turn be used for the validation of finite element method (FEM) models and eventually detect defects in microsystems. Since the structures themselves exhibit typical dimensions of the order of some micrometers, it is necessary to measure the deformation with accuracies in the nanometer range.

Digital holography[6−9] and speckle techniques[10−12] are well suited for the measurement of deformations or vibrations and have been extensively used for the investigation of both large and microscopic objects. Since these are interferometric techniques and use coherent light, there is the appearance of speckles that from one side are carrier of information but from the other side, due to their statistical nature produce noise and thus inaccuracies in the measurements. It is thus necessary to know if the setups can guarantee precision in the nanometer range. Preliminary results where optical techniques have been used for the measurement of in-plane displacements of microsystems have been presented in Refs. [13,14].

The goal of this work is to estimate the errors when in-plane deformations of microsystems are measured. At first, the reference test objects, from which we know exactly how they deform when submitted to loading, have been developed. The reference is then measured by using interferometric systems and the uncertainty of the measurement is determined according to internationally recognized guidelines.

Figure 1(a) shows an arrangement based on digital holography usually used for the measurement of deformations. The interference between the wavefront reflected by an object and a reference wave is recorded by an electronic device (usually charge-coupled device (CCD) or complementary metal-oxide semiconductor (CMOS) detectors). Notice that in the figure there is a lens to image the object on the sensor but in principle the lens can be omitted in order to get a lensless holographic setup. When a lensless setup is used, we need to propagate the reconstructed wavefront in order to get an image of the object. The sensitivity of the arrangement with respect to object deformations is given by its geometry. For the determination of the three-dimensional (3D) deformation, we need at least three sensitivity vectors which can be produced by illuminating the object from three different directions. The acquisition of the deformation along the different sensitivity vectors can be done sequentially (this needs more time) or in parallel[9]. In this letter, we are interested only in the in-plane deformations along one direction and thus an arrangement which uses two illumination sources shown in Fig. 1(a) is used. Consider a deformation described by the vector $\vec{d}$. When the object is illuminated along the directions $\vec{k}_1, \vec{k}_2$, and observed along the direction $\vec{k}_0$, the phase changes of the two scattered wavefronts are

$$\Delta\phi_1 = \frac{2\pi}{\lambda}(\vec{k}_0 - \vec{k}_1)\vec{d}, \tag{1a}$$

$$\Delta\phi_2 = \frac{2\pi}{\lambda}(\vec{k}_0 - \vec{k}_2)\vec{d}. \tag{1b}$$

Since digital holography allows the direct measurement of the phase of a wavefront (or more precisely, the measurement of the phase difference between a reference wave and a wave reflected by the object), $\Delta\phi_1$ and $\Delta\phi_2$ may be easily determined and their difference

$$\delta = \Delta\phi_2 - \Delta\phi_1 = \frac{2\pi}{\lambda}(\vec{k}_2 - \vec{k}_1)\vec{d} \tag{2}$$

contains the information about the deformation along the sensitivity vector $\vec{k}_2 - \vec{k}_1$. We consider a symmetrical illumination of the sample where the components of the two unitary vectors $\vec{k}_1$ and $\vec{k}_2$ are $(-\sin\theta, 0, \cos\theta)$ and $(\sin\theta, 0, \cos\theta)$, respectively, and $\vec{k}_2 - \vec{k}_1 = (2\sin\theta, 0, 0)$ is a vector parallel to the x axis. By knowing δ and using Eq. (2), we may get the projection d_x of the displacement $\vec{d}$ on the x axis:

$$d_x = \frac{\delta\lambda}{4\pi\sin\theta}. \tag{3}$$

The measuring sensitivity is defined by the angle of illumination and the light source wavelength.

Figure 1(b) shows another classical, simple, and robust method based on electronic speckle pattern interferometry (ESPI)[10−12], which is usually used for the measurement of in-plane deformation. The object is illuminated from two different directions and the sensitivity is given by the vector $\vec{k}_2 - \vec{k}_1$ like the case in the setup shown in Fig. 1(a), but in this case there is no reference and the phase shifting method is used to determine $\Delta\phi_1$ and $\Delta\phi_2$ and their difference δ which is related to the displacement by Eq. (2). Usually, for the application of the phase shifting technique, a piezo controlled mirror is inserted in one arm of the interferometer.

Notice that both arrangements are able to determine the wrapped phase which does not distinguish between multiples of 2π, or in other words, the phase is known only with modulo 2π. The unwrapped phase can be determined by using a phase unwrapping algorithm.

The MEMS and MOEMS samples are usually made of polysilicon and crystalline silicon which have roughnesses of typically 8 and 1 nm, respectively. For the measurement of in-plane displacement by using the above described techniques, it is necessary to illuminate the sample with a strong source in order to get some light scattered on the detector.

We choose a MEMS (see Fig. 2) as the test object, which has exceptional characteristics since it has been designed to have a very accurate in-plane displacement along one direction only. This mean that we are able to control the displacement with an accuracy of 1 nm or better. The uniaxial and in-plane displacements along x direction are insured by geometrical constraints[13,14]. The application of a voltage produces translations given by

$$d_x = cV^2, \tag{4}$$

where V is the applied voltage, c is a constant that depends on material properties and device geometry.

For both arrangements described above, the base of our error analysis is the function given in Eq. (3) relating the displacement with the phase, the wavelength, and the geometry of the setup. We perform the estimation of these errors according to "The Guide to the Expression of Uncertainty in Measurement" (GUM) [15,16] published by the International Organization for Standardization (ISO) which provides general rules for evaluating and expressing uncertainties of measurements. According to GUM, in each measurement made there are errors that may be divided into the following two types.

Type A. The evaluation of the uncertainties is based on the statistical analysis of a series of measurements. Important parameters are the mean value and the standard deviation.

Type B. The evaluation of the uncertainties is based on other sources like instrument specification, calibration,

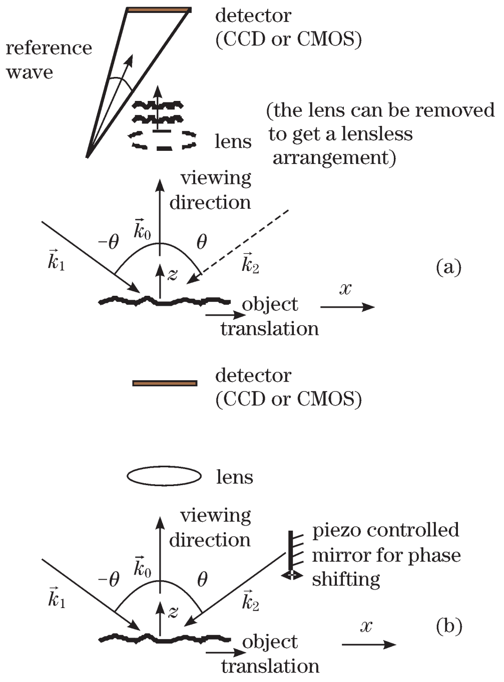

Fig. 1. (a) Digital holography and (b) ESPI set-ups for the measurement of in-plane deformation.

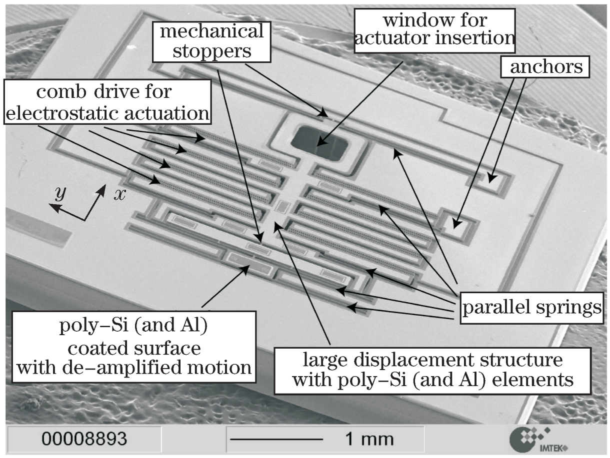

Fig. 2. Scanning electron micrograph of the reference device for one-dimensional translation.

or other available data. A measurement may include uncertainties of both types.

We have already pointed out that the geometrical parameter of the set ups (illumination angles) may be accurately measured to ± 0.1° (mean of a sequence of measurements, incertitude of Type A)[14]. This incertitude in the geometry of the arrangement is quite small and it will eventually produce a systematic error that can be compensated. The wavelength can be measured with an accuracy of ±0.01nm by using a spectrometer (incertitude of Type B since it is determined from the instrument specifications), and is thus a very accurate value.

The error in the measurement of the phase δ (incertitude of Type A) is the most significant and can be produced by the noise of the detector, speckle decorrelation, laser instabilities, unwanted superposition of parasitic coherent fields, and mechanical instabilities.

In order to illustrate this kind of error, we performed measurement by using the arrangements sketched in Fig. 1. For the experiments, we used a 20-mW laser diode emitting at the wavelength of $\lambda = 406$ nm and having a coherence length of 100 μm. This short coherence laser has been chosen in order to avoid parasitic interference between the measuring beam and unwanted wavefronts due to reflections inside the microscope objective and the protective glass of the detector. By using a laser emitting in the ultraviolet (UV) range, we have more light scattered from the low roughness surface (few nanometers). Furthermore, the short wavelength increases the sensitivity. The angle θ was 60° ($2\sin\theta = 1.73$), thus according to Eq. (3), a change of phase of 1° corresponds to an in-plane displacement of 0.65 nm. The sample was the reference MEMS which displaced according Eq. (4). The light scattered by the illuminated sample was collected by a microscope objective (10×, aperture $D = 8$ mm) that imaged a part of the device on the CCD located at the distance $L = 160$ mm. The mean speckle size on the detector was $\lambda L/D = 8.1$ μm and thus larger than the camera pixel which was 6.45 μm (resolved speckles). For the acquisition of the intensity pattern, we chose a high quality CCD camera manufactured by the PCO company (Pixelfly QE) with 1392 × 1024 pixels and high dynamic range (12 bits, 4096 gray level).

Figure 3(a) shows the measurement results obtained from 500 camera pixels which in principle should give the same results since they measure the same surface translation. The arrangement used for the measurements was the one sketched in Fig. 1(b) but similar results have been obtained by using the digital holography arrangement shown in Fig. 1(a). The 500 selected pixels have all a good intensity modulation (> 0.5) and are not saturated, since it is well known that low modulated or saturated pixels give wrong results[10]. The results presented in Fig. 3(a) show a quadratic behavior as would be expected from Eq. (4), but each pixel measures a different displacement. Figure 3(b) shows the results obtained by averaging the data from Fig. 3(a). The obtained motion is now in good agreement with the theoretical expected values (dashed line) calculated using Eq. (4), but it appears clearly that even after averaging 500 pixels there are still incertitudes that in some parts are $3-4$ nm. The standard deviation calculated from the 500 pixels is quite large and not constant, in particular there are peaks of standard deviations completely random (see Fig. 3(c)). We may see from one side that the error increases with the object deformation and this can be easily explained with the decorrelation due to the in plane translation[12]. The phase error (standard deviation) due to the image decorrelation for the case of the interferometer shown in Fig. 1(b) and resolved speckles is given by Eqs. (37) and (38) in Ref. [12]. The error depends on the intensities and modulations of the speckles, and since we choose only well modulated speckles, we may approximate the error dependence from the displacement with the linear relation:

$$\sigma_{\Delta\varphi}(d_x) = \frac{2Md_x}{\Delta s}\ , \tag{5}$$

where M is the magnification factor of the system (M=10 in our case) and $\Delta s = 8.1$ μm is the speckle size. An in-plane shift of 90 nm involves a phase error

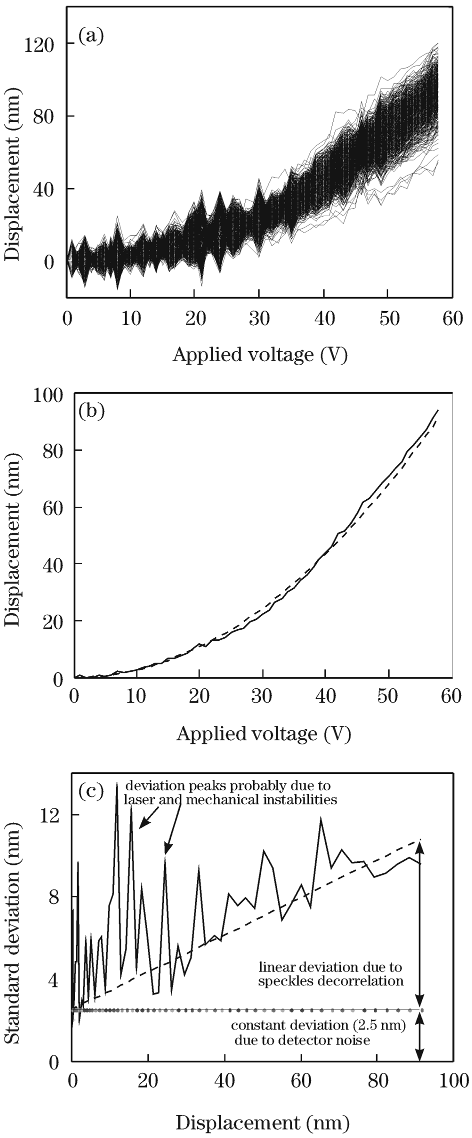

Fig. 3. (a) In-plane displacement measured by 500 pixels when the applied voltage is increased from 0 to 59 V; (b) mean values of the displacement calculated from (a), the dashed line indicates the theoretical expected values; (c) standard deviation of the displacement.

of 0.22 rad (13°), corresponding to an error of about 8.5 nm, since for our arrangement a change of phase of 1° corresponds to an in-plane displacement of 0.65 nm. We can see from Fig. 3(c) (dashed line) that this can easily be identified as a linear component depending on the displacement d_x. The constant incertitude of about 2.5 nm could be caused by the detector, for which the signal-to-noise ratio (SNR) is

$$\mathrm{SNR} = \frac{n_{\mathrm{signal}}}{\sqrt{n_{\mathrm{signal}} + n_{\mathrm{CCD}}^2 + n_{\mathrm{readout}}^2}} \quad , \tag{6}$$

where n_{signal} is the number of electrons due to the illumination, n_{CCD} and n_{readout} are the electron numbers due to the CCD and readout noise, respectively. For the camera used in the experiments, the manufacturer gives values of approximately 10 electrons/pixel for $n_{\mathrm{CCD}} + n_{\mathrm{readout}}$. During the investigations, we always choose well illuminated pixels, and thus according to Eq. (6) the shot noise is dominant. The full well capacity, which is the largest charge that a pixel can hold before saturation, is 15000 electrons. For illumination equal to one third of the saturation we get $1/\mathrm{SNR} = \sqrt{5000 + 100}/5000 = 1.5\%$. Considering that for calculating the phase, four patterns are used (4-step algorithm), the phase error produced by an uncorrelated uncertainty of $1/\mathrm{SNR} = 1.5\%$ in the intensities can be easily determined and is less than 1° corresponding to a displacement error of 0.65 nm, which is smaller than the 2.5 nm constant standard deviations reported in Fig. 3(c). It can be found that the detector noise is larger as assumed.

The completely random peaks of standard deviations are difficult as well to explain. They could be produced by the laser or mechanical instabilities. Further investigations are necessary to clearly identify the problem.

In couclusion, a micromechanical reference component that displaces in a reproducible and precise way when submitted to a standard electrostatic loading (application of a voltage) has been measured by using optical methods based on digital holography and speckle interferometry. Good agreement has been found between the expected and the measured displacements by averaging the measurements obtained from hundreds of camera pixels. Some of the causes of the incertitudes have been discussed. The standard deviation of the displacements measured by the single camera pixels is still too large and further investigations are necessary to reduce it. Improvements of the accuracy in the phase measurement by building a more stable setup can be expected.

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References

1. J. Korvink and O. Paul, (eds.) *MEMS − A Practical Guide to Design, Analysis and Applications* (William Andrew Publishing, Norwich, 2006).
2. W. Osten, (ed.) *Optical Inspection of Microsystems* (CRC Press, Boca Raton, 2006).
3. W. Osten, (ed.) *Optical Microsystems Metrology I.* Special Issue of Opt. Lasers Eng. **36,** (2) (2001).
4. W. Osten, (ed.) *Optical Microsystems Metrology II.* Special Issue of Opt. Lasers Eng. **36,** (5) (2001).
5. J. Gaspar, M. Schmidt, J. Held, and O. Paul, in *Proceedings of IEEE MEMS 2008* 439 (2008).
6. U. Schnars, J. Opt. Soc. Am. A **11,** 2011 (1994).
7. G. Pedrini, Y. L. Zou, and H. J. Tiziani, J. Mod. Opt. **42,** 367 (1995).
8. G. Pedrini and H. J. Tiziani, "Digital holographic interferometry" in P. K. Rastogi, (ed.) *Digital Speckle Pattern Interferometry and Related Techniques* (Wiley, Chichester, 2001) pp.337−362.
9. S. Schedin, G. Pedrini, H. J. Tiziani, and F. Mendoza, Appl. Opt. **38,** 7056 (1999).
10. K. Creath, Appl. Opt. **24,** 3053 (1985).
11. R. Jones and C. Wykes, *Holographic and Speckle Interferometry* (2nd edn.) (Cambridge University Press, Cambridge, 1989).
12. M. Lehmann, Appl. Opt. **36,** 3657 (1997).
13. G. Pedrini, J. Gaspar, T. Wu, W. Osten, and O. Paul, Opt. Lasers Eng. **47,** 203 (2009).
14. G. Pedrini, J. Gaspar, W. Osten, and O. Paul, "Development of reference standards for the calibration of optical systems used in the measurement of microcomponents" Strain (Published Online: Jan. 23, 2009).
15. "Guide to the expression on uncertainty in measurement" DIN V ENV 13005 (1999).
16. B. N. Taylor and C. E. Kuyatt, "NIST technical note 1297 1994 edition guidelines for evaluating and expressing the uncertainty of NIST measurement results" (1994).