Video Article

Compact Lens-less Digital Holographic Microscope for MEMS Inspection and Characterization

Thomas Bourgade[1], Sun Jianfei[1], Zhaomin Wang[1], Rosmin Elsa[2], Anand Asundi[1,2]

[1]School of Mechanical and Aerospace Engineering, Center of Laser and Optical Engineering, Nanyang Technological University

[2]d'Optron Pte Ltd

Correspondence to: Thomas Bourgade at thomas.bourgade@gmail.com

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Abstract

A micro-electro-mechanical-system (MEMS) is a widely used component in many industries, including energy, biotechnology, medical, communications, and automotive. However, effective inspection and characterization metrology systems are needed to ensure the functional reliability of MEMS. This study presents a system based on digital holography as a tool for MEMS metrology. Digital holography has gained increasing attention in the past 20 years. With the fast development and decreasing cost of sensor arrays, resolution of such systems has increased broadening potential applications. Thus, it has attracted attention from both research and industry sides as a potential reliable tool for industrial metrology. Indeed, by recording the interference pattern between an object beam (which contains sample height information) and a reference beam on a CCD camera, one can retrieve the quantitative phase information of an object. However, most of digital holographic systems are bulky and thus not easy to implement on industry production lines. The novelty of the system presented is that it is lens-less and thus very compact. In this study, it is shown that the Compact Digital Holographic Microscope (CDHM) can be used to evaluate several characteristics typically consider as criteria in MEMS inspections. The surface profiles of MEMS in both static and dynamic conditions are presented. Comparison with AFM is investigated to validate the accuracy of the CDHM.

Video Link

The video component of this article can be found at https://www.jove.com/video/53630/

Introduction

Metrology of micro and nano objects is of great importance for both industry and researchers. Indeed, miniaturization of objects represents a new challenge for optical metrology. Micro electro mechanical systems (MEMS) are generally defined has miniaturized electromechanical systems and usually comprises components such as micro sensors, micro actuators, microelectronics and microstructures. It has found many applications in diverse field such as biotechnology, medicine, communication and sensing[1]. Recently, the increasing complexity as well as the progressive miniaturization of test object features call for the development of suitable characterization techniques for MEMS. High throughput manufacturing of these complex microsystems requires the implementation of advanced inline measurement techniques, to quantify characteristic parameters and related defects caused by the process conditions[2]. For instance, the deviation of geometrical parameters in a MEMS device affects the system properties and has to be characterized. In addition, industry requires high resolution measurement performance, such as full three dimension (3D) metrology, large field of view, high imaging resolution, and real time analysis. Thus, it is essential to ensure a reliable quality control and inspection process. Moreover, it requires the measuring system to be easily implementable on a production line and thus relatively compact to be installed on existing infrastructures.

Holography, which was first introduced by Gabor[3], is a technique that allows the recovery of the full quantitative information of an object by recording the interference between a reference and an object wave into a photosensitive medium. During this process known as recording, the amplitude, phase and polarization of a field are stored in the medium. Then the object wave field can be recovered by sending the reference beam onto the medium, a process known as optical reading of the hologram. Since a conventional detector only records the intensity of the wave, holography has been a subject of great interest in the past fifty years since it gives access to additional information on the electric field. However, several aspects of conventional holography make it unpractical for industry applications. Indeed, photosensitive materials are expensive and the recording process generally requires a high degree of stability. Advances in high resolution camera sensors such as charged coupled devices (CCD) have opened a new approach for digital metrology. One of those techniques is known as digital holography[4]. In Digital Holography (DH), the hologram is recorded on a camera (recording medium) and numerical processes are used to reconstruct the phase and intensity information. As with conventional holography, the result can be obtained after two main procedures: the recording and reconstruction as shown in **Figure 1**. However, if the recording is similar to conventional holography, the reconstruction is only numerical[5]. The numerical reconstruction process is shown in **Figure 2**. Two procedures are involved in the reconstruction process. Firstly, the object wave field is retrieved from the hologram. The hologram is multiplied with a numerical reference wave to get the object wavefront at the hologram plane. Secondly, the complex object wavefront is numerically propagated to the image plane. In our system, this step is performed using the convolution method[6].

The reconstructed field obtained is a complex function and thus phase and intensity can be extracted providing quantitative height information on the object of interest. The capability of whole field information storage in holography method and the use of computer technology for fast data processing offer more flexibility in experimental configuration and significantly increase the speed of the experimental process, opening up new possibilities to develop DH as a dynamic metrological tool for MEMS and micro-systems[7,8].

Use of digital holography in phase contrast imaging is now well established and was first presented more than ten years ago[9]. Indeed, investigation of microscopic devices by combining digital holography and microscopy has been performed in many studies[10, 11, 12, 13]. Several systems based on high coherence[14] and low coherence[15] sources as well as different types of geometry[13, 16, 17] (in line, off axis, common path…) have been presented. In addition, in line digital holography has been used previously in characterization of MEMS device[18, 19]. However, those systems are generally difficult to implement and bulky, making them unsuitable for industrial applications. In this study, we propose a compact, simple and lens free system based on off axis digital holography capable for real time MEMS inspection and characterization. The Compact Digital Holographic microscope (CDHM) is a lens less digital holographic system developed and patented to obtain the 3D morphology of micro-size specular objects. In our system, a 10 mW, highly stable, temperature controlled diode laser operating at 638 nm is coupled into a mono-mode fiber. As shown in **Figure 3**, the diverging beam emanating from the fiber is split into a reference and an object beam by a beam splitter. The reference beam path comprises a tilted mirror to realize the off axis geometry. The object beam is scattered and reflected by the sample. The two beams interfere on the CCD giving the hologram. The interference pattern imprinted onto the image is called a spatial carrier and permits the recovery of the quantitative phase information with only one image. The numerical reconstruction is performed using a common Fourier transform and convolution algorithm as stated previously. The lens-less configuration has several advantages making it attractive. As no lenses are used, the input beam is a diverging wave providing a natural geometrical magnification and thus improving the system resolution. Moreover, it is free of aberrations encountered in typical optical systems. As can be seen in **Figure 3B**, the system can be made compact (55x75x125 mm^3), lightweight (400 g), and thus can be easily integrated into industrial production lines.

Protocol

1. Preliminary Preparation of the Measurement

Note: The sample used for the experiment is a MEMS electrode. The gold electrodes are fabricated on a silicon wafer using lift off process. The sample is an 18 mm x 18 mm wafer with periodic structures (electrodes) with 1 mm period

1. Sign into the logbook before using the system.
2. Turn on the computer, LASER and translation stage power.
3. Place the MEMS electrode/micro-diaphragm sample.
    1. Place the MEMS sample in the middle of the sample holder using a tweezer.
    2. Adjust the sample holder to position the electrodes in the beam path. The maximum measurement field of view is defined by the camera sensor size. It is a rectangle of 2.3 mm x 1.8 mm.
4. Using the vertical direction motorized stage, move the system approximatively 1.5 cm away from the sample.

2. Software Settings Adjustment

1. Open the 3DView software. 3DView is our in-house program developed in C++.
2. Click imaging source button to select the proper camera for the experiment. Choose the monochrome CCD camera. Avoid a color camera in this setup since a monochromatic diode laser is used. Additionally, for the same number of pixels, resolution would be lower when using color cameras.
    1. In the device settings tab, select Y800 (1,280 x 960) video format and 15 frames per second video rate.
3. Click yellow play button to start the camera. An image of the object with imprinted fringe patterns (Hologram) should appear.
    1. Adjust optimum gain and exposure parameters to avoid image saturation if needed.
4. Using the live video window camera view, adjust the sample position to select the exact area to investigate on the sample.
5. Open settings tab.
    1. In the configuration tab, select the type of surface (reflective or transparent), wavelength of laser, and pixel size of the camera. The laser is a diode laser operating at 633 nm. The pixel size of the camera is 4,650 nm. The sample is a specular MEMS electrode device so reflective mode should be selected.
    Note: The CDHM configuration allows only reflective surfaces to be measured. However, the software can also be used to measure transparent samples when a different digital holography system is used[13]. A change in this setting changes the height calculation formula from the phase. Indeed, the optical path difference calculation is slightly different for transparent samples as it includes the object refractive index.
    2. Choose the Convolution reconstruction algorithm and set the reconstruction distance to zero. Choose a reconstruction step of 1 or 2.
    Note: The reconstruction distance parameter can be defined later by considering the intensity image obtained from the hologram and using the auto-focus. The reconstruction step defines the number of steps used to implement the Fresnel integral and simulate the beam propagation. The first method evaluate the integral once as a single Fourier Transform. A step of 2 will evaluate the integral twice. This adds more flexibility in the grid spacing but is computationally less efficient[20].
    3. In the post processing tab, select the unwrapping algorithm necessary to get the final unwrapped image. Select quality mapped algorithm.
    Note: In the software, the choice between Goldstein and Quality Mapped algorithm can be made. The later has shown robust and rapid spatial phase unwrapping. The quality mapped algorithm is based on guided phase unwrapping as described in [21].

3. Data Acquisition

1. Press the Fourier transform icon to open the Fourier spectrum window. One 0 order and two +1, -1 orders should appear. If this is not the case, check that the sample is in the right position, and adjust gain and exposure time again.
2. Stop the live measurement mode. Select one of the diffracted orders (positive or negative frequency) by using the filter tool. The selected area should be large enough so that all the frequencies needed for the phase retrieval are present. Switch on the live mode again.
   Note: The choice of the negative order will just affect the sign of the phase in the final result, *i.e.,* the final 3D image will be inverted.
3. Open the phase window. Check that the unwrapped mode is not enabled. Gray phase image of the object imprinted with wrapped fringes should appear.
4. Utilize the motorized vertical stage to reduce the number of fringes in the phase image. When only 1 or 2 fringes are left on the image, stop the motorized stage.
   Note: The system is based on interferometry. Thus it is sensitive to vibrations. After moving the z direction motorized stage, the user should wait 1 or 2 sec before the wrapped phase image appears again. It is also important to avoid vibrations during the measurement to get a stable phase image.
5. Click the auto-focus[22] button to find the best reconstruction distance. One may need to use autofocus several times to approach the optimum reconstruction distance until the intensity image appears sharp and clear. The autofocus is based on an efficient and time effective angular spectrum method as described in [22].
   Note: The focus slider bar can be used for fine adjustment. Then, click on center focus button to record the current reconstruction distance. It appears sometimes that best focus is not found with autofocus option. In this case, manually input reconstruction distance to find the best focus.
6. Enable the unwrapped mode to see the unwrapped phase image by clicking on the unwrapping button.

4. Data Visualization and Analysis for Static Measurement

1. Open the 3D image window to see the final 3D image of the sample. Use available options to observe the final result (rotate, color map, scale display…).
2. Click on the tile windows button to arrange the windows as non-overlapping and display all the measurements windows.
3. Use the line ruler to draw a line on an area of interest on the unwrapped phase image. In the line plot window, a cross sectional profile plot of the area of interest can be observed. Use the two green line markers to extract an approximate height of the object (**Figure 5**).
   Surface roughness can also be obtained on the flat top part of the sample.
4. Save the final phase image in .JPEG format to import it to other software if needed.

5. Preparation of Sample and Data Analysis for Dynamic Measurement

1. Place the micro diaphragm on a heating station plate. The sample will not be removed from the plate until the experiment ends.
2. Record a hologram of the micro diaphragm at ambient temperature by following the procedure described above in section 2 and 3. It will be used as a reference for the deformation analysis.
3. Save the phase data on the computer.
4. Turn on the laboratory heating plate.
5. Using the temperature knob, vary the temperature in steps of 50 °C from 50 °C to 300 °C. For each temperature step, save the phase map image in .JPEG format.
6. Subtract the initial ambient temperature phase map from the other phase map recorded to obtain the deformation data.
   Note: This post processing step can be realized with simple MATLAB code. The different phases obtained are loaded into MATLAB and simple matrix subtraction is performed. Then cross sectional plots of the different deformation stages can be obtained.

Representative Results

The protocol described above was designed to inspect and characterize MEMS and Micro devices using CDHM system. In our system, a mono-mode fiber is coupled to a diode laser operating at a 633 nm wavelength. Due to the diverging beam configuration, it is important to match the object beam and reference beam path in order to obtain a hologram that can be reconstructed. This is achieved through careful vertical positioning of the sample with respect to the system. In the calculated wrapped phase image, the number of fringes is reduced to a minimum by changing the system height position. It ensures that the optical paths are matched. **Figure 4** shows the result obtained from a measurement using the CDHM after proper axial positioning of the sample. The data is obtained in real time from a single image. In this experiment, a USAF target consisting in grating patterns of different highs and periods is chosen as a sample. As explained above, the phase map (**Figure 4A**) is extracted from the single image hologram. A line plot of a particular pattern is shown in **Figure 4A**. The yellow line (**Figure 4A**) represents the cross section location on the sample. Two green marker lines are used to estimate the absolute value of the sample height. In order to validate the results of the digital holographic system, an atomic force microscope (AFM) investigation of the sample is carried out. A cross section of the same sample area is shown in **Figure 4B**. For the same structure, a height difference of 2.1 nm is found between the AFM and the CDHM measurement. Thus, comparison between the two methods demonstrates the capability of the CDHM.

To specifically characterize a MEMS device, 3D static investigation of a MEMS electrode is carried out. The device is made of silicon with gold electrodes patterned using a lift off process. Generally, silicon based MEMS are fabricated using sensitive methods such as etching or lift off process. In both cases, the ability to quantify the change of the sample morphology during the fabrication process is of great importance. **Figure 5** shows the measurement result for this sample. Full 3D morphology of the sample can be observed. A cross section line (**Figure 5A**) plot shows the depth map that can be used for inspection. The depth of the channel is found to be 632 nm and the lateral distance between the electrodes is also provided by the CDH showing that it is capable of providing a complete quantitative 3D analysis of the sample. A plot in the other dimension (**Figure 5B**) exhibits the surface roughness of the electrode proving that the CDHM is also suitable for roughness measurements.

Static applications in MEMS characterization are of great value but most of interesting processes requires dynamic inspection. By selecting suitable recording methods, the CDHM system is capable of inspection and characterization micro devices for both static and dynamic situations. **Figure 6** shows a series of 3D data of a micro diaphragm obtained at different temperatures. The diaphragm was fabricated by bonding a thin plate onto a SOI (silicon on insulator) wafer sample. The sample is placed on a heating plate. In order to measure the thermal deformation, the temperature is varied in 50 °C steps starting from 50 °C and until 300 °C. The numerical reconstruction of the holograms is performed for each temperature. The hologram and phase at ambient temperature has been recorded previously. It is used as a reference phase. The subtraction of the deformed state (thermal load) and the reference state (ambient temperature) gives the deformation maps. Thus a full field analysis of the thermal deformation of the diaphragm is obtained. **Figure 6G** highlights the deformation for the different temperatures. In this case, the line plots reveal that the measurement show significant roughness compared to results obtained during static measurements.

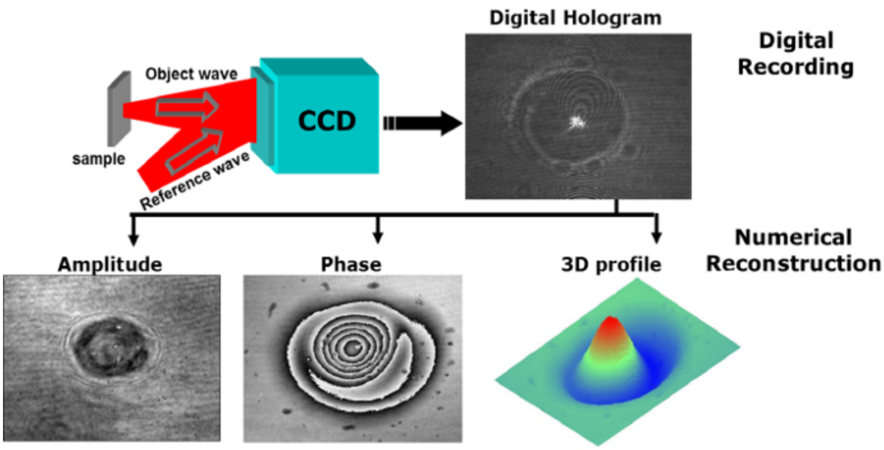

Figure 1. Digital holography recording and reconstruction process scheme. This figure shows detail of the two steps process to obtain three dimensional image of an object. A cartoon of the recording process and resultant hologram is shown. From the hologram, amplitude and phase (modulo 2π) of the object are extracted. The phase is unwrapped to remove the 2π ambiguity. The 3D reconstruction is then performed. Please click here to view a larger version of this figure.

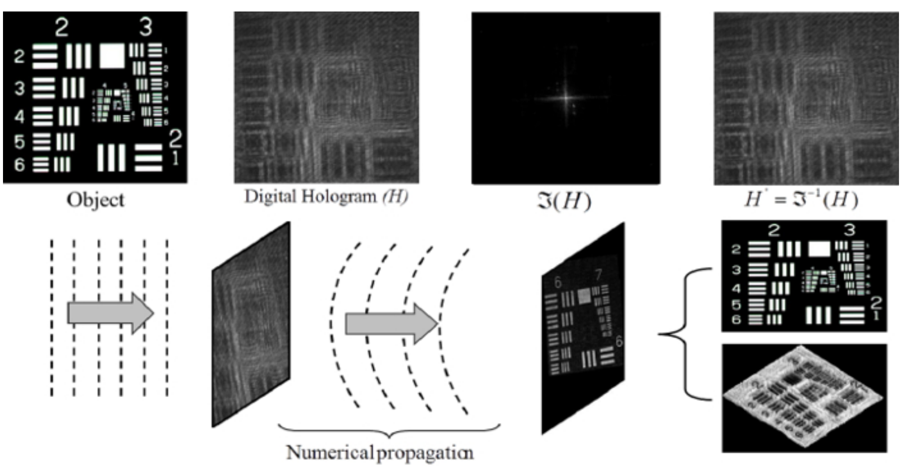

Figure 2. Detailed scheme of the reconstruction process. This figure shows a schematic of the reconstruction process scheme. The digital hologram is recorded and the Fast Fourier Transform (FFT) of the image is performed. After selecting useful information in the spectrum, the image is Fourier Transformed back. Then numerical generation of reference beam and propagation of the hologram is simulated to retrieve the phase and amplitude of the object independently. Please click here to view a larger version of this figure.

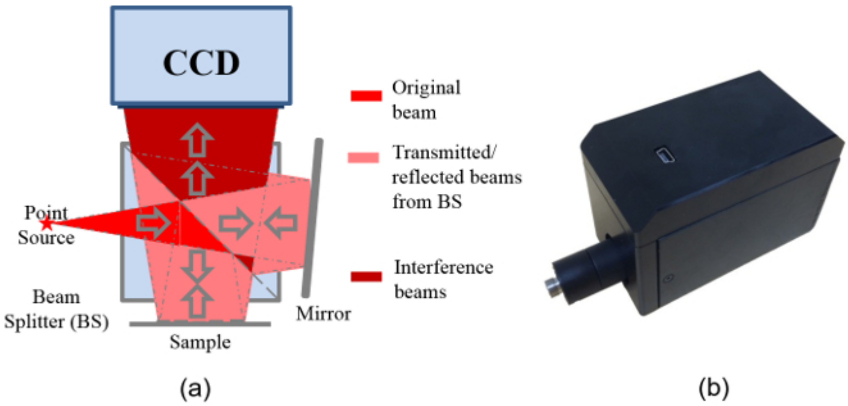

Figure 3. Schematic of the CDHM setup. This figure shows a schematic representation of the CDHM setup (**A**) and a photograph of it (**B**). Please click here to view a larger version of this figure.

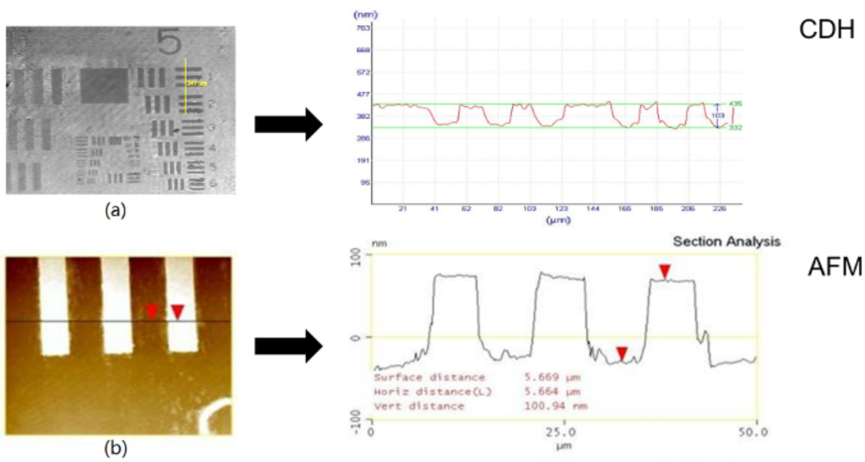

Figure 4. Comparison between CDHM and Atomic Force Microscope (AFM) height measurement of a US air force target. This figure shows the line plots from a US air force target micro structure obtained using the CDHM (**A**) and an Atomic Force Microscope (AFM) (**B**). Please click here to view a larger version of this figure.

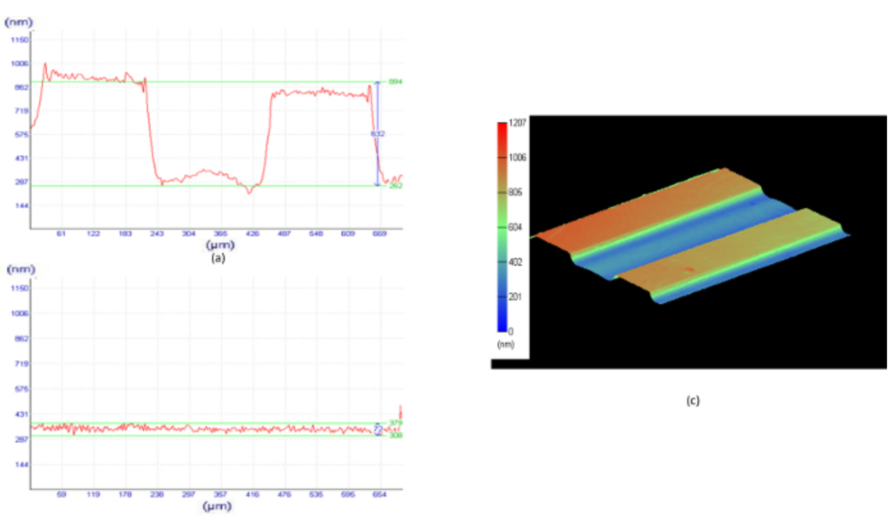

Figure 5. 3D profile and line plot of a MEMS electrode devices. Measurement results of a silicon MEMS electrode device using the CDHM. Line plot with green markers used to estimate the depth of the sample at a particular cross section in the x direction (**A**) and the y direction (**B**) and whole field image showing 3D result (**C**). Please click here to view a larger version of this figure.

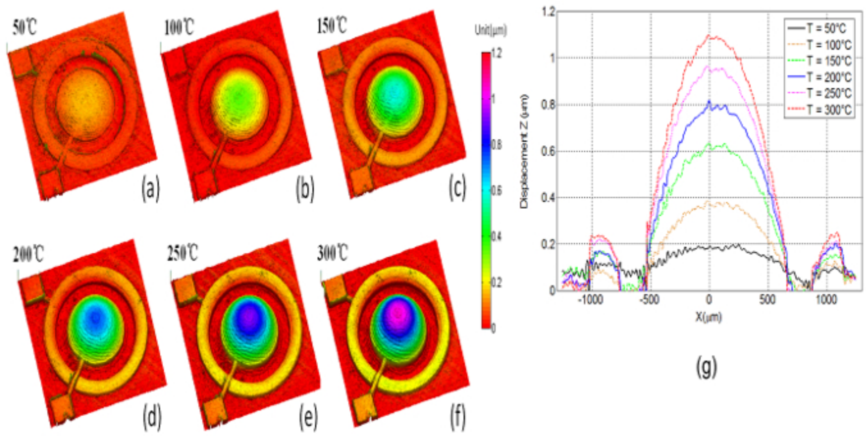

Figure 6. Deformation study of a micro diaphragm under thermal load. Pictures show 3D deformation images of a micro diaphragm under varying thermal load (**A-F**) and line plot showing evolution of the deformation at a particular cross section (**G**). Please click here to view a larger version of this figure.

Discussion

In this review, we provide a protocol to accurately recover the quantitative morphology of different MEMS devices by using a compact system relying on digital holography. MEMS characterization in both static and dynamic mode is demonstrated. Quantitative 3D data of a micro channel MEMS is obtained. In order to validate the accuracy of the system, results have been compared between the CDHM and the AFM. Good agreement is found meaning that digital holography can be a reliable technique for 3D imaging. Results indicate that the system is capable of 10 nm depth resolution. Furthermore, the results obtained on the micro channel show that the system can be used in MEMS characterization as morphology of the sample can be controlled during the MEMS fabrication process. Additionally, the magnification obtained using the CDHM correspond to what should be used for MEMS size (4.2X). The system is also capable of full field measurement. This is a considerable asset when compare to techniques typically used for MEMS inspection such as confocal microscopy, which require long scanning measurement. In addition, the lateral resolution of the system can be easily improve by changing the red diode laser to a UV laser. Lastly, the high sensitivity of the system enables roughness measurements.

Dynamic measurement on a micro diaphragm reveals that the CDHM is an appropriate tool to observe deformation in MEMS devices when thermal or electrical loading is applied. Using a double exposure method to build the deformation map, dynamic deformation study of a micro diaphragm is performed. One can see that the diaphragm shape can be carefully observed in real time. This result is possible because the 3D morphology is calculated using only one image. However differently from what was observed during static measurements, dynamic measurement using thermal load shows an abnormally rough profile. Indeed, one could consider the line plot shown in **Figure 6G** as rough when compared to the static measurement results. As the system can resolve structure as small as 10 nm, the roughness does not seem to be coming from the object. A possible explanation can be that the heat generated by the heating stage perturbs the interferences between the two waves and affects the object wave wavefront. In addition, dynamic studies have been performed using the CDHM on MEMS using electrical load[12] and this roughness does not seems to appears.

The protocol contains several critical steps, such as the sample vertical positioning, the choice of the reconstruction distance, the reconstruction method, a vibration free environment and the quality of fringes on the CCD. To ensure a reliable and stable result, all these steps should be performed carefully. For instance, the object beam path needs to be the same as the reference one, *e.g.*, the sample distance to the system is critical to obtain clear fringe patterns on the CCD. Furthermore, the numerical reconstruction distance should be well adjusted to ensure that the hologram is reconstructed in the image plane. Lastly, a sample with sharp structure higher than half of the wavelength of the laser will cause unreliable phase result. Indeed, a phase jump could appear due to phase unwrapping errors.

These results illustrate the capability of the CDHM to perform 3D quantitative depth measurements of MEMS devices. Indeed, for reflective surface as encountered in MEMS and microelectronics industry, the CDHM is a portable system that can be used for *in situ* process measurements as well as characterizing and inspecting microsystem devices. A validation study shows that the results obtained by the system are highly reliable. The CDHM covers a larger scan area and real time measurements can be performed. It is a major advantage compared to other techniques such as AFM or confocal microscopy which requires time consuming scanning. In addition to the results presented, the system can give precious information in other MEMS processes. For example, it has a proven capability in measuring very fast processes using time averaging and intensity images to observe the resonant modes in MEMS devices[11]. Future work will concentrate on imaging in real time the deflection change of the MEMS cantilever under electrical load.

Disclosures

The authors have nothing to disclose.

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