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Characterization of MEMS cantilevers using lensless digital holographic microscope

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Abstract

In this paper vibration characterization of MEMS cantilevers are presented using lens-less in-line digital holographic microscope (LDHM). In-line digital holography provides larger information capability with higher phase sensitivity, and full CCD sensor area is utilized for real image reconstruction. In lensless in-line digital holographic microscope, a highly diverging beam replaces the conventional microscope objectives to provide the required magnification. The diverging wave geometry also reduces the effect of twin-image wave caused by the in-line holographic geometry. For vibration analysis, the time averaged holograms were recorded corresponding to different vibration states of the cantilevers. Direct numerical evaluation of the amplitude and phase information from single time averaged hologram provides the full-field real time quantitative analysis. The experimental study of vibration measurements of Aluminum nitride (AlN) driven cantilevers is performed. The full field study shows the simultaneous vibration behavior of many cantilevers corresponding to same input conditions. Our study shows the shift in the resonant condition of cantilevers both for first and second resonant frequencies. This kind of analysis is most suitable to optimize and monitoring the fabrication process of cantilevers.

Keywords: MEMS Cantilevers, Vibrations, Digital holography, lensless microscopy, CCD, time averaged, numerical reconstruction.

1. INTRODUCTION

Holography is the two step method for wavefront recording and reconstruction process [1]. It has been an established tool for scientific and engineering studies along with wide range of applications. With the recent developments of digital computers and Charged Coupled Devices (CCD), digital holography (DH) was proposed [2], to overcome the problems of classical holography. Digital recording devices (CCD sensors) provide flexibility to record holograms directly in digital form. The reconstruction process is then performed numerically giving quantitative access to the amplitude and phase of the wavefront [3]. This offers new possibilities for a variety of applications, which in classical holography was done only qualitatively. CCD sensors as holographic recording medium allow recording of holograms at video rates and are in a format readily available for numerical reconstruction. The computer reconstruction process is very flexible and can be used in a variety of ways to focus the image at different planes or removal of background etc.

Commercially available CCD sensors have 150 times lower resolution of the pixel size in comparison to the photographic films. This restricts the angle between object and reference waves to few degrees only in DH. In case of off-axis DH, an offset interference angle is introduced to separate twin image and zero-order term from the real image wave. But in this condition the full area of CCD sensor is not utilized in the real image reconstruction of the objects. On the other hand in-line digital holography has several advantages over the off-axis geometry e.g. larger field of view and higher imaging resolution [4]. But because of the in-line geometry, the zero order and conjugate image waves overlap

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with the real image wave during the reconstruction process. In our previous work we have proposed the methods for static and dynamic measurements for in-line digital holography [5-7]. The approach is based on double exposure method and also suitable for simultaneous suppression of background noise, caused by in-line geometry, without any pre-processing of holograms. The method requires that the amplitudes and phases from the individual holograms be determined first and then subtracted.

In this paper we present the study of MEMS cantilevers using lensless in-line digital holographic microscopy. The lensless magnification has achieved using a diverging beam. The study of the digital recording mechanism of holograms, and reconstruction methodology are explained. The vibration characterization of MEMS cantilevers is studied using time averaged principle [8] and the amplitude deformations at resonant frequencies are presented.

2. LENSLESS DIGITAL HOLOGRAPHIC MICROSCOPE

2.1 Optical system configuration

The lensless in-line digital holography microscope (LDHM) system geometry is shown in fig 1. A diverging laser beam is coming from the fiber end and provide the magnification in a lensless geometry. The beam is divided into two parts by using a beam splitter, one beam illuminates the sample and other incident on the plane mirror. The sample is illuminated by the diverging beam, coming from the beam splitter. The reflected light from the sample (called object beam) is combined with the other diverging beam, reflected from the mirror (called reference beam) and the resulting interference pattern is recorded by the CCD. The distance between object and CCD controls the magnification of the system. This set-up presents a lensless reflection microscopic geometry by using a very simple and compact optical set-up best suited for micro-size objects. The novelty of the system is the compact optical geometry with minimum number of optical components (only a beam splitter and mirror). The effect of zero-order term and twin image wave can be suppressed during reconstruction algorithm (discussed later).

The system shown in fig 1 is best suited for the study of highly specular objects. The distance from point source to object is constrained by the beam splitter, which restricts the magnification of the system. Also the system is not best suited for the study of the diffused surface objects. It is because the scattered beam from diffuse surface is significantly smaller than the reference beam intensity, and thus does not provide good contrast of the interference pattern.

Fig 1 Optical system of lensless in-line digital holographic microscope

Lateral resolution

In order to make sure the proper reconstruction of object image from hologram, the main requirement is the recording of proper holographic fringes. However, the lateral resolution of system depends on the numerical aperture (NA) and wavelength, similar to a conventional microscope. According to the Rayleigh resolution criteria, the minimum distance Δx , between of two points to be resolved, is defined as,

$$\Delta x \geq \lambda / 2 \cdot (\text{NA}) \quad (1)$$

Depth Resolution

The depth resolution defined in optical systems,

$$\Delta z \geq \frac{\lambda}{2 \cdot (\text{NA})^2} \quad (2)$$

Both lateral and depth resolution can be improve significantly, if hologram is recorded with sufficiently larger CCD sensing area and with larger NA. Also, the core diameter size of pinhole significantly effects the resolution of the system, the smaller size (ideally of the order of wavelength) increases the cone of the emitted light coming through it. This increases the NA of the system and thus improves the system resolution.

2.2 Reconstruction methodology

Reconstruction is performed by using a converging reference wave. The reconstruction wave is the conjugate of the diverging wave same as using during recording process. The reconstruction geometry is shown in fig 2. The object wavefield is reconstructed and its amplitude gives the images of the object in different sections parallel to the hologram plane. Thus it provide the 3-D reconstruction of the image from the two dimensional hologram. The reconstruction is performed using the Fresnel transform approach. Another advantage of such geometry is that, the twin image does not create any problem in the reconstructed real image [9]. This is because the twin image is on the opposite side of the real image and appears as a defocused image at the real image plane. In case of small objects, the amplitude of the twin image wave is significantly small at the real image plane. Also, when the hologram is reconstructed with a converging beam, the divergence of the out-of-focus twin image at real image plane further increases, and thus the amplitude becomes almost negligible compared with the real image wave. The lateral size of hologram also effects the twin image noise during reconstruction, the smaller lateral size increase the background noise created by the twin image. For zero-order suppression, the recorded digital hologram is processed by high pass filter before reconstruction process.

Fig 2 Reconstruction with converging reference wave

3. EXPERIMENTS AND RESULTS

3.1 Cantilevers fabrication and measurements requirements

Aluminium nitride (AlN) films have piezoelectric properties, and represent an alternative to PZT films [10]. Vibration analysis of the AlN cantilevers is performed using the lensless in-line digital holographic method

Fabrication details

Fabrication of cantilevers (fig. 3) is elaborated in the following 8 steps:

Fig. 3 Fabrication steps of cantilevers

Step 1: Si wafers of orientation and thickness of $\langle 100 \rangle$ and $380\ \mu\text{m}$ respectively, was used for the fabrication of cantilevers.

Step 2: This steps shows the formation of Si membrane. Anisotropic etching using KOH was done on the back side of the Si wafer, till a thickness of $15\ \mu\text{m}$ was achieved.

Step 3: The deposition of first layer of Cr Ni is shown in this step. $\text{Cr}_{50\%}\text{Ni}_{50\%}$ alloy was been sputtered on a heated substrate (200°C) at 230 watt (0.5 A) using a 7 mTorr Ar gas. A CrNi layer of thickness 150 nm was sputtered and patterned.

Step 4: AlN layer has been deposited in this step. A pulsed reactive DC sputtering machine on a non heated substrate with an input power of 650 watt, an Ar / N_2 gas ratio of 0.65 sccm / 6 sccm and a pressure of 4.9 mTorr, was used for the deposition. Two thicknesses of $1\ \mu\text{m}$ and $1.4\ \mu\text{m}$ were used.

Step 5: The deposition and patterning of the second layer of Cr Ni is shown in this step. Conditions similar to step 3 were used. The thickness of layer deposited was 350 nm.

Step 6: The top CrNi patterned layer was used as a hard mask for AlN etching, as shown in this step.

Step7: This step shows the deposition and patterning of 500 nm thick aluminum pads that were used for wire bonding.

Step 8: The last RIE step removed the silicon which was not protected by the CrNi hard mask, transforming the initial Si membranes into an array of free standing cantilevers.

The chip of the MEMS cantilevers device is attached to a standard SD card holder as shown in fig 4, which is attached to the frequency generator.

Fig 4 Layout of the $300 \times 50\ \mu\text{m}$ long cantilevers. The actuation of the cantilevers is done by applying a voltage between the upper and bottom metal electrodes

3.2 Imaging and vibration analysis using the LDHM system

A lensless in-line digital holographic microscopy is explored for imaging and dynamic characterization of MEMS cantilevers. The optical as shown in fig 1 is used. A single mode fiber (core diameter is $10\mu\text{m}$) is attached to the He-Ne laser. The hologram is recorded using the CCD, having 960×1280 pixels with $4.65\mu\text{m} \times 4.65\mu\text{m}$ in size. The distance between sample and CCD adjust the magnification of the system. The magnification of the system is limited because the pinhole (fiber end) and object distance is restricted by the beam splitter. The holograms of the cantilevers are recorded in static, and vibrations corresponding to resonance frequencies.

Imaging:

The optical microscopic image of the 4 cantilevers electronically connected together are shown in fig. 5 (a), and numerically reconstructed image using digital holographic system is shown in fig. 5 (b).

Fig. 5 (a) Optical microscopic image of the cantilevers with 5X magnification, (b) Numerically reconstructed image using the LDHM set-up

Full field vibration analysis

The behavior of the cantilevers vibrating at the first frequencies is shown in fig. 6. Five cantilevers are studied simultaneously. The applied excitation voltage is 0.5 Volts. It is clearly seen that all the cantilevers are not vibrating at the same resonant frequency. The scanning the frequencies at the first resonant frequency are performed from 66.85 KHz to 74.40 KHz, with the difference of 0.05 KHz and the vibration behavior of the cantilevers are shown.

Fig. 6 Vibration behavior of cantilevers at first resonant frequency: (a) 66.85KHz, (b) 66.90KHz, (c) 66.95KHz, (d) 67.0KHz, (e) 67.05KHz, (f) 67.10KHz, (g) 67.15KHz, (h) 67.20KHz, (i) 67.25KHz, (j) 67.30KHz, (k) 67.35KHz, (l) 67.40KHz

The vibration amplitudes of each cantilever are calculated at each frequency and plotted as shown in fig 7. It can be clearly observed that, the resonant frequencies of the cantilevers changes from right to left side. This means in term of fabrication process these are the cantilever from edge to centre side of the wafer. We suspect that this behavior is because of change in the stiffness coefficient at various location of wafer during fabrication process [11]. Similar effect is also observed for the second resonant frequency, and shown in fig 8. Here the frequencies are tune from 411 KHz to 422 KHz with the interval of 1 KHz.

Fig. 7 Change in vibration amplitudes of cantilevers for first resonant frequencies

Fig. 8 Vibration behavior of cantilevers at second resonant frequency: (a) 411KHz, (b) 412KHz, (c) 413KHz, (d) 414KHz, (e) 415KHz, (f) 416KHz, (g) 417KHz, (h) 418KHz, (i) 419KHz, (j) 420KHz, (k) 421KHz, (l) 422KHz

4. CONCLUSIONS

A lensless in-line digital holographic microscope (LDHM) is presented for MEMS device measurements. In LDHM system, a highly diverging beam replaces the conventional microscope objectives to provide the required magnification. The advantages of in-line holography i.e. larger field of view and higher imaging resolution improve the system capability. The experimental study of vibration measurements of aluminum nitride (aln) driven cantilevers is presented. Direct numerical evaluation wavefront provides the full-field quantitative analysis the full field study. The simultaneous vibration behaviors of many cantilevers corresponding to same input conditions are presented. Our study shows the shift in the resonant condition of cantilevers both for first and second resonant frequencies. This kind of analysis is most suitable to optimize and monitoring the fabrication process.

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