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Hybrid numerical—experimental approach for investigation of dynamics of microcantilever relay system

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Abstract

The time average holography measurements of the vibrating microelectromechanical switch (MEMS) were performed in this study. Experimental measurement results exhibit good agreement with computer generated holographic interferogram analysis. The validation of experimental investigations versus numerical analysis provides the necessary background to analyze the dynamical characteristics of micromechanical systems in virtual numerical environments. Direct application of fringe counting techniques for reconstruction of motion from time average holograms cannot be straightforward if the analyzed micromechanical systems contain motion limiters. Modifications of a classical time average holographic

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technique enable qualitative analysis of MEMS and can be applied for investigation of dynamical properties of much broader classes of MEMS systems.

Keywords: Microelectromechanical systems; Laser interferometry; Holography

1. Introduction

When miniaturizing any device or system, it is critical to have a good understanding of the scaling properties of the transduction mechanism, the overall design, the materials and the processes involved. Evaluating the mechanical properties and dynamic behavior of such components is a new challenge in mechanical engineering. It is important to keep in mind that homogeneity, commonly used with accuracy for bulk materials, becomes unreliable for modeling devices that have dimensions comparable to the material intrinsic lengths (grain size, microscopic fluctuations, interaction distances, etc.). Especially, investigation of the dynamics of microelectromechanical systems (MEMS) is an important problem from the point of view of engineering, technology and metrology [1–3]. Recent interest in applying MEMS technology to miniaturization of relays for a variety of applications requires the designing of appropriate testing and measurement tools for investigation of dynamic properties of those systems. Though MEMS technology offers great promise in addressing the need for smaller electromechanical arrays, the development of new types of micro relay systems is a very costly and complicated procedure [3]. On the other hand, the direct application of principles of design of macro-mechanical systems is rather limited in MEMS applications [4]. Therefore, application of measurement technologies capable of detecting the dynamic properties of microscale systems may help to understand and evaluate the functionality of the systems.

Time average holography—optical method initiated in the 1970s [5–7] has found many industrial applications and still is a promising method (like others: laser interferometry [8], TV holography [9,10], etc.) in small object displacement analysis. Time average holography involves creating a hologram while the object is subjected to some periodic forcing function. This yields a visual image of the vibration pattern. This technique can reveal the shape, direction, and magnitude of the stress-induced displacement in the structure under study [11]. The fringes seen in the holographic image are the contours of constant vibrational amplitude. Bright regions indicate regions of the surface that remain stationary. In this way, time average holography is a powerful tool for analysis of microscale vibrations [12]. The threshold of sensitivity of this measurement technique is defined by the magnitude of the wavelength of the illuminating laser beam. Also, this is a whole field non-destructive technique capable to register the motion of the whole surface instead of a single point.

In this paper, we propose to use time average holography to control kinetics of oscillations of the microrelay, operating at the different amplitudes of periodical excitation. Theoretical calculations as well as experimental verification are described.

2. Theoretical background

For sinusoidal excitation of the object, the intensities at various points of the object follow the square of the Bessel function of first kind and zero order [13]

$$I(a(x,y)) = \left(J_0\left(\frac{2\pi}{\lambda}a(x,y)\right)\right)^2 = \lim_{T\to\infty}\left|\frac{1}{T}\int_0^T \exp\left(\mathrm{j}\frac{2\pi}{\lambda}a(x,y)\sin(\omega t+\varphi)\right)\mathrm{d}t\right|^2, \tag{1}$$

where $a(x,y)$ denotes the field of amplitudes on the flat surface of the analyzed body, λ is the laser wavelength, t is the time, ω is the angular frequency, φ is the phase, T is the time of exposition and, $T \gg 2\pi/\omega$; j is the imaginary unit.

The center of the first band occurs at the first zero of the Bessel function — when the value of the argument of the Bessel function is equal to 2.4048 [13]. That means that no interference bands will be formed if the amplitudes of vibration at any points on the analyzed surface will be lower than

$$a(x,y) < \frac{2,4048 \cdot \lambda}{2\pi}. \tag{2}$$

Keeping in mind that the wavelength of the He–Ne continuous laser is 0.6328 μm, no interference fringes will be formed if the amplitudes will be lower than 0.24 μm. If such a threshold value is neglected in dynamics of macro mechanical systems, it becomes a serious physical limit for the applicability of time average holography in micromechanical applications.

On the other hand, the specific dynamical properties of a microswitch cantilever need to adopt the existing numerical simulation techniques. First of all, it is necessary to evaluate the fact that the period of motion is generally not a harmonic function as the cantilever's tips touch the drain. In a high-frequency repetitive mode of operation the deflection from the status of equilibrium can be characterized as the time function $\eta(t)$ (3) that is schematically presented in Fig. 1

$$\eta(t) = \begin{cases} \sin(\omega t+\varphi) & \text{if } \sin(\omega t+\varphi) > -c, \\ -c & \text{if } \sin(\omega t+\varphi) \leqslant -c, \end{cases} \tag{3}$$

where c is a constant satisfying inequalities $-1 \leqslant -c \leqslant 0$ and characterizing the clearance between the cantilever and the drain.

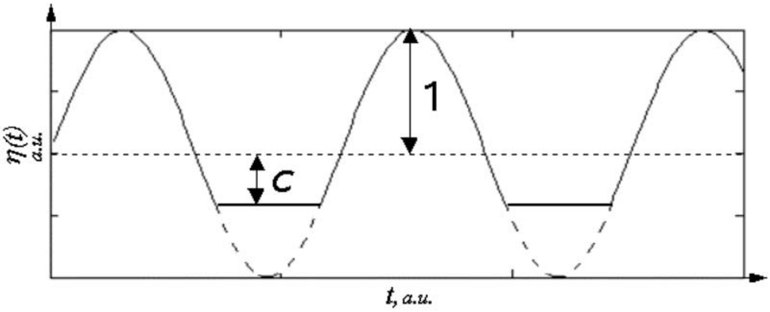


Fig. 1. Displacement of a cantilever tip in time with a limiter.

3. Numerical investigations

The relationship between the number of points of discretization in a period of harmonic motion and the number of interference bands with satisfactory quality of reconstruction is presented in [14]. The intensity of illumination when the surface performs quasi-harmonic vibrations defined by (3) will be determined by the following relationship:

$$I(a(x,y)) = \lim_{T\to\infty}\left|\frac{1}{T}\int_0^T \exp\left(\mathrm{j}\frac{2\pi}{\lambda}a(x,y)\eta(t)\right)\mathrm{d}t\right|^2 \approx \left(\frac{1}{n}\sum_{i=1}^{n}\cos\left(\frac{2\pi}{\lambda}a(x,y)\eta(t_i)\right)\right)^2 + \left(\frac{1}{n}\sum_{i=1}^{n}\sin\left(\frac{2\pi}{\lambda}a(x,y)\eta(t_i)\right)\right)^2, \quad (4)$$

where n is the number of points of discretization in a period of motion, t_i is the discrete time moments in the analyzed period.

It can be mentioned that the sum with the sine part does not converge to zero, as the function $\eta(t)$ is not symmetric. This fact must be evaluated while building numerical simulation procedures for visualization of the interference pattern of micromechanical switch. The decay of intensity of illumination at increasing amplitude a is presented in Fig. 2. It may be noted that the value of intensity of illumination 1 corresponds to the white color (motionless structure), and value 0 corresponds to the black color (centers of interference fringes).

Assuming that the centers of interference fringes are shifted in the scale of amplitudes for non-harmonic oscillations, it is possible to track these changes for different values of parameter c. This effect of shifting is illustrated in Fig. 3. When $c = 1$ (harmonic vibrations), the centers of interference fringes coincide with the amplitudes bringing intensity to zero in Fig. 2.

The illustrated results—straightforward interpretation of experimental fringe pattern in time average laser hologram of micromechanical elements — can be

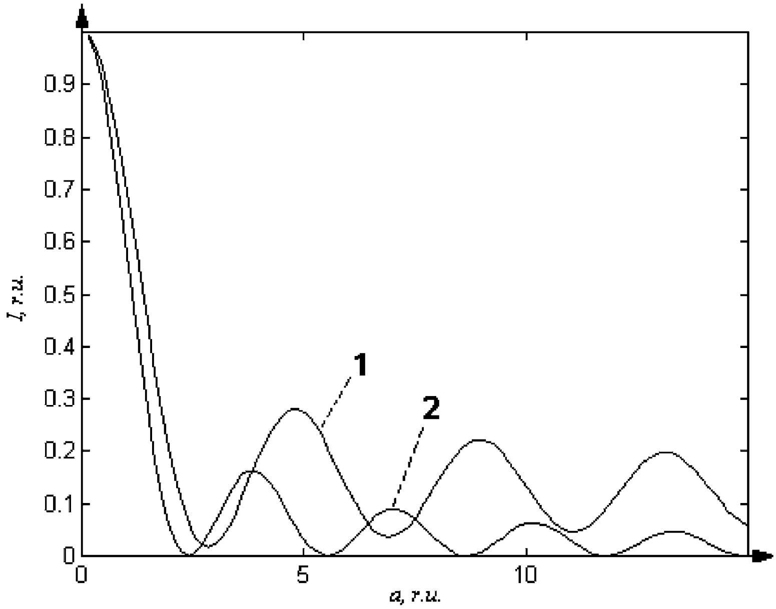


Fig. 2. The decay of intensity of illumination at increasing amplitude a (horizontal axis—a; vertical axis—intensity of illumination): (1) for oscillations described by Eq. (3) at $c = 0.5$; (2) for harmonic oscillations.

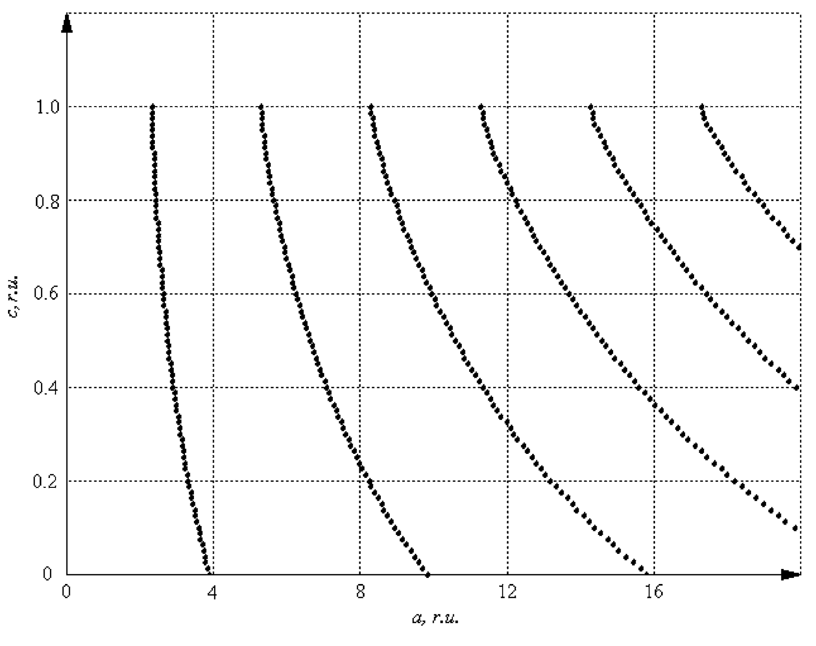


Fig. 3. Relationship between the parameter c and the location of the centers of interference fringes.

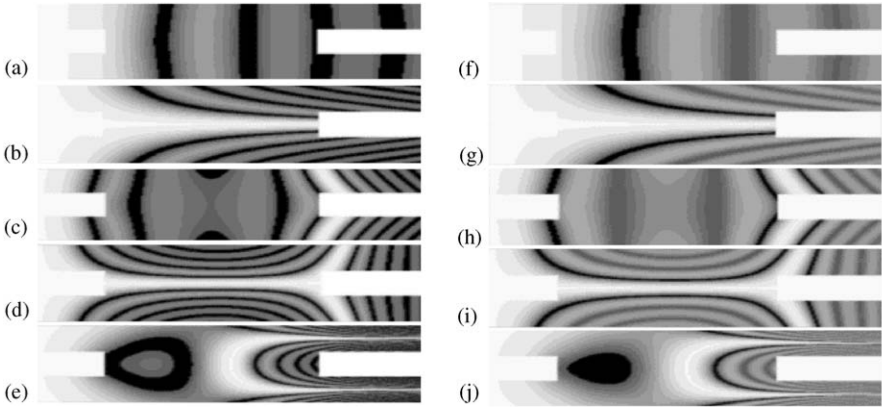


Fig. 4. Numerically reconstructed interference fringes for the first five eigenshapes; a, b, c, d, e—representing harmonic vibrations of cantilever without limiter (no drain contact).

incorrect. Specifically, the reconstruction of motion of micromechanical switch cantilever plate from its holographic image is not correct if it does not perform free harmonic oscillations. Hence standard motion reconstruction procedures [15] are not applicable to vibrating systems with limiters.

Therefore there exists a primary interest not only in calculation of natural eigenforms of the analyzed micromechanical system but also in the visualization of its eigenshapes. The modeling of dynamics is performed using finite element analysis,and the visualization of interference fringes is performed using methodology described in [14]. Fig. 4 represents patterns of interference fringes for the first ten eigenforms.

Numerically developed interference fringe patterns serve as an important reference for the interpretation of experimental results [16]. Moreover, numerical simulations can help to optimize the developed structure without the necessity of building numerous experimental models.

Naturally, if the time function is not harmonic, the indefinite integral in (1) will not converge to the zeroth order Bessel function of the first kind. Thus, a direct comparison between experimental results and simulated interferographic images in Fig. 4 would be misleading. The described complication in the interpretation of holographic fringes is illustrated by a hologram of a vibrating micro cantilever shown in Figs. 5 and 6.

It may be noted that finite element modeling of the cantilever beam was produced with the best possible conformity to experimental MEMS cantilever with appropriate selection of the geometric shape of the system. Therefore, the white rectangle zones in computer simulated holographic interferograms represent perforations directly related to the analyzed system presented in Fig. 5. The boundary conditions are reconstructed at the clamped left section of the cantilever.

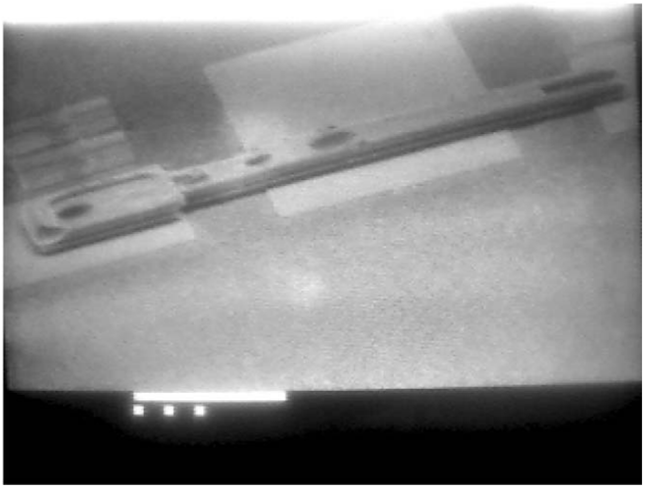


Fig. 5. SEM microphotograph of the microelectromechanical switch. Mark size 100 μm.

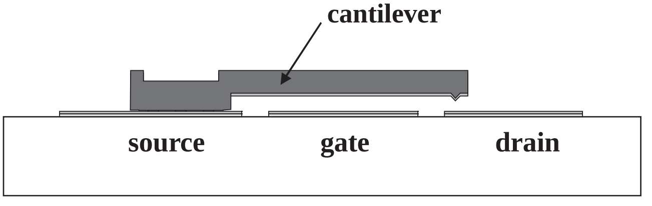


Fig. 6. Schematic presentation of the switch construction.

4. Experimental analysis

4.1. Microelectromechanical switch: Technology and construction

The fabrication sequence of the micro-electromechanical switch begins with the patterning and reactive ion etching of silicon using SF_6/N_2 gas chemistry in the cantilever source (support) area fabricating microstructures to increase the cantilever bond strength and durability of the device. After treatment of the substrate in the O_2/N_2 gases mixture plasma, a chrome layer of about 30 nm thickness and a gold layer of about 200 nm thickness were deposited. Patterning of the source, gate and drain electrodes was performed using lift-off lithography. Electron beam evaporation was performed to deposit a sacrificial copper layer with a thickness of about 3000 nm. The copper layer covered the whole area of the substrate. Patterning of the copper layer was performed in two steps. First of all, the copper layer was partially etched (etchant: H_2SO_4:CrO_3:H_2O) to define the contact tips for the cantilever and etching duration directly determined the spacing between the tip's top and the drain electrode. Next, the copper layer was etched away to uncover the source cantilever support area. The next step was photoresist patterning on the top of the sacrificial layer to define the mask for the cantilever sector, and lift-off lithography of the evaporated gold layer with thickness of about 200 nm was performed. Afterwards, the photoresist was spun and patterned once again in the same sector and the nickel layer (thickness—3000 nm) was electroplated (sulfamate electrolyte: $Ni(NH_2SO_3)_2$: $4H_2O$) fabricating cantilever structure. Finally, the sacrificial layer was removed using the same wet copper etchant to release the free-standing cantilever with a length of about 200 μm and width with about thirty micrometers. Figs. 5 and 6 present geometry of the final product—the electromechanical switch that was investigated using time average holography. One extra set of relays without limiters (no drain contact) was produced for investigation of the influence of the limiter to the dynamics of MEMS. The distance between the tips of the cantilevers and the drain allows one to estimate the value of constant c in (3) and reconstruct the form of the cantilever vibration as shown in Fig. 1.

4.2. The time average holography measurements of the vibrating microswitch

The holographic interferogram was recorded using the Denisiuk hologram recording method [17] (He–Ne laser with the wavelength 0.6328 μm was employed). The array of cantilevers was illuminated through the high density holographic material (recording density over 10,000 lines per mm). The array of cantilevers was placed directly under the holographic plate and the holographic interferogram was recorded using the principles of time average holography for vibrating opaque bodies. The Denisiuk hologram recording method enables the reconstruction of holographic images in daylight illumination. The optical measurement setup is illustrated in Fig. 7.

Fine grain silver halide holographic photo plate PFG-03C (resolving power-$\geqslant 10{,}000\,mm^{-1}$) was used. Thus the image of stationary array of cantilevers A (Fig. 7) with vibrating tips was recorded onto Denisiuk hologram. The tips of the cantilevers were brought into high-frequency oscillatory motion by exposing the array plate to ultrasonic acoustic excitation. The used frequency of ultrasonic excitation was 63 kHz.

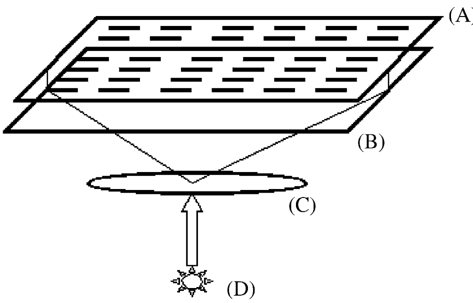
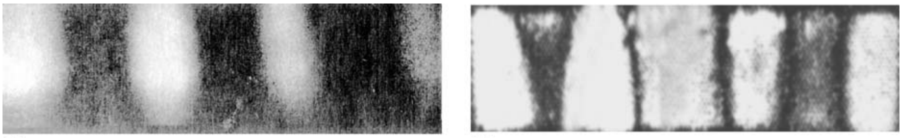


Fig. 7. The schematic diagram of the holographic set-up for recording Denisiuk hologram: (A) the array of cantilevers; (B) holographic plate; (C) lens; (D) laser light source.



(a) (b)

Fig. 8. Time average holograms of cantilever beams: (a) representing cantilever without limiter (no drain contact); (b) cantilever with limiter (drain contact representing $c = 0.5$).

After the development of the recorded hologram the holographic picture of cantilevers was reconstructed using a red light diode source. Such diode source illumination is necessary to avoid the formation of speckle structure in a laser image. A microlens system was used to enlarge the image of the cantilevers (magnification up to 200 times enabling registration of the interference fringes of a single cantilever). It should be noted that the last procedure is complicated due to the fact that quality of the magnified image is greatly affected by the speckle structure of the reference laser beam. Thus the speckle microstructure of the beam was minimized using a red light diode source.

Figs. 8a and b represent time average holographic images of the microcantilever beams. The image of the harmonically excited cantilever beam of the micro-mechanical switch without limiters is presented in Fig. 8a. The holographic image of cantilever beam with limiters at $c = 0.5$ (Eq. (3)) is presented in Fig. 8b. The left white zones in both pictures correspond to the clamped part of the cantilever beams. The determination of the centre of interference fringes is straightforward and does not require special phase unwrapping techniques basically due to the fact that the analysed shape of the vibrating beam is very simple—in both cases it is the first eigenshape. Application of the shape reconstruction procedures confirms the proposition that the motion of the cantilever beam is similar to the first eigenshape.

Fig. 9 illustrates the procedure of reconstruction of motion from a time average hologram. It is clear that the problem has no unique solution if the magnitude of c is not pre-determined. Application of the fringe counting method for reconstruction of motion from time average holographic images can be applied with satisfactory accuracy only when it is known that the exposed structure is performing harmonic vibrations. Otherwise Figs. 2 and 3 as well as earlier presented numerical analysis show the shift of interference fringes. Direct comparison of the two pictures a and b in Fig. 8 also confirms the fact that the centres of the interference fringes are shifted if the vibration is not harmonic. According to our experimental investigation, the reconstructed maximum deflection from the state of equilibrium (at the right edge) in Fig. 8a is 0.441 μm (fringe counting technique is used for the determination of the value of amplitude). Assuming that the vibrations were harmonic, the reconstruction of the motion in Fig. 8b would give only 0.403 μm as a maximum deflection (that is, about 9% away from the correct value).

The produced experimental results show good agreement with computer generated holographic interferogram analysis presented in this paper.

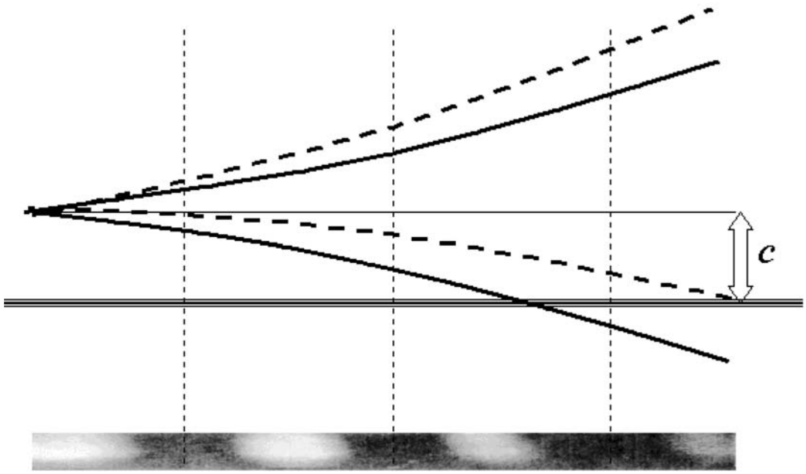


Fig. 9. The procedure of reconstruction of the cantilever motion: (solid lines)correspond to the assumption that the vibrations are harmonic; (dashed lines)the assumption that the clearance between the tip and the drain is c.

5. Conclusions

The validation of experimental investigations versus numerical analysis provides the necessary background to analyze the dynamical characteristics of micromechanical systems in virtual numerical environments.

Direct application of fringe counting techniques for reconstruction of motion from time average holograms cannot be straightforward if the analyzed micromechanical systems contain motion limiters.

Modifications of a classical time average holographic technique enable qualitative analysis of microelectromechanical switches and can be applied for investigation of dynamical properties of much broader classes of MEMS systems.

Acknowledgement

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