332. Analysis of Holographic Interferogram of Microelectromechanical System with Non Harmonic Cycles Excitation

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Abstract. Recent technological trends based on miniaturization of mechanical, electromechanical and photonic devices to the microscopic scale have led to the development of microelectromechanical systems (MEMS). Effective development of MEMS components requires the synergy of advanced design, analysis, and fabrication methodologies as well as application of quantitative metrology techniques for characterizing their performance, reliability and integrity during design stage. In this paper, we describe analysis of holographic interferograms of MEMS links which includes interferometric fringes related to deformation appearing because of the non-harmonic excitation of MEMS links.

Keywords: microelectromechanical system, holographic interferometry, mechanical vibration.

Introduction

Holographic interferometry is the powerful tool for analysis of dynamics of microelectromechanical systems [1-6]. It is a non-destructive full-field measurement technique capable of registering micro-scale oscillations of MEMS components [2]. There exist numerous methods [3] used for interpretation of patterns of fringes in the holograms of analyzed objects. Unfortunately, sometimes straightforward application of these motion reconstruction methods (fringe counting technique, etc.) does not produce acceptable results. A typical example is holographic analysis of a micro-electromechanical switch which is described in [7].

The vibration of cantilever of micro-electromechanical switch produces nonlinear effects in a microstructure. Holographic interferogram of vibrating surface of such cantilever cannot be evaluated directly using characteristic function for distribution of interference fringes in the case when time-averaging method for recording hologram is used. The characteristic function of distribution of interference fringes of the vibrating surface of the object should be chosen taking into account the nature of nonlinearities taking place in working regimes of microelectromechical system.

In the paper [5] it was demonstrated that 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 cantilever 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 $\eta(t)$ (1) that is schematically presented in Fig. 1:

$$\eta(t) = \begin{cases} \sin(\omega t + \varphi) \text{ if } \sin(\omega t + \varphi) > -c \\ -c \text{ if } \sin(\omega t + \varphi) \le -c \end{cases}$$

(1)

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

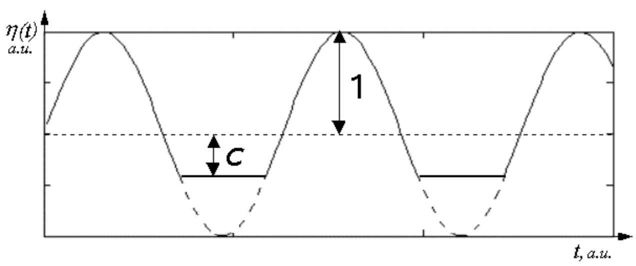
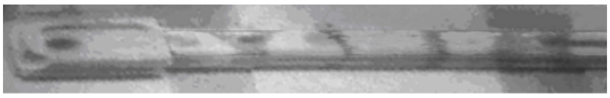


Fig. 1. Displacement of a cantilever tip in time with a limiter

Because of this cantilever produces non-harmonic cycles of fluctuations and the system of dark interference fringes of the recorded holographic interferogram of cantilever should be analyzed using characteristic function which have to be derived for this case of periodical excitation of cantilever.

To illustrate this case the holographic interferograms of vibrating cantilever were recorded using Denisiuk hologram recording method [7] (He-Ne laser with the wavelength 0,6328 μm was employed). Fig. 2 a and b represent time- averaged 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 2 a. The holographic image of cantilever beam with limiters at c = 0,5 (Eq. 1) is presented in Fig 2 b. 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 analyzed shape of the vibrating beam is very simple – in both cases it is the first eigenshape.

a



b

Fig. 2. Time-averaged holograms of the cantilever beams: a - representing cantilever without limiter (no drain contact); b - cantilever with limiter (drain contact representing c = 0,5)

The problem is that for analysis of holographic interferogram presented in the Fig. 2b characteristic function for the interpretation of holographic interferogram is different than is used usually in time-averaging holography in case of sinusoidal vibration of object and characteristic function should be derived taking into account nonlinearities of vibrating cantilever. The derivation of the characteristic function of distribution interference fringe in case of non-harmonic oscillation is presented in this paper.

Characteristic Functions for Interpretation of Holographic Interferogram

In full-field nondestructive testing using holographic interferometry methods it is necessary to describe the physical origin of the interference bands, the function describing the intensity of these bands and the methodology of their interpretation.

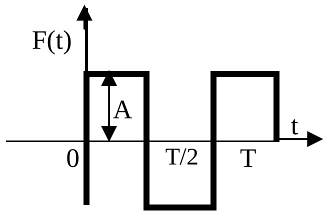
The applied method for development of the interference patterns on the surface of a vibrating body is based on the time-averaging methodology which presumes that the exposition of the vibrating surface to the laser beam is many times longer than the period of vibrations.

In the case when each point of the surface performs harmonic oscillations, the averaged lightening intensity distributed on the vibrating surface may be described by the following formula [5]:

$$I \approx \left| \frac{a}{T} \int_0^T \exp\left\{ -i\left[\psi_0 + \frac{2\pi}{\lambda} \int_0^t (\cos\theta_1 + \cos\theta_2) F(t) dt \right] \right\} dt \right|^2, \quad (2)$$

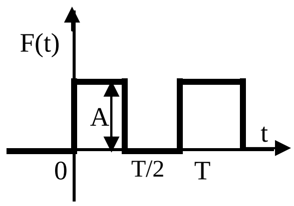
where I − intensity; T − time of exposition; λ − length of the laser beam light; R − the vector of vibration; t − time; θ_1 − angle between the lightening and the vibration vectors; θ_2 − angle between the observation and the vibration vectors; $\psi_0 = \frac{2\pi \sin\theta}{\lambda}$; θ − angle between the observation and the normal vector of the hologram plane; a − the coefficient of the light reflection of the surface; *F(t)* – harmonic function related to vibrating surface of the object.

Let us consider that for excitation of links of microelectromechanical system is used the signal with the period T which is described as presented in Fig. 3.



$$F(t) = \begin{cases} A, kT \le t \le kT + T/2 \\ -A, kT + T/2 \le t \le (k+1)T/2 \end{cases}$$

a)



$$F(t) = \begin{cases} A, kT \le t \le kT + T/2 \\ 0, kT + T/2 \le t \le (k+1)T/2 \end{cases}$$

b)

Fig. 3. Signal for external excitation of the links of the microelectromechanical system

The time-averaged holographic interferogram analysis of microelectromechanical systems in case when their parts perform non-harmonic oscillations is based on non-harmonic periodic cycles decomposition using Fourier transformation.

In general case signal *F(t)* is expressed as

$$F(t) = \frac{AT_0}{T_1} + 2A\frac{T_0}{T_1}\sum_{k=1}^{\infty} \frac{\sin\frac{\pi k_i T_0}{T_1}}{\frac{\pi k_i T_0}{T_1}} \cos k_i \omega_0 t \quad (3)$$

where T_0 – period of rectangular signal; $\omega_0 = \frac{2\pi}{T_0}$ - frequency of the signal; A – amplitude of vibrations normal to the surface of the analyzed part of the MEMS; $k_i\,\omega_0$ - k_i – harmonic components (k_i = 1,2,3,…..n); T_1 – number less than 5 – 7.

Characteristic function of distribution of interference fringes taking into account (3) is expressed as follow

$$M\{F(t)\} = \frac{1}{T}\int_0^t \exp[i4\pi F(t)/\lambda]dt =$$
$$= \frac{1}{T_0}\int_0^t \exp\left[i\frac{4\pi}{\lambda}\left(\frac{AT_0}{T_1} + 2\frac{AT_0}{T_1}\sum_{k=1}^{\infty}\frac{\sin\frac{\pi k T_0}{T_1}}{\frac{\pi k T_0}{T_1}}\cos k\omega_0 t\right)\right]dt \qquad (4)$$

It is shown in [8] that in the case when T_1 is less than 5 – 7, $T_0/T_1 = \eta_1$ and number of harmonics is 7 the formula (3) could be transformed as follow:

$$M\{F(t)\} = \exp\left(i4\pi\eta_1\frac{A}{\lambda}\right) +$$
$$+\ \frac{1}{T_0}\int_0^t \cos\left(\frac{8A}{\lambda}\sum_{k=1}^{7}\frac{\sin k\pi\eta_1}{k\pi\eta_1}\cos k\omega_0 t\right)dt\ + \qquad (5)$$
$$+\ \frac{i}{T_0}\int_0^t \sin\left(\frac{8A}{\lambda}\sum_{k=1}^{7}\frac{\sin k\pi\eta_1}{k\pi\eta_1}\cos k\omega_0 t\right)dt$$

The results of calculation by formula (5) in case η_1 = 0,1; 0,25; 0,5; 0,75 are presented in Table 1 and Fig. 4 a,b.

Table 1.

The values of the characteristic function in the center of the dark interference fringes at the various intervals of the period

Dark interference fringes.	η_1								
	0,1	0,25	0,5	0,75		0,1	0,25	0,5	0,75
1	0,25	0,25	0,25	0,25	11	2,45	2,75	2,8	2,8
2	0,45	0,5	0,5	0,5	12	2,7	3,0	3,05	3,05
3	0,69	0,75	0,75	0,75	13	2,95	3,3	3,35	3,35
4	0,9	1,0	1,0	1,0	14	3,2	3,55	3,6	3,6
5	1,14	1,25	1,24	1,24	15	3,6	3,8	3,8	3,8
6	1,29	1,49	1,49	1,49	16	4,0	4,05	4,15	4,15
7	1,49	1,7	1,7	1,7	17	4,3	4,3	4,45	4,45
8	1,69	1,95	1,99	1,99	18	4,55	4,6	4,75	4,75
9	1,999	2,249	2,249	2,249	19	4,8	4,85	5,0	5,0
10	2,24	2,5	2,5	2,5	20	5,0	5,05	5,35	5,35

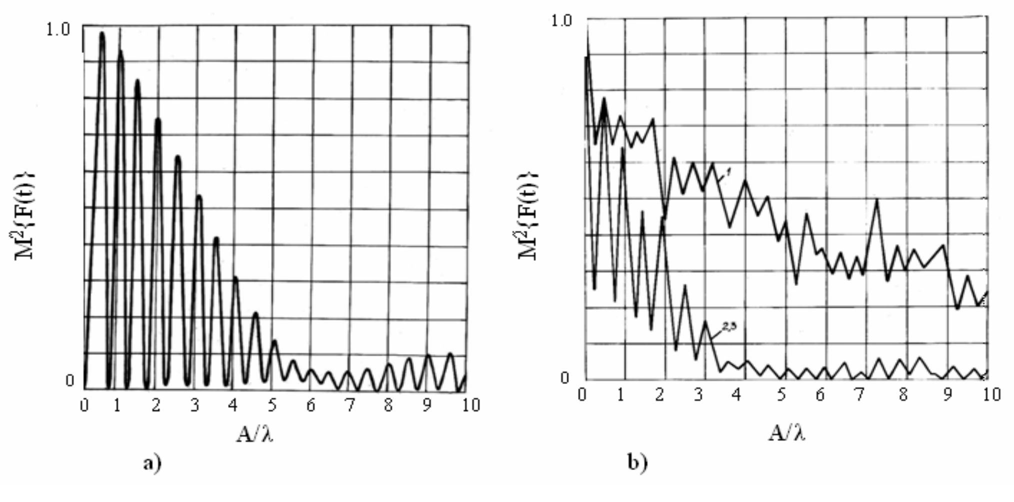


Fig. 4. Distribution of the intensity of interference fringes versus amplitude of vibrating surface of the MEMS: a) η_1 = 0,25; b) 1 - η_1 = 0,1; 2, 3 η_1 = 0,5; 0,75

Characteristic function of interference fringes distribution in case when excitation is expressed as periodic triangle signal is expressed as follow

$$F(t) = \frac{AT_0}{4T_1} + \sum_{k=1}^{7} \frac{AT_0}{T_1} \left(\sin \frac{\frac{k\pi\eta_1}{2}}{\frac{k\pi\eta_1}{2}} \right)^2 \cos k\omega_0 t \qquad (6)$$

The results of calculation using formula (5) are performed in case η_1 = 0,1; 0,25; 0,5; 0,75 (Table 2 and Fig. 5).

Table 2.

The values of the characteristic function in the center of the dark interference fringes at the different intervals of the period

Dark interference fringes	η_1								
	0,1	0,25	0,5	0,75		0,1	0,25	0,5	0,75
1	0,4	0,49	0,4	0,4	11	4,0	3,1	2,9	2,9
2	0,7	0,6	0,6	0,65	12	4,1	3,45	3,2	3,15
3	1,04	0,9	0,85	0,9	13	4,65	4,05	3,45	3,4
4	1,24	1,15	1,1	1,15	14	4,95	4,45	3,7	3,65
5	1,65	1,5	1,35	1,4	15	5,4	4,75	3,95	3,9
6	1,5	1,7	1,6	1,6	16	5,7	5,0	4,2	4,15
7	2,6	2,0	1,9	1,85	17	6,0	5,35	4,5	4,45
8	2,7	2,45	2,15	2,1	18	6,25	5,6	4,75	4,7
9	3,5	2,55	2,4	2,4	19	6,65	5,9	5,0	4,95
10	3,6	2,8	2,65	2,65	20	6,95	6,20	5,25	5,20

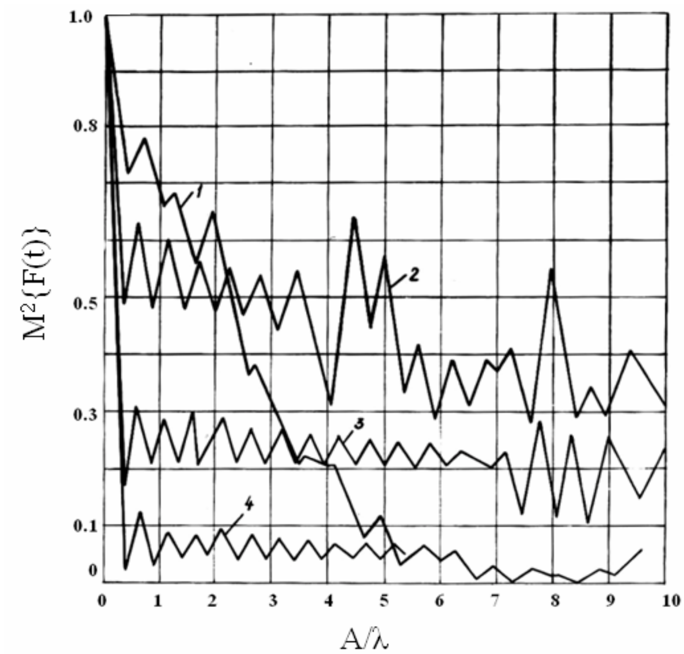


Fig. 5. Distribution of the intensity of interference fringes versus amplitude of vibrating surface of the MEMS when triangle signal is used for excitation

3. Concluding Remarks

Though time-averaging holography is a powerful experimental technique for analysis of MEMS dynamics, the interpretation of produced patterns of fringes in holograms must be performed with care. Complex physical and nonlinear dynamical processes taking place in MEMS systems may influence the results produced by optical methods and require additional analysis of the vibrational processes and the derivation of the characteristic function of distribution of interference fringes which must correspond to the character of vibration that appear in real design of microelectromechanical systems.

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