The article presents a method of control of functional surfaces of MOEMS elements of special purpose, which can be used in the technology of production of such structures. This method of non-destructive testing allows to obtain information about the parameters of the topology of the surface of functional structures, by eliminating the accompanying components in the interference signal. The method, in comparison with others, allows to increase the reliability of technological operations of production of functional surfaces of optical signal switches by more than 20% and to reduce labor costs up to 35%. Using the proposed method, it is possible to give recommendations for improving the technological process of manufacturing MOEMS functional surfaces, to ensure the specified values of their topology. The modeling by means of computer processing is performed in the paper in order to determine the extremes of the bands of interference images of the functional surfaces of MOEMS elements.

Keywords: method, non-destructive control, optical component, batterword filter, moems, manufacturing defect.

Introduction

MEMS-technology of manufacturing optical mirrors involves the application of metal coatings mostly on a silicon base (to which metals can be added in small quantities to give certain properties).

Various metals, multilayer metal structures, metal silicide, glass enamels, polycrystalline silicon, carbon nanotubes, polymers and other materials are used as functional reflective surfaces. The use of several technological modes to obtain such structures, leads to all sorts of inevitable in them defects, introduced by the manufacturing technology [1].

The fact that the switching of the beam is carried out without converting light-electric signal-light, avoids limitations of the spectrum and distortion of the signal, but imposes additional, clear limitations and requirements for the quality of functional characteristics of reflective components and MOEMS in general.

The relevance of the study is due to the fact that despite the large number of experiments, proposed methods for analyzing the quality of functional elements, there is still the problem of ensuring the quality of such structures and processes.

There is no universal method, both for obtaining materials and quality control of such structures, control of their topology, which could be recommended as the best.

The used methods of linear processing are based on the developed theoretical basis, have high accuracy and wide functionality. However, in some cases, special methods of nonlinear computer processing of interference signals are appropriate [1].

The use of one or another approach depends on the type of interferometric problem to be solved and the following factors:

– the required accuracy of measurements and noise immunity of the system;
– the speed of the recording device and the computer system;
– the presence of independent channels for obtaining information about the characteristics of signals and external influences;
– the possibility of obtaining reliable a priori estimates of the parameters of interference images [1].

The proposed method of computer signal processing has a fairly high accuracy and wide functionality, does not require the use of specific equipment and allows you to analyze the qualitative micro characteristics of reflecting surfaces and obtain their three-dimensional image with the ability to cut (eliminate) noise and background components.

Statement of basic materials

Real interference signals can be represented for a one-dimensional case in the form [3]:

\[ s(x, \Theta) = s_0(x) + s_m(x) \cos[\varepsilon + 2\pi m x + \psi(x)] + n(x), \]

where \( \Theta \) – the parameter vector;
\( s_0(x) \) – the background component;
\( \psi(x) \) – coefficient of phase fluctuations;
\( n(x) \) – additive noise (white Gaussian noise).

In (1) there is a harmonic information component, which indicates the feasibility of processing interference signals in the frequency domain.
Signal (1) is characterized by two important parameters – frequency $u_0$ and initial phase $\varepsilon$. In practice, there is the influence of a priori unknown parameters $s_m(x)$, $\psi(x)$, and $s_0(x)$, and, as a result, the type of signal can change significantly.

This gives grounds for the use of nonparametric methods in computer processing of interference signals based on the Fourier transform apparatus: discrete (2) – when processing the $N$-point sequence of the signal value $s(p)$ and discrete inverse transformation (3) to determine the periodicities in interference signals of the form:

$$ S(q) = \sum_{p=0}^{N-1} s(p) \exp(-j2\pi pq/N),$$

(2)

Using the results of research on the pre-processing of the interference image, we took a two-dimensional distribution of the interference field formed by the functional layer of the optical switch, obtained the original data (Fig. 1, a). Fig. 1, a shows the presence of high-frequency and pulsed noise of the structure under study in the signal. We use an interactive environment for programming numerical calculations and visualization, which allows you to parse photos into a matrix of digital data. Fig. 1, b shows a fragment of the distribution of the amplitude of the interference field in the one-dimensional version, fig. 1, c – the signal with the noise component in the multidimensional version.

Taking into account that the signal has significant noise components, which do not allow to find reliable interference maxima for the obtained matrix and to minimize the noise components, it is necessary to filter the input signal.

The procedure of electronic filter synthesis includes two main stages. The first stage is an approximation – a procedure for obtaining a transfer function with a given accuracy; reproduces the specified frequency or time characteristics.

Let’s use the Butterworth functions. The transfer function of the $n$-th order Butterworth low-pass filter is characterized by the expression (4):

$$ [H(jw)]^2 = \frac{1}{1 + w^{2n}}. $$

(4)

The amplitude-frequency characteristic of the Butterworth filter has the following properties:

1. At any $n$-th order the AFC value is $H(j_0) = 1$.
2. At the cutoff frequency $\omega_c$ ($H(j_0) = 0.7$).

The AFC of the filter decreases monotonically with increasing frequency. For this reason, Butterworth filters are called filters with the flattest characteristics.

$$ [H(jw)] = \frac{1}{\sqrt{1 + w^{2n}}} \approx \frac{1}{w^n}. $$

(5)

Fig. 1. Initial interference image of the fragment of the surface of the mirror under study
a – interferogram of a fragment of the mirror surface;
b – the distribution of the amplitude of the interference field in the one-dimensional version;
c – a signal with a noise component in a multidimensional version
The order of the transfer function is determined by the approximate formula (6).

\[ n = \frac{20 \log |H(j\omega)|}{20 \log (w/w_c)} \]  

(6)

Fig. 2, a shows the filtered interference signal of the fragment using the Butterward filter, and fig. 2, b shows the noise allocation. Fig. 2, c – the interference signal before filtering and after in the one-dimensional version for comparison.

![Fig. 2. The signal is filtered by the Butterward filter](image)

Fig. 2. The signal is filtered by the Butterward filter

Fig. 3 shows a three-dimensional graph of the distribution of the amplitude of the interference field on the sample before filtering (a), after filtering – (b).

Obviously, the use of the Butterworth filter made it possible to smooth out the amplitude of the interference field, almost eliminate the background, reduce the amount of noise at the border of the bands and between them, and increase the sharpness of the mirror sample under study, thereby improving accuracy in subsequent processing.

![Fig. 3. Three-dimensional graph of the distribution of the amplitude of the interference field](image)

Fig. 3. Three-dimensional graph of the distribution of the amplitude of the interference field
a – before filtration; b – after filtration

One of the problems that arise when processing interference signals is the uneven bypass \( s_m(x) \) of the signal (1). It is a multiplicative interference that prevents accurate recovery of signal phase values. To
eliminate the effect of this non-uniformity, a method can be used in which, regardless of the shape of the useful component of the signal, it is matched by a Gilbert-linked component having the same envelope \( s_0(x) \). The obtained phase values do not depend on \( s_0(x) \). Thus, the use of the Gilbert transform and the theory of analytical signals allows to reduce the influence of multiplicative noise and phase distortions of the interference signal.

The function \( s_c(x) \) is valid, \(-\infty < x < \infty\) then it can be aligned with the function \( s_s(x) \) expressed by the Gilbert transformation \( H\{s_c(x)\} \):

\[
s_s(x) = H\{s_c(x)\} = \int_{-\infty}^{\infty} \frac{s_c(\xi)}{\pi(x-\xi)} d\xi
\]  

(7)

or when using convolution characters:

\[
s_s(x) = s_c(x) * (1/\pi x).
\]

(8)

Using the Cauchy integral, namely \( \lim_{x \to a} s(x) = \infty, b < a < c \), then the principal relation is determined as:

\[
\left\{ \begin{array}{l}
s(x)dx = \lim_{x \to a} \int_{b}^{a-c} s(x)dx + \int_{a+c}^{c} s(x)dx.
\end{array} \right.
\]

(9)

The analytical signal is determined by a complex function:

\[
z(x) = s_c(x) + js_s(x).
\]

(10)

Expression for polar coordinates:

\[
z(x) = |z(x)| \exp[j\varphi(x)],
\]

where

\[
|z(x)| = \sqrt{s_c^2(x) + s_s^2(x)} = s_{\text{en}}(x)
\]

(12)

is the enveloping,

\[
\varphi(x) = \arctg\left(\frac{s_s(x)}{s_c(x)}\right)
\]

(13)

is the local phase of the signal.

The local frequency is determined:

\[
u(x) = (1/2\pi) \left(\frac{d\varphi(x)}{dx}\right).
\]

(14)

If the spectrum of the analytical signal is expressed as:

\[
Z(u) = F\{z(x)\} = F\{s_c(x) + js_s(x)\} = S_c(u) + jS_s(u),
\]

(15)

then the inverse Fourier transform leads to the following result:

\[
z(x) = F^{-1}\{Z(u)\} = s_c(x) + js_s(x).
\]

(16)

The interference signal (1) is subjected to a Fourier transform to obtain a frequency spectrum whose components are centered relative to \( \pm u_0 \).

It should be noted that the Gilbert transformation is performed as a result of the inverse Fourier transform obtained only at positive frequencies. Therefore, the spectrum \( Z(u) \) of the complex analytical signal \( z(x) \) generated by the information component of the interference signal is described as

\[
Z(u) = \begin{cases} 
2S_c, & u \geq 0; \\
0, & u \leq 0.
\end{cases}
\]

(17)

The inverse Fourier transformation of \( Z(u) = 2S_c(u), u > 0 \), obviously gives \( z(x) \), at which

\[
s_s(x) = \text{Im}\{z(x)\}.
\]

The maxima of the filtered signal can be determined in several ways: to use the differentiation of the filtered signal or by means of Gilbert transformations.

Fig. 4 shows markers that separate the area of the useful signal spectrum of the input signal.

Fig. 4. Spectrum of the input signal
As a result of the Gilbert transformation of the interference signal, the conjugate component \( s_x(x) \) in the analytical signal is restored:
\[
z(x) = s_c(x) + js_x(x),
\]
where
\[
\begin{align*}
s_c(x) &= \text{Re}\{z(x)\} = s_n(x)\cos[\varepsilon + 2\pi u_0 x + \psi(x)], \\
s_x(x) &= \text{Im}\{z(x)\} = s_n(x)\sin[\varepsilon + 2\pi u_0 x + \psi(x)]
\end{align*}
\]
(19)

quadrature components of (19) we obtain an estimate of the phase of the interference signal (1) performing the operation:
\[
\hat{\phi}(x) = \hat{\varepsilon} + 2\pi u_0 x + \hat{\psi}(x) = \arctg\left[s_x(x) / s_c(x)\right]
\]
(20)
for all values of \( x \). It should be borne in mind that in operation (20) the phase values are calculated taking into account all the frequency components of the signal, which is significant and significantly improves the quality of control.

In practice the Hilbert transformations are performed on the basis of the FFT algorithm (fast Fourier transformation) using the relation (17), which connects the spectra of the analytical signal and the useful component of the interference signal \( s_c(x) \).

It is important to study the errors of the recovery of the bypass and phase as a module and argument of the analytical signal.

When forming the analytical signal (10) using the relations (17) the condition of narrowband was implicitly assumed: the width of the spectrum of the signal (1) was small in comparison with the frequency, i.e.,
\[
\hat{z}(x) = z(x) + \hat{\delta}z(x) = (1/2\pi)\int_0^\infty [S(u-u_0) + S(-u-u_0)]\exp(j2\pi u x)du.
\]
(21)

After filtering the signal, using filters, we obtain its phase pattern (Fig. 5).

![Fig. 5. Phase pattern](image)

Fig. 6 shows the phase pattern, the filtered signal, and the input signal:

![Fig. 6. Filtered signal, input signal, and phase pattern on one graph](image)

As you can see from the graph, the 3rd order Butterworth filter has too “cut” signal amplitude, the filtered signal has a much smaller amplitude, so you need to reduce the order of the Butterworth function.

Since the 3rd order Butterworth function does not allow the experiment, so perform the above steps, but for the 1st order Butterworth function, select a useful signal. Fig. 7 shows the spectrum of the input signal with a selected root signal:
As can be seen, using the 1st order Butterworth function to filter the input signal, the amplitude is also “killed”, but within acceptable limits.

Also, it can be noted that the waveform repeats the input, so the spectrum of the useful signal is chosen correctly.

To determine the maxima, using the Gilbert transform, it is necessary to correlate the point at which the phase image is zero and the point of the filtered signal. The coordinates of these points correspond to the interference maxima from the matrix of the filtered signal.

Having received maxima of the filtered signal it is necessary to define RMS root mean square. Formula (22) for each column (interference band) according to the ISO standard.

\[ x_{RMS} = \sqrt{\frac{1}{n} (x_1^2 + x_2^2 + \ldots + x_n^2)}, \]  

where \( x_1 \ldots x_n \) is a set of numbers, 
\( n \) – quantity of numbers.

The obtained results show that the order of the Butterworth function and by changing \( w_n, w_n \) it was found that it is necessary to apply a 1st order filter and frequencies in the range from 0.08 to 0.35.

Based on the results of the experiment, a “route” was constructed that represents the maxima of the inter-vention signal corresponding to the relief of the functional surface (topology) (Fig. 9).
Conclusions

The article presents a method for controlling the functional surfaces of components of micro-opto-electro-mechanical systems, which is used to find the extremums of the bands of interference images of such structures.

The method can be used to assess the quality of the surface in the production of functional elements of micro-opto-electro-mechanical components.

The method allows to increase the level and reliability of technological operations of production of functional reflecting surfaces of micro-opto-electro-mechanical systems and the elements of electronic engineering.

Using the proposed technique for indexing the extrema of the image bands of the MOEMS elements, the maxima of the interference fringes were detected using the Hilbert transform and the finding of the phase roots.

Based on the results, the “route” of interference fringes was constructed and the root mean square values for the considered functional surface were calculated. The obtained results should be used in the formation of technology for the production of surfaces of components of micro-opto-electro-mechanical systems.

The method, in comparison with others, allows to increase the reliability of technological operations of production of functional surfaces of optical signal switches by more than 20% and labor costs up to 35%.

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МЕТОД КОНТРОЛЮ ФУНКЦИОНАЛЬНИХ ПОВЕРХНОСТЕЙ КОМПОНЕНТІВ МІКРООПТОЕЛЕКРОМЕХАНИЧНИХ СИСТЕМ

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Предметом статті є метод комп’ютерної обробки сигналів інтерференційних зображень функціональних поверхонь компонентів мікросхем електромеханічних систем. Метою є підвищення точності та зниження трудомісткості контролю при розробці технології виробництва компонентів мікросхем електромеханічних систем. Завдання: аналіз технологічних особливостей виробництва компонентів мікросхем електромеханічних систем та розробка методу контролю для підтвердження теоретичної достовірності виконаних на попередніх етапах роботи для визначення топології поверхонь на основі відфільтрованих, засобами комп’ютерного моделювання екстремумів, зображених інтерференційних функціональних поверхонь МОЕМС, проведення експерименту для отримання відповідности методу та отримання статистичних даних оцінки значень. Використовуваними методами є методи планування експерименту та комп’ютерної обробки експериментальних даних з використанням ряду Фур’є, перетворення Гілберта та складових фільтрів. Отримані такі результати. Для контролю функціональних поверхонь МОЕМС-компонентів запропоновано використовувати фазовий метод, який дозволяє швидко та точно проводити численну оцінку параметрів шероховатості зразків. Даний метод має достоїнства по точності, за рахунок виключення супутніх складових в сигналах, широкі функціональні можливості, не потребує використання спеціального обладнання, дозволяє аналізувати характери зразків поверхонь та отримувати їх тривимірне зображення. Висновки. Наукова новизна отриманих результатів полягає в наступному. Розроблений метод сприяє удосконаленню операції контролю функціональних поверхонь МОЕМС, за рахунок використання інтерференційного методу, на якому відмінні від існуючих, запропоновано використовувати складовий фільтр для зменшення супутніх складових в інтерференційному сигналі, що дозволяє підвищити точність та знищити трудомісткість контролю.

Ключові слова: інтерференційний метод, контроль, функціональний компонент, складовий фільтр, МОЕМС.