Результаты. Спроектирована мехатронная система, благодаря использованию трех шаговых двигателей, управляемых микроконтроллером, позволяет полностью автоматизировать процесс сканирования поверхностного потенциала, повысить точность и быстродействие измерения контактной разности потенциалов на основе метода Кельвина. Разработан ряд новых моделей для проведения модельного эксперимента на макроуровне в среде ECAD программ. Спроектирован опытный образец системы и проведены натурные эксперименты с разными материалами и покрытиями.

Научная новизна. Разработаны новые модели элементов систем автоматического управления, отвечающие критериям адекватности и экономичности, которые дополняют математическое обеспечение и расширяют возможности ECAD для анализа мехатронных систем.

Практическая значимость. По сравнению с прототипами разработанная система имеет такие отличительные признаки, как малая себестоимость при полной автоматизации сканирования, вариация размеров и количества шагов, автоматическая компенсация разности потенциалов. Предложенная система, учитывая полную автоматизацию, расширяет возможности анализа структурного и физико-химического состояния поверхности, а ее низкая себестоимость и адаптивность расширяет сферу ее возможного применения для учебного процесса. Разработанные модели элементов модели системы установлены в библиотеку ECAD и доступны для анализа мехатронных систем.

Ключевые слова: *электрофизические свойства материалов, поверхностный потенциал, метод Кельвина, динамический конденсатор, сканирование, мехатронная система, автоматизированные измерения, моделирование на макроуровне*

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DEFINITION OF VIBRO DISPLACEMENTS OF DRIVE SYSTEMS WITH LASER TRIANGULATION METERS AND SETTING THEIR INTEGRAL CHARACTERISTICS VIA HYPER-SPECTRAL ANALYSIS METHODS

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ВИЗНАЧЕННЯ ВІБРОПЕРЕМІЩЕНЬ СИСТЕМ ПРИВОДІВ ЗА ДОПОМОГОЮ ЛАЗЕРНИХ ТРІАНГУЛЯЦІЙНИХ ВИМІРЮВАЧІВ ТА ВСТАНОВЛЕННЯ ЇХ ІНТЕГРАЛЬНИХ ХАРАКТЕРИСТИК МЕТОДАМИ ГІПЕРСПЕКТРАЛЬНОГО АНАЛІЗУ

Purpose. Experimental measurements of vibro movement of the spatial drive system using laser triangulation sensors and definition of integrated dynamic characteristics of a drive using hyperspectral analysis methods.

Methodology. Experimental research methods using high-precision laser triangulation sensors of vibro movement and application of hyperspectral analysis methods based on multiple (two-dimensional) Fourier series for processing the measurement results of vibro movement of the table of spatial drive system .

Findings. The technique of precision dimensions (0.2 mm) of vibro movement of the table of the spatial drive system was developed. Projections of displacement of the table and the trajectory of its movement are determined. We established that the set of trajectories is described by the fuzzy sets and proposed analytical dependencies that describe the membership functions of the fuzzy sets. Application of hyperspectral analysis methods for determining the integrated dynamic characteristics of the spatial drive system was substantiated.

Originality. High-precision measurements of vibro movement of the spatial drive systems were obtained for the first time. In this study it was established that on exposure to the dynamic load we receive the displacement projection of a table with high-frequency oscillation parameters, which are fuzzy. This causes ripple movement of the table and uncertainties of the trajectories, which are located within the elliptical stripe. The location of the table within the band is a fuzzy set. Characteristic membership function looks like Gaussian curve, and its parameters depend on the polar angle. This fuzziness of a fuzzy set changes by 2...3 times within the polar angle of 2π. The efficiency of using the integrated dynamic characteristics of a drive that are represented as a spectrum of squared absolute value of two-dimensional Fourier series, that is one of the varieties of hyperspectral analysis, was proved for the first time.

Practical value. The regularities of vibro movement of the drive system that has the poorly defined (fuzzy) high-frequency components were determined. Methods for evaluating a fuzzy effect on the trajectory of the moving table were developed, and practical recommendations to establish patterns of the fuzzy oscillation using hyperspectral analysis methods were provided .

Keywords: *drive systems, table, vibro movement, laser triangulation sensor, trajectory, fuzzy sets, characteristic functions, hyperspectral analysis*

Introduction. Spatial drive systems with parallel kinematic connections are fundamental for the advanced technological equipment. Manipulator constructions, industrial robots and metal cutting machines have been realized efficiently so far.

The technology equipment based on spatial drive systems demonstrates wide range of functionality and high performance. Tough dynamic modes of work make the main feature of the equipment. The equipment speed drive-up requires its dynamic characteristics refinement. Therefore, the study of spatial drive systems vibration characteristics is currently important.

The key issue is to determine dynamic properties of highly-refined technological equipment on the basis of spatial drive systems with parallel kinematic connections.

The issue is connected with essential scientific and practical targets of robotic system implementation into industry.

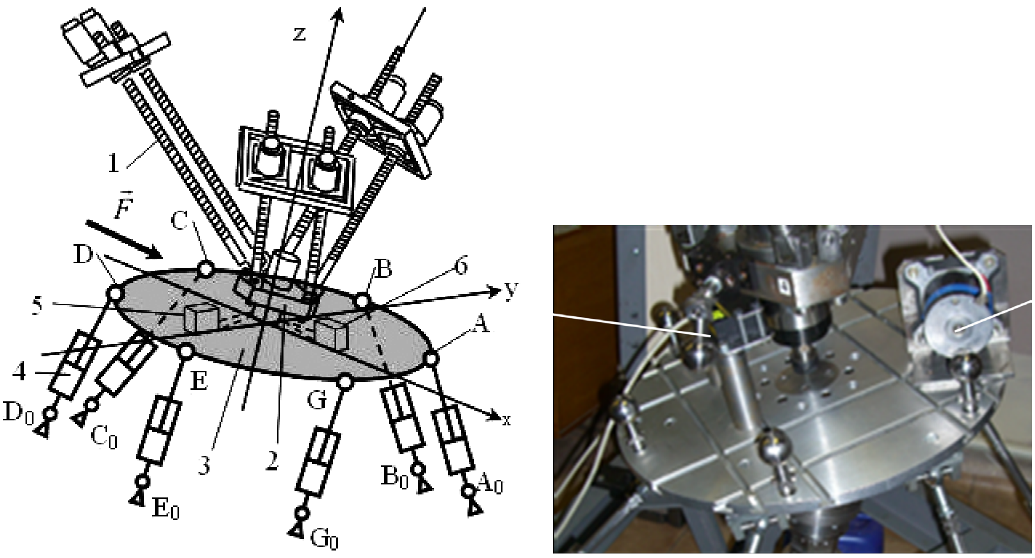
The recent research studies focus on the theoretical and experimental studies of spatial drive system dynamics [1]. Drive system dynamic characteristics have been observed to be more complex and are described by random regularities [2]. In series of research studies it is claimed that the study of dynamic characteristics requires special methods and equipment [3, 4]. Noncontact laser triangular sensors have been verified to be optimal measurement constructions [5]. Some researchers [6] outline the vagueness of drive system dynamic parameters and indicate the necessity of introducing integral parameters in order to determine the spatial drive system dynamic properties [7].

The literature review analysis allows us to state that currently the methods for determining integral dynamic parameters of spatial drive systems are absent. Thus, the experimental determination of vibro movements in spatial drive systems and analysis methods for experimental measurements, which measure their integral dynamic properties, are considered to be unsolved within earlier issues.

The objective of the study is to make experimental measurements of vibro movements of spatial drive systems by means of laser triangular sensors and to determine integral dynamic characteristics of drive systems by hyper spectral analysis.

To reach the objective it is necessary to make the experimental measurement of drive system vibro movements by laser triangular sensors and to determine integral dynamic parameters of drive systems by hyper spectral analysis with two-dimensional Fourier series.

Presentation of the main research. Multi-coordinate technological equipment [7] which has been developed combines two independent drive systems: one is for the independent spatial displacement of the tool, and the other is for the spatial displacement of parts (Fig. 1, *a*).



a *b*

Fig. 1. Scheme of technological equipment which combines two autonomous spatial drive systems (a) and location of laser triangulation meters V and device of harmonic dynamic load S on the table (b)

Tool displacement is provided by the drive system featuring six rods of variable length *1* moving from platform *2* with a spindle mounted on it. Spatial tool displacement takes place continuously within the working area of the system.

To expand the workspace of the equipment it has a movable table 3 with drives fixing the table in the correct position in space. Each of the drives AA_0, BB_0, ..., GG_0 is designed as a discrete multi-positional pneumatic actuator [8]. The drives are operated by a special system that provides installation of pneumatic actuators of the drives in a fixed position on the support. The drives are connected to the table with high precision spherical joints located at points A, B,..., G. The drives are pivotally mounted on a fixed basis at points A_0, B_0,..., G_0. The Table is fixed in the necessary position in the process of work. Dynamic displacements of the table result from dynamic loads. The accuracy of the multi-coordinate equipment is most significantly affected by the dynamic displacements of the table in the plane perpendicular to axis z (the plane of joints A, B,..., G location). The dynamic table load with the harmonic force $\vec{F}$ was carried out during the research.

The table displacement was measured in two mutually perpendicular directions along the axes *x* and *y* with two laser meters 5 and 6.

The dynamic processes in spatial drive systems feature considerable complexity. They are determined by numerous factors of random nature. Therefore, experimental and theoretical methods were used for the study.

High-frequency triangulation laser distance meters RF603-10/2 with a working range of 2 mm and measuring precision of 0.2 μm [5] were used for measuring the table displacement in two mutually perpendicular directions under the influence of harmonic load acting on the table. The meters were installed on the table. They measured the distance from the moving table to the fixed cylindrical surface of the platform (Fig. 1, *b*). The frequency of harmonic load was changed by the control system in the range of 10...150 Hz. The results of the displacement measurements were presented digitally with discretion in time of 0.5; 1.0 ms and were formed as arrays. The vibro displacements of the table in two directions which we obtained are poly-harmonic processes (Fig. 2, *a*).

As a result of the research, it is found that the harmonic load of the table leads to the oscillation of the Table with projections that are close to sinusoidal (dashed lines in Fig. 2, *a*). Thus, there is an unclear (blurred) high-frequency oscillation of the table whose amplitude is less than 5...10 % of fixed amplitude of sinusoidal oscillations of the table.

High-frequency oscillation periods do not exceed 10...15 % of the fixed period of sinusoidal oscillations and undergo random changes in the experimental measurements. Changes in amplitude and high-frequency oscillation periods are explained by the influence of the numerous factors including characteristics of the compounds in the drive, a design feature of joints, spatial fluctuations of the table and others. It is found that the changes of oscillation parameters are insignificant. Therefore, it is efficient to use unclear (blurred) arrays for their study.

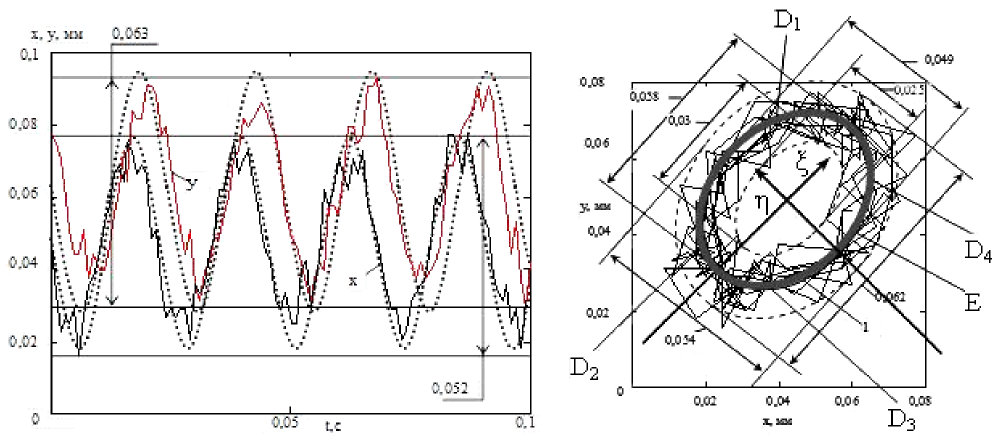
According to measured table displacements in x and y directions, the experimental trajectories of table displacement affected by a harmonic load are found (Fig. 2, *b*).

Due to the occurrence of high-frequency oscillations of the table trajectory, its movements are within the band of the elliptical shape. The band width of the location of the table trajectories is 13...16 microns at a maximum rate of diametrically elliptical area of 62 microns.

Current position of the table is characterized by the radius vector ρ, and the polar angle φ located on the projection of the table displacement according to functional connections

$$\rho = \pm\sqrt{x^2 + y^2}; \quad \varphi = \text{arctg}\, y/x. \tag{1}$$

The table location varies in a chaotic manner. Thus, there are unclear (blurred) changes of the radius vector ρ(φ). Statistical average value of the radius vector changes is conducted and it is established that the average value of the radius vector within the elliptical band changes according to the law



a *b*

Fig. 2. The results of experimental measurements of projections of the table displacement (a) and experimentally determined trajectory of table displacement affected by harmonic load (b)

$$\rho_e(\varphi) = \rho_{eo}\cos(2\varphi + \psi_{eo}), \qquad (2)$$

where ρ_{eo} is the average radius; ψ_{eo} is the initial phase determining the angular location of the elliptical area on the coordinate plane.

Calculation according to the dependency (2) results in the curve E close to an ellipse which is in the middle of the elliptical region (Fig. 2, *b*). Ellipse axes ξ, η are oriented at an angle to the coordinate axes of x and y. Further analysis of the trajectories is made in a coordinate system $\xi\eta$ which corresponds to the direction of the ellipse axes E.

The trajectories in Fig. 2 are built for fixed table positions that define intervals of 4 ms. That is why they look like broken lines. Statistical data processing of fixed positions of the table is carried out; they are two-dimensional coordinates of sample pairs where the table is at any given time. M frequency histogram of the table in the appropriate section of elliptical trajectories of band arrangement has been built by statistical processing of the array of the number of the table positions in a separate square area obtained from experimental measurements.

Ordinates of the histogram are defined by the formula

$$M_k(x_k, y_k) = \frac{n_i}{n_\Sigma},$$

where n_i is the number of points that fall on k-square area, the center of which has coordinates x_k, y_k; n_Σ is the total number of points.

Ordinates of histogram M normalized to maximum value define the probability of the table location in this part of the elliptical area (Fig. 3, *a*).

Areas of minimum (D_1, D_3) and maximum (D_2, D_4) values are traced on the histogram. They alternate in the tangential direction and reflect the changing probability of the table location with its random movement along the arc of the elliptical area. Changes of the histogram ordinates are an integral feature of dynamic properties of spatial drive system. Areas $D_1 \ldots D_4$ are not allocated on the bands of trajectories location (Fig. 2, *b*). Special methods were used to investigate these areas.

Projections of vibro displacements determined experimentally (Fig. 2, *a*) using differentiation made it possible to define vibro velocities projections $V_x(t)$ і $V_y(t)$. Velocity components projected on a tangent $\vec{V_\tau}$ and normal $\vec{V_n}$ of the elliptical curve that defines the midline trajectory were calculated. Statistical analysis of stochastic processes that define normal and tangential vibro velocity of the table was conducted. In particular, rpm velocity values were defined by dependencies

$$\overline{V_n^2} = \frac{1}{Nt_0}\int_0^{Nt_0} V_n^2 \cdot dt; \quad \overline{V_\tau^2} = \frac{1}{Nt_0}\int_0^{Nt_0} V_\tau^2 \cdot dt,$$

where t_0 is the average time of traversing the elliptical part of the trajectory by the table; N is the total number of table displacement cycles in the elliptical trajectory.

During the statistical analysis of pulsating velocity values, a mixed point was defined

$$\overline{V_n V_\tau} = \int_0^{Nt_0} V_n V_\tau dt.$$

As a result of calculation, it was established that the following can be taken with sufficient practical reliability

$$\overline{V_n V_\tau} \approx 0.$$

The resulting ordinates of the histogram in an integral form (Fig. 3, *a*) reflect correlation of chaotic displacement of the table in the direction perpendicular to tangent to the arc of the ellipse to movement in the direction of the tangent. The correlation between the ordinates of the histogram and the ratio of rms values of pulsating vibro velocity of the table $\vec{Vn}$. and tangent velocity of the table $\vec{V_\tau}$ was determined. It was found that in the first approximation it can be taken that

$$\sqrt{\overline{V_n^2}/\overline{V_\tau^2}} \cong C_\mu \cdot M,$$

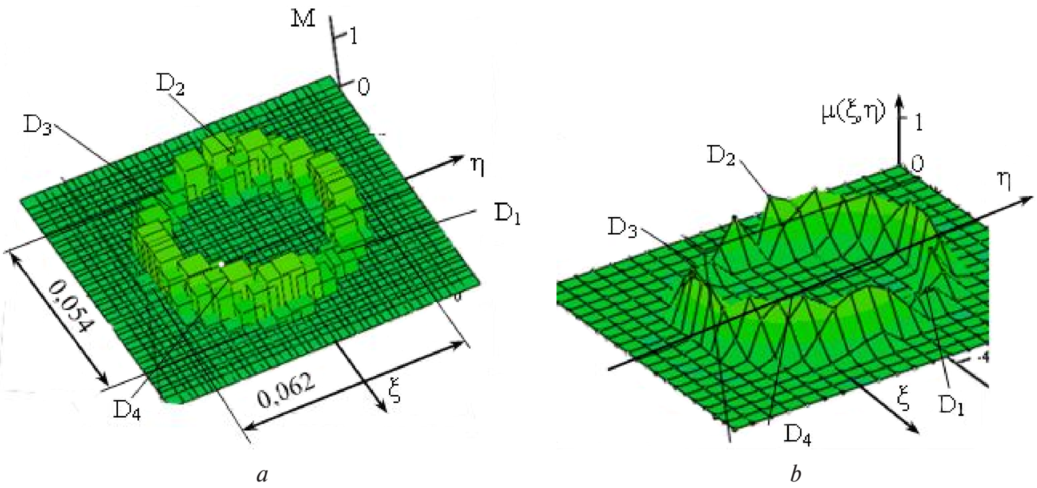


Fig. 3. Experimentally determined histogram of frequency of the table centre location in certain areas of elliptical band of trajectories location (a) and characteristic functional surface describing unclear position of the table at some points of elliptical band location of trajectories of the table centre displacement (b)

where C_μ is a constant factor that depends on the ACS average transition time of an elliptical trajectory.

The histogram is smoothed by two-dimensional cubic splines and normalized to the maximum value with receiving surface which describes the reliability of hitting of the table centre in a certain spatial area. The resulting spatial surface looks like a protuberance of the elliptical ring with variable height and width in the tangential direction (Fig. 3, *b*).

The resulting characteristic surface $\mu(x, y)$ is generalization for the two-dimensional area of the fuzzy sets characteristic function [9] which determines the reliability of the table position in a certain area of elliptic band of trajectories locations. The characteristic function is given in the form of two-dimensional graphics which includes a series of isolines (Fig. 4, *a*).

The graph clearly traces D_2 and D_4 areas with a maximum reliability of finding a table. D_1 and D_3 areas have less reliability for finding a table in them. The areas $D_1, \ldots, D_4$ determine extreme values of the function. They are arranged in pairs around the greater axis of the ellipse E which corresponds to the central part of elliptical bands of trajectories locations (limited by dashed lines).

To establish appropriate patterns of fuzzy dynamic characteristics of the table, the hyper spectral analysis methods are applied [10]. They are based on the use of multiple (two-dimensional) Fourier series. According to the proposed method, two-dimensional characteristic function of fuzzy set μ is given in the form of multiple (two-dimensional) Fourier series. The function on the periphery of the elliptical area is equal to zero. Thus, periods T_x, T_y are presented in coordinates which cover elliptical band with a certain excess.

At the same time, the function μ can be considered periodic along two coordinates x and y, and considering only one (central) period is relevant. This assumption makes it possible to apply a two-dimensional characteristic membership function as a series in a complex form

$$\mu(x, y) = \sum_{k=-\infty}^{+\infty} \sum_{m=-\infty}^{+\infty} C_{k,m} e^{j(k\omega_x x + m\omega_y y)}, \quad j = \sqrt{-1}, \qquad (3)$$

where $\omega_x = 2\pi/T_x$, $\omega_y = 2\pi/T_y$ are basic values of frequencies; $C_{k,m}$ are complex two-dimensional Fourier series coefficients which are associated with the value of characteristic function by integral functional connection

$$C_{k,m} = \frac{1}{T_x T_y} \int_{-\frac{T_x}{2} - \frac{T_x}{2}}^{\frac{T_x}{2} + \frac{T_x}{2}} \mu(x, y) \cdot e^{-j(k\omega_x x + m\omega_y y)}.$$

The range of coefficients $C_{k,m}$ is calculated by integrating the smoothed cubic spline histogram. Complex coefficients have real and virtual part. For hyper-spectral analysis squared absolute values of complex series coefficients are used (power process spectrum). The two-dimensional power spectrum is presented in the form of a bar graph (Fig. 4, *b*).

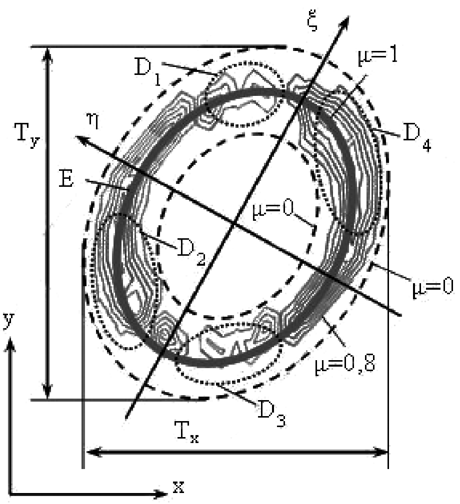
The analysis of the spectrum shows that significant components in the Fourier series (3) are components with coefficients $C_{8.7}$ and $C_{11.9}$. The main component is a component which corresponds to coefficient $C_{8.7}$. Therefore, to define the approximate value of characteristic function type we can use a simplified range which includes 1...2 components. In its simplest form, it is

$$\mu_f(x, y) = \mathrm{Re}\left[C_{8.7} \cdot e^{j(8\omega_x x) + 7\omega_y y}\right]. \qquad (4)$$

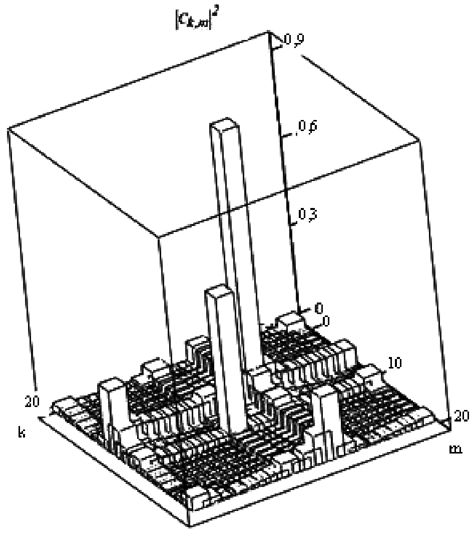
For more exact characteristic function description, the following functional connection should be used

$$\mu_f(x, y) = \mathrm{Re}\left[C_{8.7} \cdot e^{j(8\omega_x x + 7\omega_y y)} + C_{11.9} \cdot e^{j(11\omega_x x + 9\omega_y y)}\right]. \qquad (5)$$

Thus, hyper-spectral analysis makes it possible to simplify the mathematical model describing the two-



a



b

Fig. 4. Presentation of a two-dimensional characteristic function of fuzzy location of the table through isolines of exact reliability (a) and hyper-spectrum of squared absolute value of complex two-dimensional Fourier series coefficients which describes the fuzzy trajectory characteristic function of table displacement trajectory (b)

dimensional characteristic function that determines the trajectory of the table.

Spectral analysis gives integrated dynamic characteristics of the trajectory of the table with regard to fuzzy (blur) trajectory of the table within vibration loads.

The functional connections (4) and (5) make it possible to predict the probability of finding a table in the relevant area of an elliptical band of the trajectory location. They describe parameters of blur of the trajectories of the table stipulated by various structural and exploitation factors determined experimentally in an integral form.

Conclusions.

1. Vibro displacements of an actuating element (the table) of the spatial drive system affected by harmonic load through laser triangulation sensors feature projections which are close to sinusoidal dependencies including high-frequency fuzzy (blur) components. Therefore, the trajectories of the table displacement are located within elliptical band with the width of 8...12 % of the greater axis of the ellipse according to the average values of trajectories.

2. Probability of the table location in a certain area of elliptical band is defined with two-dimensional characteristic function. But the maximum values of characteristic function are located on the elliptic curve and change by 10...20 % along the length of the elliptic curve and the blur of the characteristic function varies by 2...3 times along the length of an elliptic curve reaching extremes in the vicinity of larger axis of the ellipse.

3. It is appropriate to use hyper-spectral analysis methods based on decomposition of characteristic function in multiple (2-dimensional) Fourier series as well as spectra of squared absolute values of complex two-dimensional Fourier series coefficients found by integrating the area of two-dimensional characteristic membership function. 1...3 components are significant in the spectra of coefficients simplifying the definition of chaotic (blurred) high-frequency table oscillations.

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Мета. Експериментальні виміри вібропереміщень просторових систем приводів з використанням лазерних тріангуляційних вимірювачів та визначення інтегральних динамічних характеристик систем приводів методами гіперспектрального аналізу.

Методика. Експериментальні методи досліджень з використанням високоточних лазерних тріангуляційних вимірювачів вібропереміщень і застосуванням методів гіперспектрального аналізу на основі кратних (двомірних) рядів Фур'є для обробки результатів вимірів вібропереміщень стола просторової системи приводів.

Результати. Розроблена методика високоточних (0,2 мкм) вимірів вібропереміщень стола просторової системи приводів. Визначені проекції переміщення стола та траєкторії його руху. Доведено, що набір траєкторій описується нечіткими множинами та запропоновані аналітичні залежності для опису характеристичних функцій приналежності нечітких множин. Обгрунтоване застосування методів гіперспектрального аналізу для визначення інтегральних динамічних характеристик просторових систем приводів.

Наукова новизна. Уперше проведені високоточні виміри вібропереміщень просторових систем приводів. Встановлено, що за дії динамічного навантаження проекції переміщень стола набувають високочастотних коливань, параметри яких є нечітко визначеними. Це обумовлює пульсаційний рух стола та невизначеність траєкторій, що розташовуються в межах еліптичної полоси. Розташування стола в межах полоси є нечіткою множиною. Характеристична функція приналежності має вигляд кривої Гауса, параметри якої залежать від полярного кута. При цьому розмитість нечіткої множини змінюється у 2...3 рази в межах полярного кута 2π. Уперше доведена ефективність застосування інтегральних динамічних характеристик систем приводів, поданих у вигляді спектра квадратів модулів двовимірного ряду Фур'є, що є одним з різновидів гіперспектрального аналізу.

Практична значимість. Встановлені закономірності віброперміщень системи приводів, що мають нечітко визначені (розмиті) високочастотні складові. Розроблена методика оцінки впливу розмитості на траєкторії переміщення стола та надані практичні рекомендації зі встановлення закономірності розмитості коливань методами гіперспектрального аналізу.

Ключові слова: *система приводів, стіл, віброперміщення, лазерні тріангуляційні вимірювачі, траєкторії, нечіткі множини, характеристичні функції, гіперспектральний аналіз*

Цель. Экспериментальные измерения виброперемещений пространственных систем приводов с использованием лазерных триангуляционных измерителей и определение интегральных динамических характеристик систем приводов методами гиперспектрального анализа.

Методика. Экспериментальные методы исследований с использованием высокоточных лазерных триангуляционных измерителей виброперемещений и применением методов гиперспектрального анализа на основе кратных (двухмерных) рядов Фурье для обработки результатов измерений виброперемещений стола пространственной системы приводов.

Результаты. Разработана методика высокоточных (0,2 мкм) измерений виброперемещений стола пространственной системы приводов. Определены проекции перемещения стола и траектории его движения. Доказано, что набор траекторий описывается нечеткими множествами и предложены аналитические зависимости для описания характеристических функций принадлежности нечетких множеств. Обосновано применение методов гиперспектрального анализа для определения интегральных динамических характеристик пространственных систем приводов.

Научная новизна. Впервые проведены высокоточные измерения виброперемещений пространственных систем приводов. Установлено, что при воздействии динамической нагрузки проекции перемещений стола приобретают высокочастотные колебания, параметры которых нечетко определены. Это обусловливает пульсационное движение стола и неопределенность траекторий, которые располагаются в пределах эллиптической полосы. Расположение стола в пределах полосы является нечетким множеством. Характеристическая функция принадлежности имеет вид кривой Гаусса, параметры которой зависят от полярного угла. При этом размытость нечеткого множества меняется в 2...3 раза в пределах полярного угла 2π. Впервые доказана эффективность применения интегральных динамических характеристик систем приводов, представленных в виде спектра квадратов модулей двумерного ряда Фурье, которые являются одной из разновидностей гиперспектральных анализа.

Практическая значимость. Установлены закономерности виброперемещений системы приводов, которые имеют нечетко определенные (размытые) высокочастотные составляющие. Разработана методика оценки влияния размытости на траектории перемещения стола и даны практические рекомендации по установлению закономерности размытости колебаний методами гиперспектрального анализа.

Ключевые слова: *система приводов, стол, виброперемещения, лазерные триангуляционные измерители, траектории, нечеткие множества, характеристические функции, гиперспектральный анализ*

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