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DETERMINATION OF DEVELOPMENT GROUNDS AND CHARACTERISTICS OF MOBILE MULTI-COORDINATE ROBOTIC MACHINES FOR MATERIALS MACHINING IN FIELD CONDITIONS

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ОБҐРУНТУВАННЯ РОЗРОБКИ ТА ВИЗНАЧЕННЯ ХАРАКТЕРИСТИК МОБІЛЬНОГО БАГАТОКООРДИНАТНОГО ВЕРСТАТА-РОБОТА ДЛЯ ОБРОБКИ МАТЕРІАЛІВ У ПОЛЬОВИХ УМОВАХ

Purpose. Theoretical foundation and development of equipment for precision machining of objects in the field condition.

Methodology. Mainly, the theoretical research methods which include the determination of the elastic system stiffness matrix of the machine and the manipulator were applied. Circuit and structural solutions of mobile multicoordinate robotic machine were theoretically grounded. Mathematic simulation of the object processing with the mobile robotic machine was conducted. On the basis of the mathematic simulation analysis, the peculiarities of deformation characteristics of machine were defined through the determined stiffness matrices.

Findings. The concept of precision machining of objects in the field conditions with a mobile robotic machine was substantiated. It is based on the application of equipment with low stiffness in conjunction with a special manipulator, which is tightly linked to the object and provides the necessary movement of a tool. The circuit of the precision machining of objects with mobile robotic machine was grounded. This circuit fulfills the use of two dual mechanisms-hexapods, one of which is the pivotal system of the machine and the other is the system of manipulator. The means of machine working space increase by means of telescopic rods of the variable length with the pneumatic drives were suggested. Conditions for the improvement of the accuracy of the robotic machine during the process of machining with a rotary cutting tool were determined. They include accordance of the main axes of the manipulator stiffness matrix and the movement direction of the rotary cutting tool. The type and nature of the machining faults and their interrelation with the parameters of the machine stiffness and the manipulator stiffness were determined.

Originality. For the first time the concept of precision machining with robotic machines that have low stiffness of the carrying system is developed. The concept consists in the application of the manipulator that is rigidly fixed to the processed object and associated with the final controlling element of the machine. The component of stiffness matrix of the machine and the manipulator are brought into proper correlation, which provides the possibility of precision machining with mobile robotic machines. The fault calculation methods of the details processing with a rotary cutting tool on machines with parallel kinematic structures have attained the further development.

Practical value. The results of the research are the basis for the development of high-performance robotic machines for machining the hazardous objects in the field conditions. On the basis of the obtained results the working space of the mobile robotic machine increases by 3–5 times and precision of machining in the field condition increases to 8–9 accuracy degree.

Keywords: *mobile robot machine, charts, models, stiffness, axial tools, precision error*

Introduction. It is determined that there is a vast scientific and technical problem of high-precision, mechanical, engineering and physical machining of hazardous facilities in field conditions. The range of such facilities includes mines, missiles, reservoirs with toxic materials, over-pressed pipelines or reservoirs, especially damaged reservoirs which are accompanied with leakage of liquid or escape of gaseous substances, etc. As a rule, such facilities spread pollution, are arbitrary orientated and cannot be moved. High-precision

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machining is necessary for the conduction of preparatory operations of facility transportation, determination of its condition and hazardous level or for the neutralization of facility on the spot. Development of the complexes for hazardous facilities machining in field conditions is of significant importance for the promotion of defensive capacity and national security of the country. Development of such equipment is directed toward applied results of double utilization.

Mastering of mobile complexes for high-precision machining of hazardous facilities production changes the processes of organization and realization of operations of eliminating extraordinary situations, maintaining military equipment, and utilizing explosive objects and toxic or radioactive matters. It is of great importance for organization of operations in extraordinary situations. Machining of hazardous facilities in field conditions saves lives of field engineers, liquidators of emergency situation effects and other specialists who work with hazardous facilities. Therefore, development of means for high-precision machining in field conditions is extremely urgent.

The problem in its general aspect includes development of mobile complexes that ensure high-precision machining of facilities in field conditions.

In the latest research studies and publications the range of designs of robotic machines for detail processing is given [1]. They are implemented on the basis of mechanisms with parallel kinematic structures [2]. These mechanisms have low energy and material capacity. Therefore, it is possible to use them for high-precision machining of hazardous facilities in field conditions. However, the stiffness of carrying systems of these machines is insufficient.

The range of publications [3, 4] present devices of aggregate-module type designed for details processing in restrained areas. The research studies of a number of authors are aimed at increasing the accuracy of machines with low stiffness. Here the special measurement systems of tool location are used. Other range of research studies [5, 7] presents the results of development and study of separate machine systems which considerably enhance their precision.

The analysis of informational sources shows that nowadays there is a lack of mobile complexes for high-speed machinery of hazardous facilities in field conditions as well as the theoretical grounds for their development and research on their creation.

Grounds for development of high-speed machinery complexes for hazardous facilities in field conditions are an unsolved part of the general problem. Therefore, the aim of this study is to present a theoretical grounds and development of robotic machine equipment for high-precision machining of facilities in field conditions.

In order to achieve the aim of this study the following objectives were set: to develop a concept of equipment building and to synthesize rational circuit design, to present mathematical modeling of high-precision machining processes with a mobile robotic machine.

Presentation of the main research. Circuit design of mobile robotic machine complex. It is suggested to solve a problem of machining hazardous facilities in field conditions by means of a mobile robotic machine on the basis of mechanisms of parallel structures (Fig. 1).

The complex is made for machining a hazardous facility *1* which is located in an indefinite place and is arbitrary orientated. A solid model of the facility is built and the strategy of machining is developed by means of laser radar *2*. Machining is realized by robotic machine *3* with parallel kinematic structures. Machine has a final controlling element that looks like a platform with a tool *4*. Manipulator *5* is used for placing the final controlling element on the facility. The manipulator is attached to the hazardous facility and moves the final controlling element.

The complex is mobile. The machine may be switched in transportation position by means of hydrocylinder and fixed on the vehicle if necessary (Fig. 2).

Weight and size parameters of the mobile complex meet the requirements for vehicles of general use. It is possible to install the complex on two-wheeled trailer of a car and to transport it even in the cross-country conditions due to its small weight (approximately 1.5 kilos).

The robotic machine with parallel kinematic structures has six rods of changeable length that include electromechanical gears and ball screw rolling drives (Fig. 3).

Every rod has a roll drive that includes electric motor *1*, which is connected with a belt gear drive *2* to the rotating nut *3* that moves a screw *4*. The roll drive is installed on a framework *5*, which is situated in universal joint with bearings *6* and *7* and can rotate relative to stationary base of the machine. Change of the screw length *4* leads to the movement of the machine platform *8*, where a movable sleeve with a motor-driven spindle is placed.

Necessary tools can be automatically installed on the machine platform from the automatic tool changer magazine placed on the machine. Different tools for identification and machining of the facility (in particular, tools for facility examination, such as video cameras, laser scanners, feeler gages, tactile devices, analyzers of chemical composition, hardness and other properties of the facility) are used. Moreover, devices for facility cleaning (especially sand-blowing and high pressure water cleaning devices) are proposed.

Precision mechanical machining is projected to be the main method of the machining (6...9 accuracy degree). Spindle heads with one or several spindles are projected for the mechanical machining of the facility. They are assigned to installation of various tools, e.g. circular saws, milling tools, drilling tools, screwing taps, etc. Besides, it is possible to use brushes for facility cleaning (such as a wipe brush).

Robotic devices such as automatic wrenches, screwdrivers, rotary vises can be used as possible tools for mechanical processing. It is also possible to use hydraulically operated compressing devices for extruding, bending, cutting, hole sewing, etc.

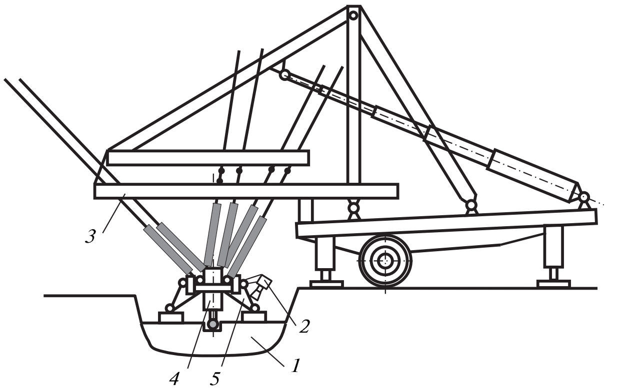

Fig. 1. Mobile remote-controlled complex on the basis of a robotic machine with parallel kinematic structures:

1 – hazardous facility; 2 – CCTV system and laser radar; 3 – robotic machine with parallel kinematic structures; 4 – final controlling element of the machine with machining attachment and a tool; 5 – machine manipulator made for interaction between the final controlling element and hazardous facility

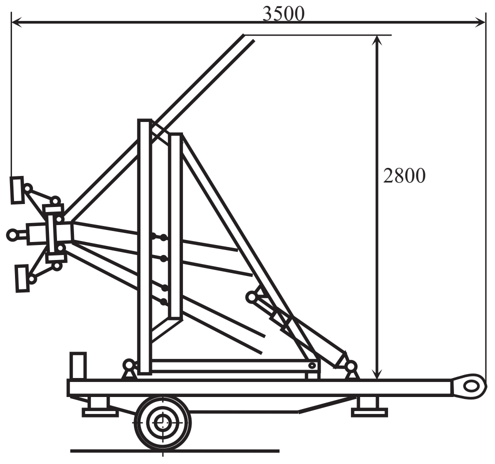

Fig. 2. Mobile robotic machine in transportation position

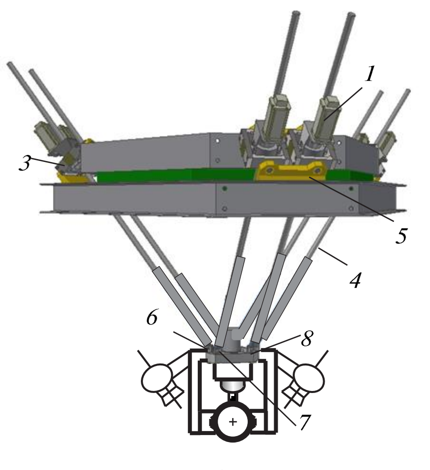

Fig. 3. The solid model of a mobile robotic machine

Various devices for implementation of engineering and physical methods of machining are projected, e.g. gas cutters, plasma cutters, laser cutters and/or welding machines for spot welding, gas welding, electric welding.

All devices are parts of a set and can be automatically interchanged. Device selection is correspondent to the technological process of the machining.

The carrying system of the robotic machine consists of rod-shaped spatial mechanisms. It changes its configuration automatically (has a self-forming structure) and adapts to the facility under machining.

It is proposed to ensure substantial change of machine working space by introducing self-forming rod-shaped spatial mechanisms. The base of such mechanisms is made of telescopic rods with hydraulic or air-powered drives (Fig. 4).

Telescopic rods enable discrete change of their length on the cylinder travel dimension $L_{04}, ..., L_{06}$. Additional rods can be installed between the platform and pneumatic cylinder if necessary. Discrete changes of the length of any rod are stored with working travel of rods $L_{04}, ..., L_{06}$. This creates a possibility to change working space of machine many times and implement different locations of the final controlling element relative to immovable basis (Fig. 5).

Under conditions of retracted rod cylinders, the working space of the machine, area R_1, is determined by travel of ball screw drive transmission of platform movement. Under conditions of extended rod cylinders and rated position of the machine, the working space increases and covers area R_2. Change of diametrical-angular position of the machine by means of hydro-cylinder G broadens the working space to area R_3. Change of working space reaches $H/H_0 = 4...5$; $B/B_0 = 2...3$. The system of machine drives provides overall dimension of minimal working space $H_0 \approx$ ≈ 1.5 m, $B_0 = 1.2$ m. Respectively, maximal overall dimension of mobile complex working space makes up $H = 6$ m., $B = 3.6$ m.

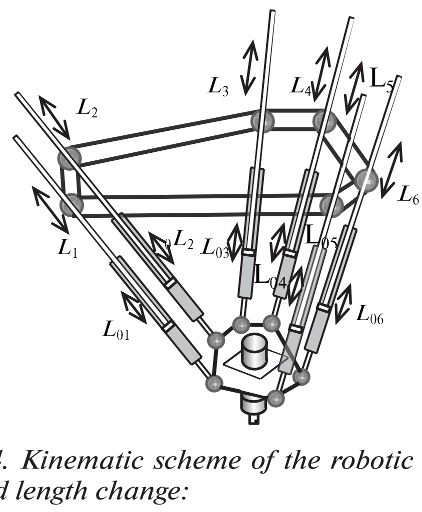

Fig. 4. Kinematic scheme of the robotic machine rod length change:

$L_1, ..., L_6$ – rod length changes by electric motor; $L_{01}, ..., L_{06}$ – rod length changes by hydraulic cylinders

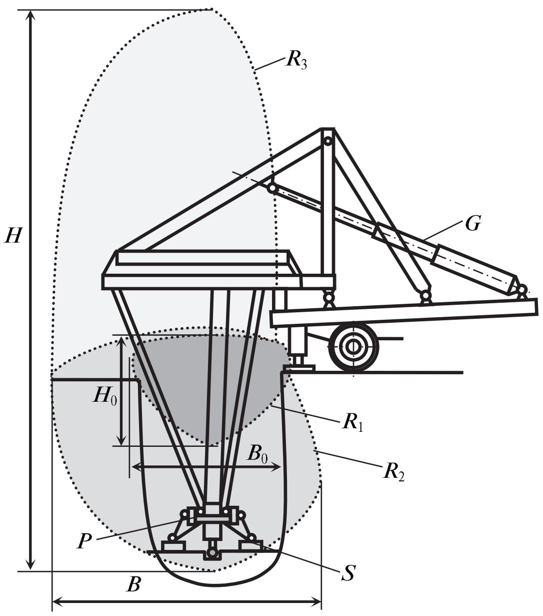

Fig. 5. General working space of the mobile robotic machine and possible locations of the final controlling element:

H_0, B_0 – height and width of the robotic machine operating space with the minimum length of hydraulic cylinders; H, B – maximum height and width of operating space; R_1 – operating space of the machine with a minimum length of hydraulic cylinders; R_2 – operating space with a maximum length of hydraulic cylinders; R_3 – the maximum possible operating space of the machine

Herewith, it is possible to machine facilities from above, from below and from the sides. Machining of the facilities located in holes or niches is admissible. Proposed machining of facilities with mobile robotic machine differs essentially from traditional machining on work-benches in workshop conditions.

Precision machining of dangerous facilities requires development of a special concept. It includes gathering of information, description of facility shape and location. Methods for laser radar location with facility scanning and its solid model development in determined absolute coordinate system linked to the facility are provided. Firstly, dimension and location of the facility in the initial coordinate system are determined. Reference points are established on the facility and machine platform is fixed directly on the facility by means of the manipulator. Thereafter, the transition to the basic coordinate system linked to the facility is made. Ulteriorly, the machining is done by programmed trajectories of manipulator numerical program control (NPC) systems determined in the absolute coordinate system.

The proposed concept of precision machining under conditions of insufficient information on facility is based on available experience of solid model construction and its usage for development of detail processing strategies on work-benches with NPC. Considerable distinctions of the proposed concept consist in usage of the coordinate system that is linked to the facility, rather than to the coordinate system of the machine, as it usually is in traditional detail processing.

The proposed plan of precision machining of facilities by means of mobile robotic machines is new in its essence and consists in usage of equipment that has low stiffness with additional devices. Such devices include manipulators with high stiffness *M*, which are installed directly on the facility.

Ends of manipulator rods *M* are connected with machine platform *P*. A coordinative manipulator with six rods constituting mechanism-hexapod is shown on the scheme. The given manipulator provides spatial movement of machine platform 8. Manipulator rods have length change drives that are controlled with the NPC system. Inferior ends of rods are fixed on the facility by means of special grippers *G*.

Grippers provide stiff connection of the machine frame and machined facility. The robotic machine operates the hazardous facility, its rotation or removing of facility parts or foreign objects that hamper technological machining process if necessary or possibly. When the length of manipulator rods *M* is changing the tool implements limited movements in relation to machined facility while machining it. The control of the machining process is provided by video support of the process.

Design of the manipulator is chosen on the condition of its most possible stiffness. In general, it is similar to machine scheme (Fig. 3), but the length of its rods is minimal and travel of rods is limited. Additionally, rotary joints are strengthened. Accordingly, stiffness of the manipulator carrying system is much higher than stiffness of the mobile robotic machine. Therefore, during the process of facility machining non-stiff elastic pivotal system of robotic machine deforms and has little influence on machining precision, which is determined only by precision of the manipulator.

Mathematical modeling of the precision machining with a mobile robotic machine. The processes of precision machining with mobile complex on the basis of a robotic machine have peculiarities that are connected with special features of its circuit design and characteristics of actual loadings. The complex is a circuit design that interconnects two mechanisms-hexapods with essentially different weight and stiffness parameters. Loadings on the tool that occur during the process of machining are presented as equivalent force vector F_p and rotational moment M_p. Loading data are added to the gravitational force and other loadings and, therefore, form general loadings on the machine platform presented as resultant vector $\vec{F}$ and principal moment $\vec{M}$ (Fig. 6).

Loadings on the machine controlling element cause deformations of the carrying system, which is characterized by the vector of x-coordinates of the platform

$$[x_i] = [x\ \ y\ \ z\ \ \varphi_x\ \ \varphi_y\ \ \varphi_z]^T, \qquad (1)$$

here x, y, z stand for movement of the platform center P in the directions of x, y, z axes of the absolute coor-

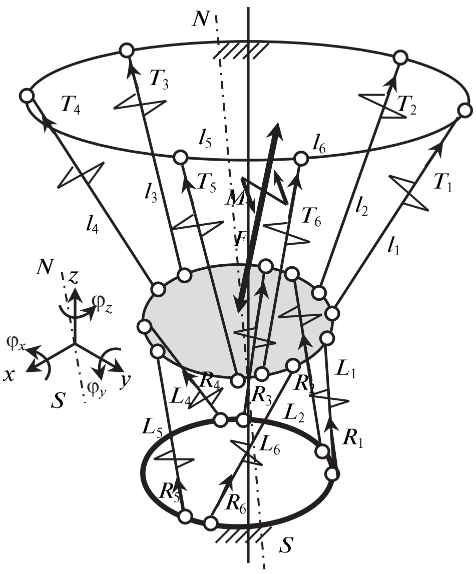

Fig. 6. Effect of power factors in mobile complex on the basis of a robotic machine:

SN — axis of maximum stiffness; $l_1...l_6$ — robotic machine rods of variable length; $T_1...T_6$ — loading in machine rods; $L_1...L_6$ — manipulator rods; $R_1...R_6$ — loading in manipulator rods; $\vec{F}$, $\vec{M}$ — effective force and moment that are acting upon the platform

dinate system linked to the machined facility; φ_x, φ_y, φ_z stand for angles of platform travel relative to axes of the absolute coordinate system.

Force vector (f_i) on the controlling element is connected with its movement by way of stiffness matrix $[c_{ij}]$ relative to the functional connection

$$[f] = [F_x\ F_y\ F_z\ M_x\ M_y\ M_z]^T = [c_{ij}] \cdot [x_i], \quad (2)$$

here F_x, F_y, F_z stand for projections of the main force vector that affect the platform on the axis of absolute coordinate system; M_x, M_y, M_z stand for projections of principal moment.

General stiffness matrix of mobile complex, which is included in (2) is a sum of stiffness matrices of the manipulator $\left[c_{ij}^M\right]$ and the machine $\left[c_{ij}^B\right]$. Accordingly,

$$\left[c_{ij}\right] = \left[c_{ij}^M\right] + \left[c_{ij}^B\right]. \quad (3)$$

In the study [7] stiffness matrix of machine-hexapod is determined, H/mkm

$$\left[c_{ij}^B\right] = \begin{pmatrix} 83.9 & 0 & 0 & 0 & -75.25 & -2.78 \\ 0 & 72.29 & 3.08 & 68.28 & 0 & 0 \\ 0 & 3.08 & 443.81 & 3.17 & 0 & 0 \\ 0 & 68.28 & 3.17 & 70.81 & 0 & 0 \\ -75.25 & 0 & 0 & 0 & 76.21 & 2 \\ -2.78 & 0 & 0 & 0 & 2 & 5.29 \end{pmatrix} \cdot 10^6. \quad (4)$$

Components of manipulator stiffness matrix are higher by several orders. Manipulator stiffness was determined by ECM calculations and is the following, H/mkm

$$\left[c_{ij}^M\right] = \begin{pmatrix} 17.2 & 0 & 0 & 0 & -0.74 & -0.11 \\ 0 & 14.6 & 0.15 & 0.62 & 0 & 0 \\ 0 & 0.15 & 18.4 & 0.18 & 0 & 0 \\ 0 & 0.62 & 0.18 & 11.5 & 0 & 0 \\ -0.74 & 0 & 0 & 0 & 9.3 & 0.2 \\ -0.11 & 0 & 0 & 0 & 0.2 & 12.5 \end{pmatrix} \cdot 10^8. \quad (5)$$

Characteristic units in the shapes of square matrices with size 3 are singled out of stiffness matrices.

Matrix units represent progressive $\left(c_{ij}^P\right)$, torsional $\left(c_{ij}^G\right)$ and joining $\left(c_{ij}^S\right)$ stiffness of systems

$$\left[c_{ij}\right] = \begin{bmatrix} \left(c_{ij}^P\right) & \left(c_{ij}^S\right) \\ \left(c_{ij}^S\right) & \left(c_{ij}^G\right) \end{bmatrix}.$$

Proper figures of progressive and torsional matrices are half-axes of corresponding stiffness ellipsoids, and proper vectors set their directions in space.

Maximal torsional stiffness relative to axis x is observed when the fixed center of the movable platform is placed under the center of the base joint which is situated in yOz plane; maximal torsional stiffness in relation to axis y is observed when the fixed center of the movable platform is placed between two opposed base joints.

The mobile complex is a compound mechanism that combines two mechanisms-hexapods with a joint movable platform that is built on the basis of dual circuit. Stiffness of separate mechanisms is substantially different. It can be observed on the sizes and orientation of stiffness ellipsoids.

Stiffness matrices are presented as graphs (Fig. 7) for the analysis of the stiffness of general mechanism components.

Points of graphs determine component indexes of stiffness matrices; edges of graphs determine component value.

Comparison of graphs shows that components of manipulator stiffness matrices considerably exceed components of machine stiffness matrix (except com-

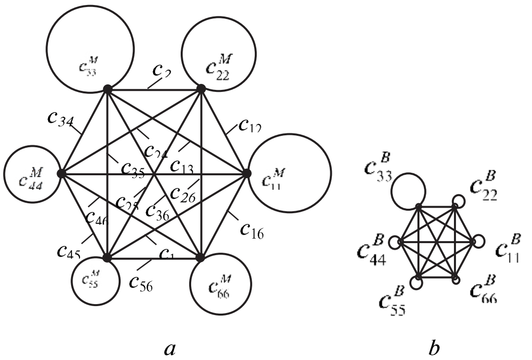

Fig. 7. Matrices of mobile complex mechanism components are presented as graphs:

a — manipulator stiffness matrix; b — machine stiffness matrix ponent c_{33}). Therefore, with sufficient accuracy for the practice the following can be taken

$$\left[c_{ij}\right]=\left[c_{ij}^{M}\right]+\begin{bmatrix}0&0&0&0&0&0\\0&0&0&0&0&0\\0&0&c_{33}^{B}&0&0&0\\0&0&0&0&0&0\\0&0&0&0&0&0\\0&0&0&0&0&0\end{bmatrix}. \qquad (6)$$

Accordingly, elastic strength of the machine system will be insignificant in any direction during the platform movement by the manipulator, except the direction that is in line with the direction of equable tension and compression of machine rods (direction N-P-S in Fig. 6). Therefore, axis of tools movable sleeve should be located in this direction.

It is possible to determine tool movement under the action of force factors from matrix-vector functional connection (2)

$$[x_i] = [E_{ij}][f_i], \qquad (7)$$

here strain matrix is opposite to stiffness matrix.

$$[E_{ij}] = [c_{ij}]^{-1}.$$

Strain matrix is determined taking into account functional connections (6, 4) and (5). It is detected that system deformability in direction N-P-S is minimal.

The given matrix-vector functional connections (7, 5, 6) are the base for calculating the tool movement under different technical operations of facility machining. An important technological operation is machining with rotary cutting tools (drilling operation and further machining with multi-flute drill and reamer). It can be assumed that in the course of machining with rotary cutting tools the cutting resistance is directed to the spindle axis; and the cutting torque M coincides with direction of the force direction (Fig. 8).

The center of the absolute coordinate system is placed on the force direction. The direction of force and moment is determined by angles φ, θ. The vector of force factors which affect the machine platform is determined from geometrical relationship and made out as follows

$$f(\varphi,\theta,F,M)=\begin{pmatrix}F\sin\theta\cdot\cos\varphi\\F\sin\theta\cdot\sin\varphi\\F\cos\varphi\\M\sin\theta\cdot\cos\varphi\\M\sin\theta\cdot\sin\varphi\\M\cos\varphi\end{pmatrix}.$$

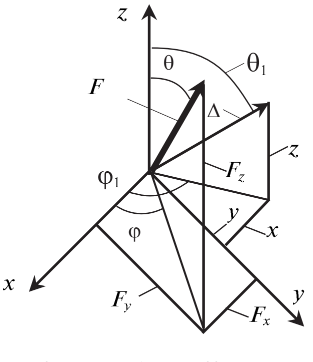

Fig. 8. Force factors that affect machine platform during rotary cutting tool machining:

$\vec{F}$ *– loading vector;* $\vec{\Delta}$ *– displacement vector of the tool end*

Displacement vector (x_i) for the given force factor is found using the formula (7). It depends on the machine and manipulator stiffness matrices (6).

Components of obtained displacement vector $[x_i]$ are correspondent to formula (1) and determined progressive x, y, z, and diametrical-angular φ_x, φ_y, φ_z platform movement and, respectively, the rotary cutting tool.

In order to implement rotary cutting tool machining, it is necessary to provide its free motion in the hole. It occurs providing that the machine platform moves in the force direction. General movement of platform Δ is determined by movement vector sum

$$\Delta=\sqrt{x^2+y^2+z^2}.$$

Movement direction relative to axes z is determined by directional cosine angle

$$\Theta_1=\arccos\frac{z}{\Delta}.$$

Condition of force vectors $\vec{F}$ and movement $\vec{\Delta}$ collinearity is vector projection proportionality

$$\frac{x}{F_x}=\frac{y}{F_y}=\frac{z}{F_z}.$$

This condition is closely fulfilled in separate cases.

Displacement of a tool in relation to machined facility and tool skew (Fig. 9) take place in common cases.

Progressive movement is characteristic to the process of tool penetration and causes additional tool jumping relative to machined surface. Tool displace-

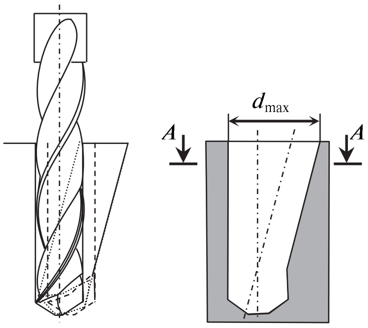

Fig. 9. Rotary cutting tool displacement and skew in a hole, which happened as a result of elastic pivotal machine system deformation

ment on angle Θ_p in the course of deep hole machining leads up to machining of the hole inlet with the tool side surface.

It is determined that in the section perpendicular to axis the change of hole form occurs, which is connected with placement directions of main axes of progressive and torsional manipulator stiffness ellipses. The results of numerous experiments conducted show that machine stiffness parameters have a little effect on stative tool movements relative to machined facility.

Calculation results show that machined hole size increases in diametrical direction that is correspondent to the location of minimal manipulator stiffness axes (Fig. 10).

The results of theoretical analysis show that deformations of the machine carrying system lead to inaccurate machining measure which is shown as a hole "breaking". Change of the hole diameter depends on detail placement relative to progressive and torsional stiffness axes. The biggest increase in the hole diameter ($d_{\max}$) happens in direction of the minimal progressive stiffness axis under condition that the minimal progressive stiffness axis is placed on the angle less than 90° relative to the minimal progressive stiffness axis.

If minimal progressive and torsional stiffness axes are perpendicular or nearly perpendicular, then hole out-of-roundness decreases (Fig. 10). In this case increasing of the hole diameter d_m is lesser than maximal size ($d_{\max}$) in previous case.

Conclusions.

1. Mobile remote-controlled robotic complex is reasonable to implement on the basis of machine-hexapod with parallel kinematic structures. It is recommended to use telescopic rods with a pneumatic cylinder in order to increase working space of the machine. In this case, machine working space increases by 1.5–2.5 times and mobile complex is able to machine hazardous facilities in holes or niches up to 2 and more meters.

2. Increase of robotic machine carrying system stiffness is provided by a special coordinative manipulator with six rods that is installed on the machine platform and is stiffly connected to machined facility with special grippers. Stiffness matrices of manipulator have components which exceed the components of robotic machine stiffness matrix in 15...25 times. Therefore, the low stiffness of the machine has almost no effect on tool deformation movements relative to raw part, which provides an opportunity for precision machining (7...9 accuracy degree) of hazardous facility.

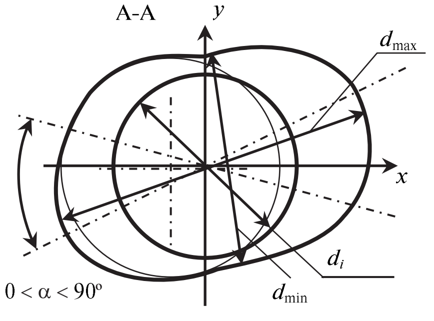

Fig. 10. Hole form that is stipulated by tool jumping as a result of elastic system deformation

3. The change of the hole form occurs during the machining of holes of hazardous facilities. When minimal progressive and torsional stiffness axes of the manipulator are located at the angle of 0...45°, then the hole form becomes similar to an oval; when the angle between axis is close to 90° then the hole form becomes similar to a circle. In both cases increase in hole sizes is rather similar, and the maximal estimated diametrical size is in control that is correspondent to 7–9 accuracy degree.

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Мета. Теоретичне обґрунтування та розробка обладнання для високоточної обробки об’єктів у польових умовах.

Методика. Застосовані, в основному, теоретичні методи досліджень, що включають визначення матриць жорсткості пружної системи верстата та маніпулятора. Теоретично обґрунтовані схемні та конструктивні рішення мобільного багатокоординатного верстата-робота. Проведене математичне моделювання процесу обробки об’єктів мобільним верстатом-роботом. На основі аналізу результатів математичного моделювання встановлені особливості деформативних характеристик верстата на основі визначених матриць жорсткості.

Результати. Обґрунтована концепція забезпечення високоточної обробки об’єктів у польових умовах мобільним верстатом-роботом. Вона основана на застосуванні маложорсткого обладнання в комплексі зі спеціальним маніпулятором, що жорстко зв’язаний з оброблюваним об’єктом і забезпечує необхідне переміщення інструменту. Обґрунтована схема високоточної обробки об’єктів мобільним верстатом-роботом, що відповідає використанню двох дуальних механізмів-гексаподів, один з яких є стрижневою системою верстата, а другий – системою маніпулятора. Запропоновані засоби збільшення робочого простору верстата шляхом використання телескопічних штанг змінної довжини з пневматичними приводами. Встановлені умови підвищення точності верстата-робота при обробці осьовим інструментом. Вони включають відповідність головних вісей матриці жорсткості маніпулятора й напрямку руху осьового інструменту. Визначено вид і характер похибок обробки та їх взаємозв’язок з параметрами жорсткості верстата й маніпулятора.

Наукова новизна. Уперше розроблена концепція високоточної обробки на верстах-роботах, що мають низьку жорсткість несучої системи, яка полягає в застосуванні маніпулятора, що жорстко закріплений на оброблюваному об’єкті та зв’язаний з виконавчим органом верстата. Уперше встановлене необхідне співвідношення компонент матриць жорсткості верстата та маніпулятора, що забезпечують можливість високоточної обробки на мобільних верстатах-роботах. Одержали подальший розвиток методи розрахунку похибок обробки деталей осьовим інструментом на верстатах з паралельними кінематичними структурами.

Практична значимість. Результати досліджень є основою розробки високоефективних верстатів-роботів для обробки небезпечних об’єктів у польових умовах. На основі одержаних результатів робочий простір мобільного верстата-робота збільшується у 3–5 разів, а точність обробки в польових умовах підвищується до 8–9 квалітетів.

Ключові слова: *мобільний верстат-робот, схеми, моделі, жорсткість, осьовий інструмент, точність, похибки*

Цель. Теоретическое обоснование и разработка оборудования для высокоточной обработки объектов в полевых условиях.

Методика. Применены, в основном, теоретические методы исследований, которые включают определение матриц жесткости упругой системы станка и манипулятора. Теоретически обоснованы схемные и конструктивные решения мобильного многокоординатного станка-работа. Проведено математическое моделирование процесса обработки объектов мобильным станком-роботом. На основе анализа результатов математического моделирования установлены особенности деформативных характеристик станка на основе определенных матриц жесткости.

Результаты. Обоснована концепция обеспечения высокоточной обработки объектов в полевых условиях мобильным станком-роботом. Она основана на применении маложесткого оборудования в комплексе со специальным манипулятором, который жестко связан с обрабатываемым объектом и обеспечивает необходимое перемещение инструмента. Обоснована схема высокоточной обработки объектов мобильным станком-роботом, что соответствует использованию двух дуальных механизмов-гексаподов, один из которых является стержневой системой станка, а второй – системой манипулятора. Предложены способы увеличения рабочего пространства станка путем использования телескопических штанг переменной длины с пневматическими приводами. Установлены условия повышения точности станка-робота при обработке осевым инструментом. Они включают соответствие главных осей матрицы жесткости манипулятора и направлению движения осевого инструмента. Определен вид и характер ошибок обработки, и их взаимосвязь с параметрами жесткости станка и манипулятора.

Научная новизна. Впервые разработана концепция высокоточной обработки на станках-роботах, которые имеют низкую жесткость несущей системы, что заключается в применении манипулятора, который жестко закреплен на обрабатываемом объекте и связан с исполнительным органом станка. Впервые установлено необходимое соотношение компонент матриц жесткости станка и манипулятора, которые обеспечивают возможность высокоточной обработки на мобильных станках-роботах. Получили дальнейшее развитие методы расчета погрешностей обработки деталей осевым инструментом на станках с параллельными кинематическими структурами.

Практическая значимость. Результаты исследований являются основой разработки высокоэффективных станков-роботов для обработки опасных объектов в полевых условиях. На основе полученных результатов рабочее пространство мобильного станка-робота увеличивается в 3–5 раз, а точность обработки в полевых условиях повышается до 8–9 квалитетов.

Ключевые слова: *мобильный станок-робот, схемы, модели, жесткость, осевой инструмент, точность, погрешности*

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VARIATION METHOD BASED ON THE INTERPOLATION FOR NAVIER-STOKES SOLUTIONS FOR TRANSIENT UNCOMPRESSIBLE FLOW

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ВАРІАЦІЙНИЙ МЕТОД НА ОСНОВІ ІНТЕРПОЛЯЦІЇ ДЛЯ РІШЕННЯ РІВНЯНЬ НАВ'Є-СТОКСА ДЛЯ НЕСТАЦІОНАРНОЇ НЕСТИСЛИВОЇ ТЕЧІЇ

Purpose. Many studies have been devoted to using variational multiscale (VMS) methods to solve the incompressible flows. The analysis differs when applying the so-called first or second fluctuation operator. On the other hand, VMS methods are used to solve unsteady incompressible flows. Error estimates dependent on the reduced Reynolds number are obtained. On the other hand, the error estimates not dependent on the Reynolds number have already been obtained by using SD and CIP methods. Thus, we desire to obtain the same or similar results by using VMS methods.

Methodology. We propose a fully discrete stabilized method for the unsteady NSEs at high Reynolds number. We use Crank-Nicolson difference in time and use the SV elements in space to preserve the incompressibility. The convective effects are stabilized by adding a new projection-based VMS term. The stability and convergence of the approximation solution are proved. The error estimates hold irrespective of the Reynolds number, and hence also for the incompressible Euler equations, provided the exact solution is smooth.

Findings. We prove the stability and convergence of the approximation solution. The error estimates hold irrespective of the Reynolds number, and hence also for the incompressible Euler equations, provided the exact solution is smooth. This method has good stability. It preserves the incompressibility and it has error estimates not dependent on the viscosity.

Originality. In this paper, we propose a new fully discrete VMS method using SV elements for the unsteady Navier-Stokes at high Reynolds number. Incompressibility is preserved by using Scott-Vogelius elements and convective effects are stabilized by adding a new projection-based variational multiscale (VMS) term.

Practical value. Numerical experiments demonstrate that our method is very effective for incompressible flows at high Reynolds number. They also confirm that our method preserves the incompressibility strongly.

Keywords: *Unsteady Navier-Stokes equations at high Reynolds number, Scott-Vogelius elements, incompressibility, convective effects, Crank-Nicolson difference, varitational multiscale method*
