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МАШИНОБУДУВАННЯ, АВТОМАТИЗАЦІЯ ВИРОБНИЦТВА ТА ПРОЦЕСИ МЕХАНІЧНОЇ ОБРОБКИ

UDC 621.881

ANALYSIS OF DYNAMICS OF ADAPTIVE THREE EDGE HEADS WITH ELASTIC GUIDES AND ELECTROMAGNETIC DRIVES

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Summary. *The paper deals with the dynamics analysis of the developed by the authors three edge head with elastic guides and electromagnetic drives in order to compare their operation dynamic features against the single tool machining ones. The three edge heads of proposed design of adaptive type have the possibility of adjustment to the changing cutting conditions. The adjustment of the head cutting edges positions in the process of machining is performed by two-direction electromagnetic drives with microcontroller based on intellectual control. So the simulation theoretical model was developed in a form of calculating scheme and the differential second order equations set. These equations are being solved using the software techniques and computer program graph interpretations. Thus the diagrams illustrating the oscillograms of the work piece and the head cutting elements vibrations in the machining process were obtained. The results of the investigation make possible to testify the developed three edge head productivity and dynamic accuracy increasing as compared with that of the single tool machining. They show that in most cases it is possible to increase the dynamic accuracy of machining in 1,2-5 to 3,17-9,6 times.*

Key words: *three edge head, oscillations, dynamical theoretical model, elastic guides.*

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Problem statement. The task of metal cutting process technical and economic efficiency upgrading can be completed by one of the following techniques: setting variable cutting conditions taking advantage of empirical engineering methods including the single parameter only and on the other hand using the cutting process adaptive control systems.

In such a case the adaptive processing requires the permanent control of the machining conditions dynamical changes by using the regular monitoring of the cutting process. It helps to take into account even those factors that are unknown on the stage of production design engineering.

Analysis of previous research. Automation machine tools machinery and the adaptive type accessories make it possible to achieve the effect of self adjusting cutting [1]. Thereby the essence of self adjusting cutting lies in the fact, that each of the identical cutting edges symmetrically located against the machining surface have a single axial state of freedom in the direction of the longitudinal feed [2]. Besides the cutting tools are interlinked with each other with taking advantage of mechanisms or techniques that perform the kinematic inter-tool linkage of adaptive type [3]. Such machine tool accessories in the structure of the total manufacturing cutting system are of substantial importance [4].

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The design process of multi-edge accessories for different machining conditions has a great number of possible functional scheme and engineering design construction options [5]. The design goal thereby lies in searching and performing of the optimal multi edge accessory design basing on the selecting the structural scheme, which will correspond to the machining productivity upgrading machine tool system accuracy increase [6].

Main idea principle of the adaptive type multi edge machining using elastic tool guides and electromagnetic drives lies in the fact that all cutting system elements characteristics were taken into account including information and dynamical properties [7]. The system fulfills the feedback control approach to reach the goal task to provide regulation of the transient cutting process behavior [8]. This allows to decrease the elastic deformation errors that affect the work piece surface roughness, dimensional and form accuracy as well as the tools and machine tool specified life and machining productivity [6].

The objective. Taking into account the actual problems of the adaptive multi edge and multi tool machining process, the analysis and mathematical simulating of the dynamical features of the proposed multi edge mechatronic cutting heads are of much value to design the engineering constructions of such accessories in order to use them widely in production. In the process of adaptive type machining on the base of the mentioned multi edge heads the integration of the precision mechanics, electronics and electric techniques is needed. That is why the paper objective is to conduct the dynamical analysis of the simulation scheme of the designed multi edge head with the elastic guides and electromagnetic drives as compared with that of single tool machining system. In regard to this investigation goal it is necessary to obtain the oscillation diagrams in order to prove the efficiency of the multi edge machining.

Simulation of theoretical model and research results. The multi edge design construction [9] with three tools was developed at the machine tools, tools and machines department of the Ternopil National Technical University. The head (Fig. 1) consists of the housing 1, in which three tool holders 2 are symmetrically mounted against the work piece surface with 120 dg angle with a help of the plate-like elastic guides 3. The tools 4 are being set into the machining dimension in the tool holders 2. The tool holders are rigidly connected to the electromagnets 5 armatures and these electromagnets are fixed to the housing. The plate-like elastic elements 6 are built in on the electromagnet armatures. The plates 6 are equipped with strain transducer indicators 7. Electromagnets as operating devices and elastic elements with transducer indicators are connected to the CNC system.

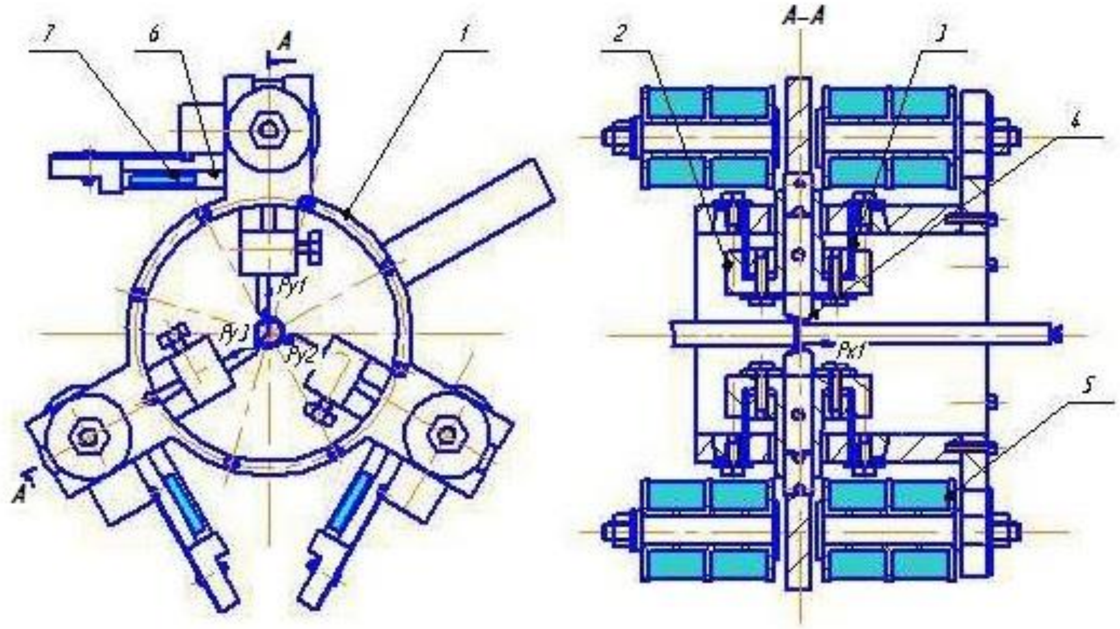

Figure 1. Scheme of multi edge head with the elastic guides and electromagnetic drives

To conduct the comparative dynamical analysis of three edge heads with elastic guides operation it is necessary to start with the case of a single tool machining. The the calculating model can be presented as a single-mass system, which is being deformed in the y direction (Fig. 2) with the mass M_y, reduced to the radial direction, damping coefficient H_y and radial rigidity C_y. Thereafter let us write the equation of such system displacements as follows:

$$M_y\ddot{y} + H_y\dot{y} + C_y y = -\Delta Py, \tag{1}$$

where ΔPy is a variation of the cutting force radial component caused by the external perturbations (they can be exemplified by the machining eccentricity radius with ratio coefficient *e*).

In this way let us represent the cutting force radial component as the static model [10]:

$$Py = Cp_y \cdot t^X \cdot S^{Yp} \cdot V_r^{np}$$

where Cp_y – coefficient that depends on the cutting conditions; *t* – instantaneous value of the depth of cut (mm); *S* – instantaneous feed value (mm per rev); V_r – cutting velocity (m per min) in accordance with the diameter *d* (mm) of machining and rotational frequency *n* (rev per min), *X*, Y_p, n_p being the exponential orders of the relative values of cutting depth, feed and velocity. Besides let us assume that the ration of tangential and radial components of the cutting force is equal to 0,5.

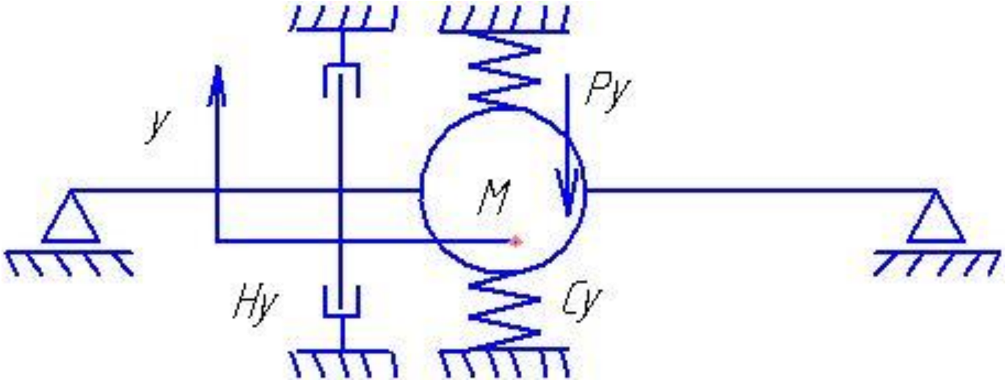

Figure 2. The single-mass system calculating model

As to the work piece radial rigidity C_y in the cutting zone, let us use the well-known dependence [11]

$$C_y = \alpha EI / l^3$$

where *l* – work piece length; *E* – the Young modulus; $I = \pi d^4 / 64$ – the work piece axial moment of inertia; *α* – coefficient that depends on the method of the work piece holding. In this way *α* = 3 in a case of single sided support; *α* = 48 in a case of conical pins holding; *α* = 102 in a case of single sided support and back conical pin tailstock holding; *α* = 66,7 in a case of machining in conical pins and rest using.

When $E = 2\cdot 10^{11}$ N/m^2 for steel and $E = 0,3\cdot 10^{11}$ N/m^2 for fiber glass, then we have $C_y = \alpha 10^{10} d/(l/d)^3$ for steel and $C_y = 0,15\alpha 10^{10} d/(l/d)^3$ for fiber glass respectively.

Let us set $l/d = \beta$ and assume that *d* is determined in mm. Then we can obtain the formula to calculate work piece rigidity in the cutting zone: $C_y = \alpha 10^7 d/\beta^3$ for steel and $C_y = 0,15\alpha 10^7 d/\beta^3$ for fiber glass respectively.

The work piece deformation static value under the effect of the radial cutting force component as follows

$$P_{yst} = 0,5\cdot 2430 t^{0,9} S^{0,6} V^{-0,3}$$

can by derived for different values of *α* and *β* and two diameters *d* = 20mm and *d* = 10mm values. Here *t* = 0,1 mm and S_0 = 0,3 mm per rev. Thus for *d* = 20mm the P_{yst} reaches the value of 21,5N and for *d*=10mm the P_{yst} reaches the value of 26,5N.

Table 1 comprises the calculated values of work piece rigidity and their static deformations in the cutting zone in a single tool machining for different *α* and *β* in regard to the work piece diameters *d* = 20 mm and *d* = 10mm.

Table № 1.
Values of work piece rigidity and their deformations in the cutting zone

	β	d=20 mm		d=10 mm	
		$C_y\cdot 10^{-7}$[N/m]	$Y_{ст}\cdot 10^7$[m]	$C_y\cdot 10^{-7}$[N/m]	$Y_{ст}\cdot 10^7$[m]
α=3	5	0,48	44,8	0,24	110,4
	6	0,28	76,8	0,139	190,6
	7	0,17	126,5	0,087	304,6
	8	0,12	179,1	0,058	456,7
	9	0,08	286,7	0,041	646,3
	10	0,06	358	0,03	883,3
	20	0,0075	2866	0,004	66250
α=48	5	7,68	2,8	3,84	6,9
	6	4,44	4,8	2,22	11,9
	7	2,8	7,7	1,399	18,9
	8	1,78	11,5	0,937	28,3
	9	1,32	16,3	0,658	40,3
	10	0,96	22,4	0,48	55,2
	20	0,12	179	0,06	441,7
α=102	5	16,32	1,32	8,16	3,25
	6	9,44	2,3	4,72	5,61
	7	5,95	3,61	2,97	8,92
	8	3,98	5,4	1,99	13,3
	9	2,8	7,7	1,399	18,94
	10	2,04	10,5	1,02	25,98
	20	0,255	84,3	0,1275	207,8

Thus, let us write the change in cutting force radial component value causing vibrations by the following equation:

$$\Delta Py = Cp_y \cdot V_r^{np} \left\{ \left[t_0 \left(1 + e \sin\left(\omega t \right) \right) \right]^2 S^{Yp} - t_0^x S_0^{Yp} \right\}$$

where t_0 – the cutting depth, mm, constant state value; y_{st} – the work piece static deformation, mm; y – the radial deformation dynamical component, mm; S_0 – the longitudinal feed, mm per rev, constant state value; ω is the work piece rotational frequency, s^{-1}. P_{yd} and P_{yst} (N) represent respectively the dynamical and static radial components of the cutting force.

In this way the simulation model (1) can be solved using the Runge-Kutta method taking advantage of the «MathCad» program.

Simulation of three tool machining using the developed head with elastic guides and electromagnet drives is based on the head elements calculating schemes. The illustration of such element diagram is presented in the Fig. 2, showing the cutting tool elements of the head that are elastically connected to the housing.

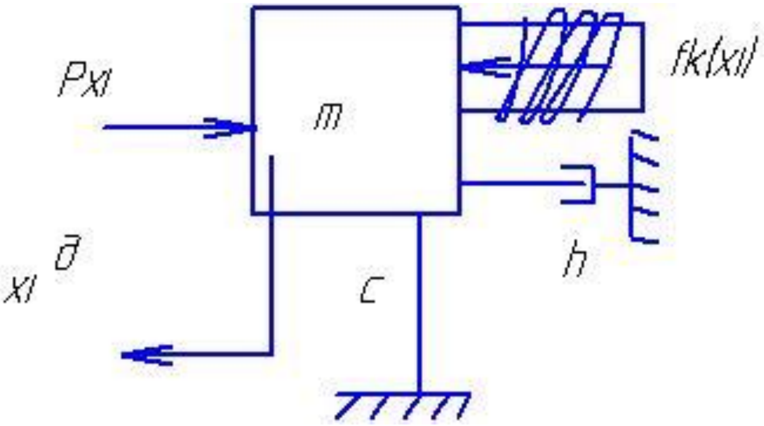

Figure 3. Calculating model diagram of the three edge head with the elastic guides

The model of such an element is presented by the single mass scheme. The reduced mass *m* of the tool element and both the elastic guide rigidity and damping reduced coefficients *c* and *h* respectively are the components of this scheme. Each of the three cutting elements is forced by the axial cutting force component P_{xi} (i = 1, 2, 3) effect. The element displacement from the steady position is of x_i value. Besides, let us consider in addition that the ratio of the axial and radial force components is 0,4, that is $P_{xi} = 0,4P_{yi}$. Here we consider the static values of the mentioned components, without their variations under the cutting conditions changing effect.

The displacement motions of the moving cutting elements due to the elastic guides are controlled by the additional electromagnetic drive. In this way it is clear that considering the cutting elements oscillation motions it is necessary to take in account the control effect of the electromagnets that can be presented as $fk_i(x_i)$ $(x_i = 1, 2, 3)$ functions that are different for certain cutting elements according to the concrete control algorithm.

As a result the differential equation of the separate cutting element motion can be derived as:

$$m\ddot{x}_i + h\dot{x}_i + Cx_i^d = -\Delta Px_i$$

where ΔPx_i – change of the cutting force axial component on the separate element. This force depends not only on the cutting conditions variations, but on the control function effect too.

Let us assume, that such a function is the signal of the summary equal-zero of the separate cutting elements displacements. In this way dynamical values of each of the cutting elements axial displacements are the following:

$$\begin{aligned} x_1^d &= x_1 - 0,5(x_2 + x_3) \\ x_2^d &= x_2 - 0,5(x_1 + x_3) \\ x_3^d &= x_3 - 0,5(x_1 + x_2) \end{aligned} \quad (2)$$

It is obvious that $\sum_{i=1}^{3} x_i^d = 0$, that is

$$\begin{aligned} & x_1^d + x_2^d + x_3^d = x_1 - 0,5(x_2 + x_3) + x_2 - 0,5(x_1 + x_3) + x_3 - 0,5(x_1 + x_2) = \\ & = (x_1 - 0,5x_1 - 0,5x_1) = (x_2 - 0,5x_2 - 0,5x_2) + (x_3 - 0,5x_3 - 0,5x_3) = 0 \end{aligned}$$

Foremost, the cutting depths variations must be taken into account and first of all the variations caused by the work piece holding eccentricity *e*. (We take into account that static deformations in radial directions are compensated in this case). Thus:

$$\begin{aligned} t_1 &= t_0(1 + e\sin\omega t) \\ t_2 &= t_0\left[1 + e\sin\left(\omega t + \frac{2\pi}{3}\right)\right] \\ t_3 &= t_0\left[1 + e\sin\left(\omega t + \frac{4\pi}{3}\right)\right] \end{aligned}$$

So the cutting elements under the effect of the control signals and due to the elastic guides are found in the process of continuous oscillation. It is obvious that the separate elements feed values are changing too.

In this way the instantaneous feed values at each of the cutting elements depend on the relative velocities of their displacements in regard to the control signal. So,

$$\begin{aligned} S_1 &= S_0 + \left[\dot{x}_1 - 0,5(\dot{x}_2 + \dot{x}_3)\right] \cdot 10^{-3} / 60n_d \\ S_2 &= S_0 + \left[\dot{x}_2 - 0,5(\dot{x}_1 + \dot{x}_3)\right] \cdot 10^{-3} / 60n_d \\ S_3 &= S_0 + \left[\dot{x}_3 - 0,5(\dot{x}_1 + \dot{x}_2)\right] \cdot 10^{-3} / 60n_d \end{aligned}$$

where n_d – work piece rotation frequency, rev per min. In this case the coefficient $10^{-3} / 60n_d$ signifies the reducing of the feed change speed in m/s to the rotational feed value in mm/rev.

Thus we can derive the ordinary differential equations system of the second order that define the axial motions of the cutting elements regarding the changing both of the cutting conditions and control signals stabilizing the summary value of the mentioned axial tool displacements. This system of equations looks like:

$$\begin{cases} m\ddot{x}_1 + h\dot{x}_1 + C\left[x_1 - 0,5(x_2 + x_3)\right] = \\ = k_x \left\{ t_0 \left[(1 + e\sin\omega t)\right]^{X_p} \left[S_0/3 + \left[\dot{x}_1 - 0,5(\dot{x}_2 + \dot{x}_3)\right]\cdot 10^{-3}/60 n_d\right]^{Yp} - t_0^{Xp} S_0^{Yp}/3 \right\} \\ m\ddot{x}_2 + h\dot{x}_2 + C\left[x_2 - 0,5(x_1 + x_3)\right] = \\ = k_x \left\{ t_0 \left[\left(1 + e\sin\omega t + \dfrac{2\pi}{3}\right)\right]^{X_p} \left[S_0/3 + \left[\dot{x}_2 - 0,5(\dot{x}_1 + \dot{x}_3)\right]\cdot 10^{-3}/60 n_d\right]^{Yp} - t_0^{Xp} S_0^{Yp}/3 \right\} \\ m\ddot{x}_3 + h\dot{x}_3 + C\left[x_3 - 0,5(x_1 + x_2)\right] = \\ = k_x \left\{ t_0 \left[\left(1 + e\sin\omega t + \dfrac{4\pi}{3}\right)\right]^{X_p} \left[S_0/3 + \left[\dot{x}_3 - 0,5(\dot{x}_1 + \dot{x}_2)\right]\cdot 10^{-3}/60 n_d\right]^{Yp} - t_0^{Xp} S_0^{Yp}/3 \right\} \end{cases} \qquad (3)$$

In this formula k_x is constant value, which takes into account the coefficient C_{pz} that depends on the cutting conditions and ratio of the axial and tangential cutting forces components.

So, it is quite evident, that we can find the total force change value of the cutting elements radial force components affecting the work piece with the reduced mass M_y. In this way we get such the second order differential equation:

$$\begin{gathered} M_y\ddot{y} + H_y\dot{y} + C_y y = \\ = k_y \left\{ t_0 \left[(1 + e\sin\omega t)\right]^{Xp} \left[S_0/3 + \left[\dot{x}_1 - 0,5(\dot{x}_2 + \dot{x}_3)\right]\cdot 10^{-3}/60 n_d\right]^{Yp} - t_0^{Xp} S_0^{Yp}/3 \right\} + \\ + k_y \left\{ t_0 \left[\left(1 + e\sin\omega t + \dfrac{2\pi}{3}\right)\right]^{Xp} \left[S_0/3 + \left[\dot{x}_2 - 0,5(\dot{x}_1 + \dot{x}_3)\right]\cdot 10^{-3}/60 n_d\right]^{Yp} - t_0^{Xp} S_0^{Yp}/3 \right\} + \\ + k_x \left\{ t_0 \left[\left(1 + e\sin\omega t + \dfrac{4\pi}{3}\right)\right]^{Xp} \left[S_0/3 + \left[\dot{x}_3 - 0,5(\dot{x}_1 + \dot{x}_2)\right]\cdot 10^{-3}/60 n_d\right]^{Yp} - t_0^{Xp} S_0^{Yp}/3 \right\} \end{gathered} \qquad (4)$$

Mutual solution of the differential equations (3) and (4) is done taking advantage of the Runge-Kutta method with a help of the «MathCad» software taking into account the initial conditions.

So, the initial data being: M_y = 100kg; H_y = 100kg/s; $C_y = 5\cdot 10^8$ N/m; t_0 = 0,2mm; S_0 = 0,3mm/rev; d = 20mm; n_d = 1000rev/min; e = 0,1; exponential orders X_p = 0,9; Y_p = 0,6; n_p = –0,3 and regarding the initial conditions $y(0) = 3\cdot 10^{-8}$ м; $y^I(0) = 0$ we obtain for the single tool machining the stable picture of the work piece vibrations in its middle zone (Fig. 4):

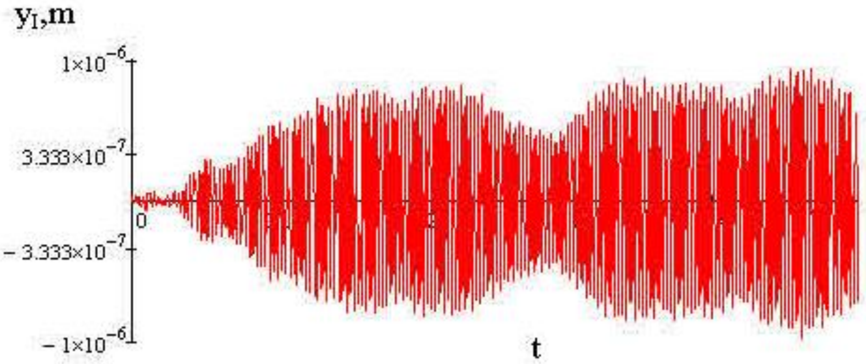

Figure 4. Work piece vibrations oscillogram picture in a case of the single tool machining

Let us compare the dynamic picture of vibrations for the case of three edges machining using the head with elastic guides and electromagnet drives under the same initial conditions as for single tool variant. Here we have the following parameters of cutting elements: m = 1kg; h = 100kg/s; $C = 10^5$ N/m together with initial conditions taking into account the cutting elements oscillations: $x_1(0) = 10^{-4}$ m; $x_1^I(0) = 0$; $x_2(0) = 10^{-4}$ m; $x_2^I(0) = 0$; $x_3(0) = 10^{-4}$ m; $x_3^I(0) = 0$. Thus we obtain the following work piece vibrations oscillogram (Fig. 5) that significantly differs from the single tool machining picture (Fig. 4).

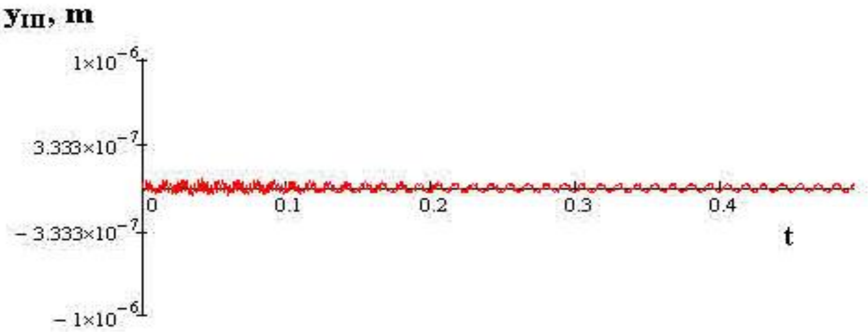

Figure 5. Oscillogram of work piece vibrations in machining using three edge head with elastic guides and electromagnet drives

In this case for the cutting elements velocities timing differences are getting stable and tend to zero (Fig. 6).

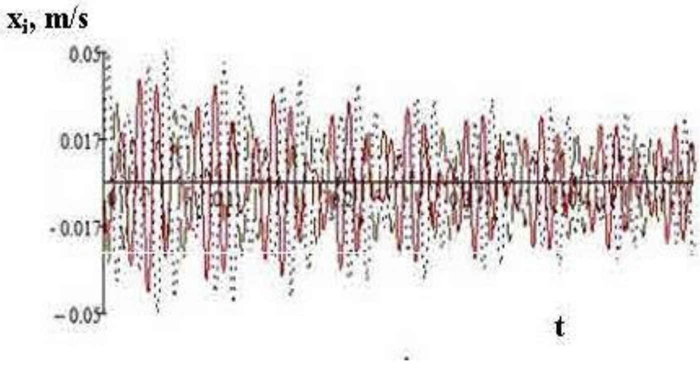

Figure 6. Oscillogram of relative velocities of three edge head cutting elements

The similar picture can be observed for the signal function $SS_{reg} \to \sum_{i=1}^{3} x_i = 0$ that provides control process (Fig. 7).

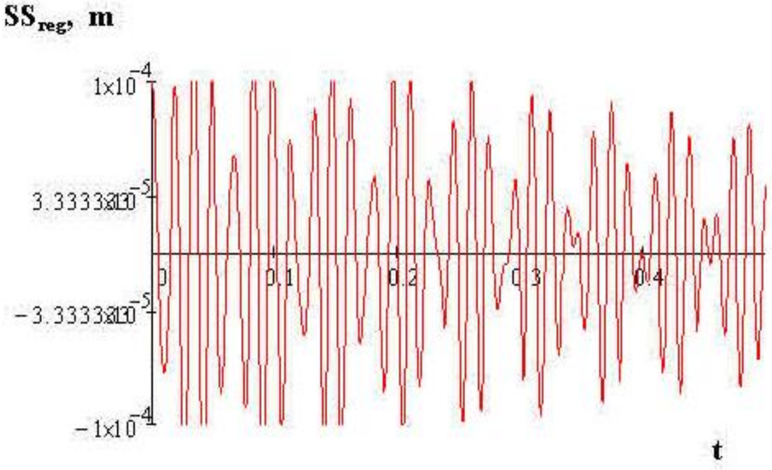

Figure 7. Control signal oscillogram in a case of machining using three edge head with elastic guides and electromagnet drives

The developed method of the three edge head machining as compared with that of single tool machining is demonstrable for a set of machining options (tables 2, 3).

Table № 2.
Comparison of the dynamical displacement amplitudes K for steel machining in the cases of single tool (y_I) and three edge head cutting (y_{III}) (d = 20mm)

	α = 3			α = 48		
d = 20 mm	β = 5	β = 10	β = 20	β = 5	β = 10	β = 20
$c \cdot 10^{-7}$,N/m	0,48	0,06	0,073	7,68	0,96	0,12
y_I, m	$3 \cdot 10^{-6}$	$4{,}5 \cdot 10^{-5}$	$12{,}5 \cdot 10^{-5}$	$6{,}9 \cdot 10^{-7}$	$1{,}7 \cdot 10^{-6}$	$9{,}5 \cdot 10^{-6}$
y_{III}, m	$0{,}6 \cdot 10^{-6}$	$6{,}7 \cdot 10^{-6}$	$1{,}3 \cdot 10^{-5}$	$6 \cdot 10^{-7}$	$6{,}33 \cdot 10^{-7}$	$3 \cdot 10^{-6}$
y_I / y_{III}, var	5,0	6,7	9,6	1,15	2,68	3,17

Table № 3.
Comparison of the dynamical displacement amplitudes K for steel machining in the cases of single tool (y_I) and three edge head cutting (d=10mm) (y_{III})

	α = 3			α=48		
d = 10 mm	β = 5	β = 10	β = 20	β = 5	β = 10	β = 20
$c \cdot 10^{-7}$,N/m	0,24	0,03	0,037	3,84	0,48	0,06
y_I,m	$4 \cdot 10^{-6}$	$1{,}7 \cdot 10^{-4}$	$0{,}9 \cdot 10^{-3}$.	$6 \cdot 10^{-6}$	$1{,}7 \cdot 10^{-6}$	$5 \cdot 10^{-5}$
y_{III},m	$1{,}7 \cdot 10^{-6}$	$2{,}7 \cdot 10^{-5}$	$1{,}1 \cdot 10^{-4}$	$5{,}1 \cdot 10^{-6}$	$0{,}8 \cdot 10^{-6}$	$0{,}9 \cdot 10^{-5}$
y_I / y_{III},var	2,36	6,29	8,18	1,18	2,13	5,5

Summarizing the presented results it is possible to obtain graph diagrams of efficiency coefficients with regard to use the three edge head cutting against the single tool machining in the cases of steel processing (Fig. 8).

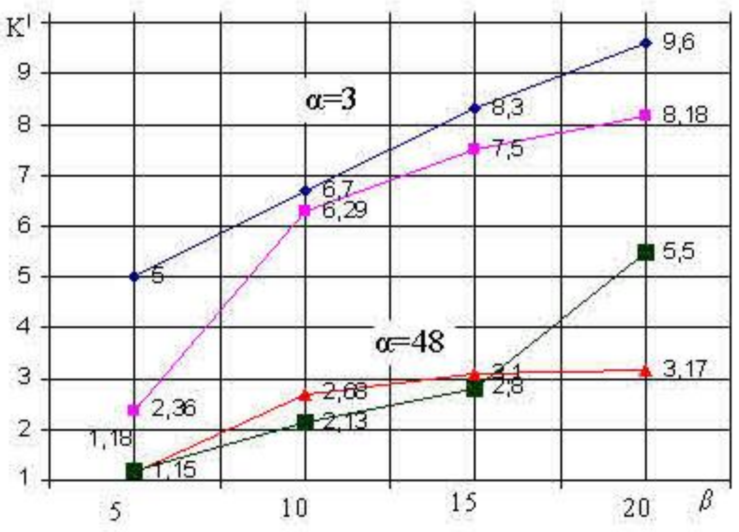

Figure 8. Graph diagrams of the efficiency coefficients with regard to use the three edge head cutting against the single tool machining

These diagrams illustrate high efficiency upgrading in a case of the developed techniques. They testify that in some cases it is possible to increase the dynamic accuracy of machining in 1,2 – 5 to 3,17 – 9,6 times. The similar diagrams can be obtained in a case of fiber glass machining.

Conclusions. The dynamic analysis of the proposed three edge head design with elastic guides and electromagnetic drives in order to compare its operation dynamic features against the single tool machining ones was conducted. The simulation theoretical model was developed in a form of calculating scheme and the differential second order equations set. As a result of the equations solution the diagrams illustrating the oscillograms of the work piece and the head cutting elements vibrations in the machining process were obtained.

The results of the investigation make possible to testify the developed three edge head productivity and dynamic accuracy increasing as compared with that of the single tool machining. They show that in most cases it is possible to increase the dynamic accuracy of machining in 1,2 – 5 to 3,17 – 9,6 times.

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АНАЛІЗ ДИНАМІКИ ТРИРІЗЦЕВИХ ГОЛОВОК З ПРУЖНИМИ НАПРЯМНИМИ І ЕЛЕКТРОМАГНІТНИМИ ПРИВОДАМИ

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Резюме. *Розглянуто аналіз динаміки розробленої авторами трирізцевої головки з пружними напрямними і електромагнітними приводами для порівняння їх динамічних особливостей однорізцевою обробкою. Трирізцеві головки запропонованої конструкції мають можливість регулювання режимів та умов різання за допомогою адаптивної системи керування. Регулювання позиції різальних лез головки в процесі обробки виконується двонаправленими електромагнітними приводами із мікроконтролерним інтелектуальним керуванням. Отже, моделювання теоретичної моделі розроблялося у вигляді розрахункових схем і диференціальних рівнянь другого порядку. Ці рівняння вирішувалися за допомогою використання програмного забезпечення та комп'ютерних графічних програм. На схемах продемонстровано осцилограми вібрацій заготовки та різальних елементів головки, що були отримані в процесі обробки. Результати дослідження дають можливість довести продуктивність розроблюваних трирізцевих головок і підвищення динамічної точності в порівнянні з однорізцевою обробкою. Вони показують, що у більшості випадків можливе підвищення динамічної точності обробки від 2 – 4 до 10 – 16 разів.*

Ключові слова: *трирізцева головка, вібрації, динамічна теоретична модель, пружні напрямні.*

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