**JOURNAL OF ENGINEERING SCIENCES**

Volume 8, Issue 1 (2021)


*Prydalnyi, B. I. (2021). Mathematical model of the tensioning in the collet clamping mechanism with the rotary movable input link on spindle units. Journal of Engineering Sciences, Vol. 8(1), pp. E23–E28, doi: 10.21272/jes.2021.8(1).e4*

# Mathematical Model of the Tensioning in the Collet Clamping Mechanism with the Rotary Movable Input Link on Spindle Units

Prydalnyi B. I.[1*][0000-0001-8565-5986], Sulym H. T.[2][0000-0003-2223-8645]

[1] Lutsk National Technical University, 75 Lvivska street, 43018 Lutsk, Ukraine;
[2] Bialystok University of Technology, 45C, Wiejska St., 15-351 Bialystok, Poland

**Article info:**

| | |
|---|---|
| Received: | March 30, 2021 |
| The final version received: | May 25, 2021 |
| Accepted for publication: | June 2, 2021 |

***Corresponding email:**
b.prydalnyi@lutsk-ntu.com.ua

**Abstract.** Increasing machining productivity causes the cutting forces acting on tools or workpieces to grow and requires extra clamping forces for their fixation reliably. In the research, a mathematical model of the operation of the clamping mechanism for fixating cylindrical objects on the spindle of machine tools at the stage of tension is presented. The presented design of the mechanism contains screw gear and provides self-braking. Based on the calculation model, mathematical dependencies are developed to describe the relationship among the movements of the parts of the mechanism when clamping forces are growing. The presented analytical dependencies allow considering the stage of growing clamping forces separately when the conservative type of forces are prevailing in the mechanism's operation. That stage of work when both types of forces of dissipative and potential characters exist is considered. The developed dependencies describe the position of parts of the clamping mechanism depending on the generalized coordinate. The angle of rotation of the input rotating link is used as the generalized coordinate. This fact allows calculating the position of the elements of the clamping mechanism of this type depending on time. Results of the research enhance understanding the pattern of the change in the interaction of the elements and forces that act in the mechanism during the final stage of clamping. The obtained mathematical dependencies are a precondition for the development of design methodology for mechanisms of this type.

**Keywords:** machining, clamping drive, clamping forces, calculation model, screw gear.

## 1 Introduction

One of the essential characteristics of metalworking machines is the productivity of machining, which determines their competitiveness. The ability to increase the feed and allowance of machining requires an increase in the power of the cutting process and, consequently, the amount of effort to fix the tool and workpieces.

The fixation effort has to ensure the absence of uncontrolled movements of tools and workpieces under the cutting forces, leading to many negative consequences. Most metalworking machines use clamping mechanisms that work in an automatic mode for fixing workpieces and tools. The clamping process can be divided into two stages: a sampling of gaps and creating a stress state of the system (tension).

The characteristics of the second stage of clamping determine the conditions of creating the required amount of clamping forces. The process that occurs during the creation of clamping forces can be described generally as converting the kinetic energy of the moving elements of the clamping mechanism into the potential deformation energy of its links. The clamping mechanism is part of the structure of the spindle assembly of machines, and as one of its largest subsystems, affects its dynamic characteristics.

Promising are the designs of clamping mechanisms that provide self-braking in the clamped position. This helps to avoid the need to supply energy to retain the fixation object in a clamped state, prevents uncontrolled release of the fixation object in case of power loss, and provides stability of clamping forces (as opposed to geometric lock) when the size of the fixation object deviates from nominal values. One example of such a design is a clamping mechanism with a screw transmission and a rotating input link.

The structure of any clamping mechanism for clamping tools or workpieces on spindle units can be divided figuratively into two systems: clamping chuck and clamping actuator. A clamping actuator can be presented as a mechanism designed for converting and transmitting mechanical energy in the form of forces from the input link to the clamping collet chuck. Characteristics of clamping actuators influence the work characteristics of clamping mechanisms.

## 2 Literature Review

Many theoretical studies relate mainly to the operation of the spindle assemblies as a whole, without highlighting the clamping mechanism as a separate subsystem. The adaptive clamping control has been developed to improve the work-piece-holding process in the research [1]. The article [2] is devoted to considering bending and translational-angular vibrations of spindles of metal-cutting machine tools. Developed in [3], the mathematical model of spindle unit bearing assembly describes the mechanism of vibration signal formation analytically. The paper [4] aims to improve the spindle's output torque and propose a novel electromagnetic structure design to improve the output torque of the spindle motor. The dynamic model of the clamping mechanism is presented in [5] as a lumped parameter system of rigid bodies connected by elastic and dissipative links. The article [6] examines the influence of different clamping chucks on energy consumption parameters and focuses on essential sustainability indicators in machining. The paper [7] deals with kinematic designing clamping mechanism with reciprocating linear motion and dead-position closed positions. The dynamic simulation analysis of the clamping and stretching processes are performed using the article's finite element method [8]. In the paper [9], the clamping-unclamping principle of the automatic collet chuck holders in their initial static state describes analytically and presents the finite element method of static analysis. In the research work [10], the spindle unit model was studied [10] and used to calculate the required adjustments to the spindle unit to eliminate loss of stability, excessive vibrations, and cracks on production pieces. A procedure intended to examine a spindle drive unit using numerical models and experimental data has been developed in work [11]. In the research [12], the contact interaction between the tooltip and the workpiece surface is investigated considering the submicrometer level through the proposed spindle. The paper [13] is a study case for a clamp mechanism design, solving both analysis and synthesis problems. The research [14] is devoted to machining thin-walled workpieces, including static workpiece displacements and large deformations caused by local indentations at contacts. It is obtained that machining strategy is essential for obtaining proper surface finish and fine control over dimensions and form. To improve the spindle system in the designing stage and predict the tool point dynamics, the paper [15] proposes modeling of spindle-holder assembly and investigates the contact characteristic under clamping and centrifugal forces. The study [16] aims explicitly to model a spindle–holder taper joint to predict the stiffness and stress distribution under different clamping and centrifugal forces. It was noted that an understanding of the contact characteristics of a spindle–holder joint in machine tools calls for an in-depth analysis of its performance, in particular under machining conditions. In work [17], the idea that measuring the clamping forces on cylindrical workpieces is a critical factor in the geometrical tolerances of such components, especially if they are slender as the case of thin rings, is expressed. The lower the clamping force, the better tolerances will be achieved, but with the disadvantage of reducing friction and increasing the risk of slipping. Therefore, achieving a minimum but safe clamping force is a critical factor in controlling the process. The operation principles of both new and improved clamping mechanisms of the CNC lathe with the automatic reinstallation workpiece manipulation are described in the article [18].

## 3 Research Methodology

### 3.1 Schemes of the calculation

The study [5] presents a scheme of calculation and dependencies that describe some kinematic characteristics of clamping mechanisms with screw self-braking transmission. The general scheme (Fig. 1) of this type of mechanism for clamping cylindrical objects on spindle units of metalworking machines is developed.

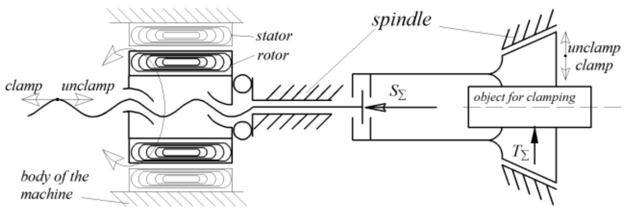


Figure 1 – The scheme of the design of the clamping mechanism with screw gear

The operation of clamping mechanisms can be separated into at least two stages. Separation occurs according to the type of forces (dissipative or potential) acting in these clamping mechanisms at a particular stage of the clamping process. For example, there is backlash elimination in the clamping mechanisms at the first stage when only active dissipative forces act. At the second stage, there is a creation of tension (mechanical stress). At this stage, potential forces' action prevails due to significant deformation of a flexible system of the mechanism with insignificant forces of dissipative character.

The relation among the kinematic parameters of the design of the clamping mechanism with screw gear can be calculated accordingly to the scheme (Fig. 2). It can be performed based on the equality between the magnitude of the rotation angle $\varphi_\partial$ of the input link in the form of rotor and the movement $x_m$ of the drawbar in the form of a tube connected to the collet [5]:

$$x_m = \frac{\phi_\partial \cdot h}{2\pi} \tag{1}$$

where $h$ – the pitch of the screw gear. As a result of differentiation (1) regarding time $t$, obtain the speed of movement of the drawbar $V_m = \frac{\partial x_m}{\partial t} = \frac{\partial \phi_\partial}{\partial t} \cdot \frac{h}{2\pi}$ and $V_m = \omega_\partial \cdot \frac{h}{2\pi} = 0{,}5\omega_\partial \frac{h}{\pi} = \omega_\partial \cdot 0{,}5 d_1 \cdot tg\psi$ where $d_1$ – the diameter of the thread of the screw gear; $\Psi$ – the angle of the rise of the thread of the screw gear. As a result of substitution, we receive $0{,}5 d_1 \cdot tg\psi = i_г$. After putting into the previous equation, we get $V_m = \omega_\partial \cdot i_г = \dot{\phi}_\partial \cdot i_г$.

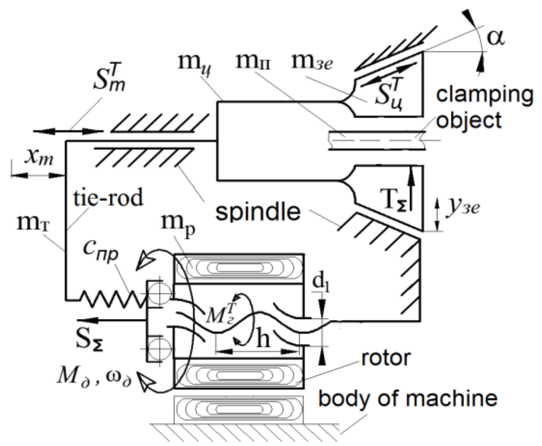


Figure 2 – The scheme for the calculation of parameters of the clamping mechanism

The relation between the elementary rotation angle $\delta\phi_\partial$ of the input link (rotor) and the elementary displacements of drawbar $\delta x_m = \delta\phi_\partial \frac{h}{2\pi}$ and clamping jaw of the collet $\delta y_{зе} = \delta x_m \cdot tg\alpha$ is represented by analogy with the previous equations, therefore $\delta y_{зе} = \delta\phi_\partial \frac{h}{2\pi} \cdot tg\alpha$, where $\alpha$ –the angle of a half of the clamping collet cone.

### 3.2 Power characteristics

The torque $M_г^T$ of friction in the thread from the tangential friction force $F_t = S_\Sigma \cdot tg\phi^T$ with arm $0{,}5 d_1$:

$$M_г^T = 0{,}5 \cdot d_1 \cdot S_\Sigma \cdot tg\phi^T, \tag{2}$$

where $S_\Sigma = \frac{2M_\partial}{d_1 tg\psi}$ – the axial force acting from the collet; $\phi^T$ – the friction angle in the thread; $M_\partial$ – the torque supplied to the input link of the mechanism..

The force of friction $S_ц^T$ in the connection between conical surfaces of the collet and the spindle:

$$S_ц^T = \frac{z \cdot S_\Sigma}{\cos\alpha + (\sin\alpha)/f_ц}, \tag{3}$$

where $f_ц$ – friction coefficient in the connection of the collet and the spindle; $z$ – the quantity of clamping jaws in clamping chuck.

The magnitude of the friction force $S_m^T$ in the connection of the tie-rod made in the form of a tube and the spindle can be calculated from the expression:

$$S_m^T = g \cdot m_\Sigma \cdot f_m, \tag{4}$$

where $g$ – free-fall acceleration; $m_\Sigma = m_m + m_n$ – the sum of masses of the object for clamping and the tie-rod; $f_m$ – friction coefficient in the connection of the spindle with the tie-rod.

## 4 Results

The stage of creating tension in the clamping mechanisms is characterized by a significant increase in the magnitude of the radial clamping force $T_\Sigma$, which is associated with the appearance of contact approximations at the junction of a clamping segment and an object of clamping. That is assumed that during the clamping time $t$ the force $T_\Sigma$ goes to its maximum value $T_{\max}$ exponentially:

$$T_\Sigma = T_{\max}\left(1 - e^{-kt}\right). \tag{5}$$

The coefficient $k$ collectively reflects the design features of the mechanism that affect the speed of reaching the maximum values of the clamping force. It also depends on the individual characteristics of mechanisms such as the contact stiffness of the joints of parts, settings, operating conditions etc. Therefore, the coefficient may change during exploitation.

During the operation of the clamping mechanisms, its kinetic energy $E$ does not depend on the angle $\phi_\partial$ of the input link rotation. The partial derivative of the mechanism kinetic energy $E$ on the angle $\phi_\partial$ is equal zero $\partial E / \partial \phi_\partial = 0$. At the stage of creation tension, the significant deformations of the clamping mechanisms' flexible system and conservative forces (potential elastic forces) at a small movement of elements appear. For this case, the differential equation of motion of the elements of the clamping mechanisms can be obtained based on the theorem on the change of the total mechanical energy of the holonomic system. The Lagrange equation, in this case, has the form:

$$\frac{d}{dt}\left(\frac{\partial E}{\partial \dot{\phi}_\partial}\right)-\frac{\partial E}{\partial \phi_\partial}=-\frac{\partial \Pi}{\partial \phi_\partial}+M_\Pi^{н}, \qquad (6)$$

where $\Pi=\frac{c\cdot x_m^2}{2}$ – the potential energy of elastic deformation forces of clamping mechanism elements, $c$ – stiffness of the elastic system of the clamping mechanism. $M_\Pi^{н}$ – generalized force in the form of reduced torque at the stage of creating a mechanical tension system. The kinetic energy of the clamping mechanism as a rotation system can be described by the expression $E=J_\Pi \dot{\phi}_\partial^2/2$, where $J_\Pi$ – the inertia moment of the clamping mechanism is reduced to the input link (rotor). The partial derivative of the previous mathematical expression of the kinetic energy $E$ at the generalized speed $\dot{\phi}_\partial$ can be presented in the form $\dot{\phi}_\partial J_\Pi=\partial E/\partial \dot{\phi}_\partial$. Taking into account the fact that when the time $t$ is changing, it causes changes only the angle $\phi_\partial$ the partial derivative of the previous expression on time is:

$$\frac{d}{dt}\left(\frac{\partial E}{\partial \dot{\phi}_\partial}\right)=\ddot{\phi}_\partial J_\Pi. \qquad (7)$$

Considering (1) and $\Pi=\frac{c}{2}\cdot\left(\frac{\phi_\partial\cdot h}{2\pi}\right)^2=\frac{\phi_\partial^2 h^2 c}{8\pi^2}$ we obtain:

$$\frac{\partial \Pi}{\partial \phi_\partial}=\phi_\partial \frac{h^2 c}{4\pi^2}. \qquad (8)$$

Generalized force $M_\Pi^{н}$ in the form of the reduced moment, which represents the action of non-potential forces in the clamping mechanisms at the stage of creating mechanical tension system, can be described as equality of small works of forces that are acting in the clamping mechanism on small movements:

$$\begin{aligned}&M_\Pi^{н}\delta\phi_\partial=M_\partial\delta\phi_\partial-M_г^T\delta\phi_\partial\\&-\delta x_m\left(S_m^T+S_ц^T\right)-T_\Sigma\delta y_{зе},\end{aligned} \qquad (9)$$

where $M_г^T$ – the torque of friction forces in the thread of the screw transmission; $S_ц^T$ and $S_m^T$ – the friction forces between surfaces respectively: the cone of the collet and the spindle; the tie-rod and the spindle.

As a result of substitution (1) (2), (3), and (4) into (9) and taking into account previously defined kinematic parameters of the clamping mechanism, we get:

$$\begin{aligned}&M_\Pi^{н}=M_\partial-0,5d_1S_\Sigma tg\phi^T\\&-\frac{h}{2\pi}\left(gm_\Sigma f_m+\frac{zS_\Sigma}{\cos\alpha+\sin\alpha/f_ц}\right)-T_\Sigma\left(\frac{h}{2\pi}tg\alpha\right).\end{aligned} \qquad (10)$$

If include $S_\Sigma=\frac{2M_\partial}{d_1 tg\psi}$, $\frac{h}{\pi}=d_1 tg\psi$ and (5) into (10):

$$\begin{aligned}&M_\Pi^{н}=M_\partial\left(1-\frac{tg\phi^T}{tg\psi}-\frac{z}{\cos\alpha+\sin\alpha/f_ц}\right)\\&-\frac{h}{2\pi}gm_\Sigma f_m-T_{\max}\frac{h}{2\pi}tg\alpha+e^{-kt}T_{\max}\frac{h}{2\pi}tg\alpha.\end{aligned} \qquad (11)$$

After denotation of the summands of (11) by symbols $\beta_2=T_{\max}\frac{h}{2\pi}tg\alpha$ and $\theta_2=M_\partial\left(1-\frac{tg\phi^T}{tg\psi}-\frac{z}{\cos\alpha+\sin\alpha/f_ц}\right)$ $-\frac{h}{2\pi}gm_\Sigma f_m-T_{\max}\frac{h}{2\pi}tg\alpha$ it takes a form:

$$M_\Pi^{н}=\theta_2+\beta_2 e^{-kt}. \qquad (12)$$

Substituting (7), (8), and (12) for (6), we obtain a differential equation:

$$\ddot{\phi}_\partial J_\Pi=-\phi_\partial\frac{h^2c}{4\pi^2}+\theta_2+\beta_2 e^{-kt}. \qquad (13)$$

After denotation $\lambda_0=\frac{h^2c}{4\pi^2}\cdot\frac{1}{J_\Pi}$, $\theta_0=\frac{\theta_2}{J_\Pi}$ and $\beta_0=\frac{\beta_2}{J_\Pi}$ we obtain:

$$\ddot{\phi}_\partial+\phi_\partial\lambda_0=\theta_0+\beta_0 e^{-kt}. \qquad (14)$$

Solution (14) can be represented as a solution to a non-homogeneous equation of the form:

$$\phi_{\partial зн}=\phi_{\partial зо}+\phi_{\partial чн}, \qquad (15)$$

where $\phi_{\partial зн}$ – the general solution of the non-homogeneous equation, $\phi_{\partial зо}$ – the general solution of the homogeneous equation, $\phi_{\partial чн}$ – the partial solution of the non-homogeneous equation. To find $\phi_{\partial зо}$, consider the equation $\ddot{\phi}_\partial+\phi_\partial\lambda_0=0$. Its characteristic equation $k^2+\lambda_0=0$; $k^2=-\lambda_0$ and assume that $\lambda_0=\frac{h^2c}{4\pi^2}\cdot\frac{1}{J_\Pi}>0$ – constant, $k_1=\sqrt{\lambda_0}i$, $k_2=-\sqrt{\lambda_0}i$. Therefore, the solution of the homogeneous equation has the form $\phi_{\partial зо}=C_1\cos(\sqrt{\lambda_0}t)+C_2\sin(\sqrt{\lambda_0}t)$.

The solution of $\phi_{\partial чн}$ is found in the following form (according to the theory of differential equations):

$$\phi_{\partial чн}=A+\beta e^{-kt}. \qquad (16)$$

After substitution of $\dot{\phi}_{\partial чн}=-\beta e^{-kt}$, $\ddot{\phi}_{\partial чн}=\beta e^{-kt}$ with the initial equation (14) we obtain $\beta e^{-kt}+\lambda_0\left(A+\beta e^{-kt}\right)=\theta_0+\beta_0 e^{-kt}$, $e^{-kt}\left(\beta+\lambda_0\beta\right)+\lambda_0 A=$

$=\theta_0+\beta_0 e^{-kt}$ where $A=\dfrac{\theta_0}{\lambda_0}$, $\beta=-\dfrac{\beta_0}{k^2+\lambda_0}$. According to (16), $\phi_{\partial чн}=\dfrac{\theta_0}{\lambda_0}-\dfrac{\beta_0}{k^2+\lambda_0}e^{-kt}$, and

$$\begin{aligned}\phi_{\partial зн} &= C_1\cos(\sqrt{\lambda_0}t)+C_2\sin(\sqrt{\lambda_0}t)\\ &+\frac{\theta_0}{\lambda_0}-\frac{\beta_0}{k^2+\lambda_0}e^{-kt}.\end{aligned} \tag{17}$$

Expression (17) describes the dependence of the generalized coordinate $\phi_\partial$ on time at the second stage of clamping the workpiece under the action of non-conservative (dissipative) and conservative forces in the clamping mechanisms. The constants $C_1$ and $C_2$ can be found from the two corresponding initial conditions and in our initial conditions $C_1=C_2=0$. After denotation of the summands of (17) by symbols $A=\sqrt{C_1^2+C_2^2}$ and $\phi_0=arctg\dfrac{C_2}{C_1}$ it can be rewritten as:

$$\phi_{\partial зн}=A\sin(\sqrt{\lambda_0}t+\phi_0)+\frac{\theta_0}{\lambda_0}-\frac{\beta_0}{k^2+\lambda_0}e^{-kt}. \tag{18}$$

The part of (18) $A\sin(\sqrt{\lambda_0}t+\phi_0)$ describes a simple harmonic motion that does not define the limits of change of rotation angle $\phi_{\partial зн}$. Given the initial conditions and the mechanical content of the processes taking place, we take $A=0$. As a result, the dependence for determining the angle of rotation of the input rotary link $\phi$ of the clamping mechanism on-time *t* has the form:

$$\phi=\frac{\theta_0}{\lambda_0}-\frac{\beta_0}{k^2+\lambda_0}e^{-kt}. \tag{19}$$

The beginning of tension creation starts after the completion of backlashes elimination and proceeds until the moment of achievement of the maximum set magnitude of the clamping force $T_{\max}$.

## 5 Discussion

The change of the generalized coordinate in the form of the angle of rotation $\phi$ of the input link of the clamping mechanism at the stage of creating tension in time is presented in the graph (Fig. 3). The graph is built under the dependence (19) for the parameters of the mechanism: $h=1.5\cdot10^{-3}m$; $g=9.81\,m/s^2$; $m_\Sigma=3.2\,kg$; $f_m=0.3$; $z=3$; $\alpha=15°$; $tg\phi^T=0.15$; $ctg\psi=5$; $c=80\cdot10^6\,N/m$; $T_{\max}=85kN$; $f_ц=0.1$; $M_\partial=7Nm$; $J_П=0{,}02kg\cdot m^2$. Values of the factors $\lambda_0$ $\theta_0$ and $\beta_0$ are determined by the mass-geometrical characteristics of the parts of the mechanism and its specified force parameters.

As shown in the graph (Fig. 3), the movement of the machine elements during clamping takes most of the time at the final stage, while at the beginning of the clamping force creation, rotation of the input link of the clamping mechanism is much faster. Therefore, to reduce the clamping duration, it is advisable to reduce the duration of tension creation. According to the obtained dependence (19), it is possible to assess the mass-geometrical characteristics of the parts of the clamping mechanism to reduce the duration of the process of creating tension in the clamping mechanism for reliable fixation of workpieces or tools.

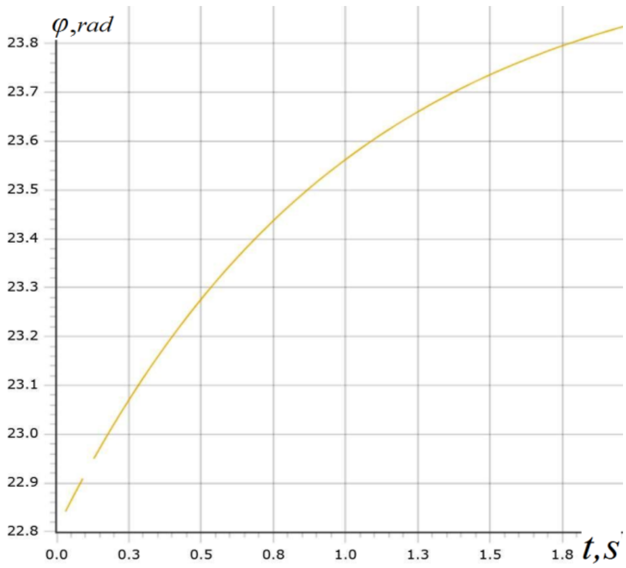


Figure 3 – The change of generalized coordinate at the stage of creating tension in the clamping mechanism

## 6 Conclusions

The research is part of a theoretical study of the automatic clamping mechanisms with the self-brake transmission for spindle units of metalworking machines. The dependence obtained due to the research describes the relationship of the generalized coordinate in the form of the angle $\phi$ of rotation of the input link and time *t* at the stage of increasing the clamping forces and creating tension. This mathematical dependence takes into account the specified values of the coefficients $\lambda_0$, $\theta_0$ and $\beta_0$. The values of the coefficients are determined by the magnitudes of the geometric-mass parameters of the elements of the clamping mechanism under the obtained mathematical dependences.

The obtained dependence provides additional opportunities to assess the impact of the design characteristics of the clamping mechanisms of this type on the characteristics of their work conditions. The result of the research can be used to identify more appropriate characteristics of the mechanism's design to obtain the specified performance characteristics. It is also a prerequisite for the creation of design optimizing methodology.

## 7 Acknowledgments

The work has been accomplished under the research activity of Borys Prydalnyi at the Faculty of Mechanical Engineering, the Bialystok University of Technology, Poland, in the frame of the PROM Project: "International Scholarship Exchange of PhD Candidates and Academic Staff" within the Operational Programme Knowledge Education Development, co-financed from the European Social Fund.

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