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Theoretical Aspects of Automated Assembly of Cylindrical and Threaded Joints Using the Pneumowhirl Method

Stefan Buchvarov, Luben Klochkov, Todor Neshkov

Technical University – Sofia

Part I. Pneumowhirl Method for Automated Assembly and Dynamic Interaction of Elements in the Mounting Head

1. Introduction

The automation of the manufacturing is strategic direction needed for achieving high efficiency: rapid growth of production and quality, low cost, rational use of the resources and market competitive power [1, 2]. Unlike the automation of machining, die-forging, casting and other discrete processes in the mechanical engineering, the automation of the assembly processes is developing slower. It is so, because of the theoretical and technological base of these processes, the theory of cutting, the theory of plastic deformation, the technology of machining and other are developed to adequate level to be created the corresponding automating machinery. Now a day the assembly processes are done by hand and there is not a complete theory about them. Mainly they are studied in terms of standardization, while one of the first tasks is to investigate the relative space-time motion of the parts that will be assembled, their compatibility, statistic and dynamic errors in the reciprocity of their positioning and others. This will allow the required conditions for functioning to be formulated, so the assembly will become theoretically and practically possible.

Most of the published researches are devoted to the technology of construction in aspect of the assembly parts' [3, 4, 5] suitability, geometry and kinematics of the relative orientation and motion. At first the method of total interchange is used, and then the method of "floating" adjustment of the assembly parts is introduced. The first method needs enough guarantee windage, which provides the required precision of coincidence of axes of the assembly parts (in most cases they have cylindrical shape) and the corresponding linear and angular movements which close the marked out chains of the product after the assembly [6, 7]. The automated assembly using this technique could be defined as hard assembly. In the second method are used special devices called adaptors or mounting heads. Their principle of work is based on the elastic deformation of the parts and the "automated searching" of the assembly parts according one to the other [8, 9]. One of the parts is fitted steady and the other, called orientated or self-centered, is situated in the mounting head (adaptor) and get "searching" motion with complex trajectory until it fits to the first part. To obtain the so called "searching" motion the mounting head do vibrated movements which could be realized in different ways: through cammed or link motion mechanism, electromagnetic or supersonic vibrator, using an aerodynamic effects, etc. [10, 11].

Most of the famous works are dedicated to the simply geometrical aspects of ensuring the accuracy of the orientating and compatibility of details in the assembly, without concerning the role of mounting **executable** mechanisms (mounting heads, regional positioning motions concerning the process, etc.) or using of their operated surfaces. In most cases, the usage of mechanical, electromechanical, vibrating and other assembly devices for automated orientation of parts and also for threaded joints, does not ensure the all six degrees of freedom. Often is admissible magnetization and accelerated rate of wear of the friction of parts' surfaces, their electromagnetic induction and sometimes there is a need of more powerful source of supply, etc.

2. Pneumowhirl method

The aspiration for greater operation, technical and economic efficiency and quality of assembly process led to searching and using of principle new methods and techniques for automating of the discrete manufacturing. One of these methods is the pneumowhirl method which is based on the pneumowhirl effect by Ranque [12] and Hilsch [13]. They invented the so called pneumowhirl tube, through which an air stream is provided under pressure in circular whirl motion, under the influence of centrifugal field of force. This effect is characterized with constant temperature of the incoming air stream in the pneumowhirl tube and it is released in the atmosphere with changed temperature, lower in the main layer and higher in the peripheral layer. So, it is considered, the air stream in the pneumowhirl tube reaches sonic and supersonic speed.

The pneumowhirl tube and the caused effect in it have found various and widely spread applications. Different technical means for heating and cooling of fluids and gases are based on them. These technical means are used to be reached suspensions and emulsions for surface cleaning, dispersing of lubricant materials, measuring and controlling the temperature and moisture, etc. [4, 15, 16].

For a first time the pneumowhirl effect is used for relative orientation and assembling parts from type: shaft-sleeve and screw-nut by Levchuk [17, 18]. The part that must be orientated is placed directly in the pneumowhirl head and its motion is accomplished by the pneumowhirl air stream. The influence of the geometric parameters (dimensions, eccentricity of the relative position, etc.) and the mass of the assembling part upon its motion in the presence or absence of a contact with the main (basic) part have been examined. The occurred vibrations in horizontal or vertical direction were experimentally studied establishing their amplitudes and frequencies so as the time needed to joint the parts. The referred time turns out to be very short (0.5–1 s), which confirms the quick-action and efficiency of this assembling method.

Later Ganovski, Klochkov and Levchuk examined some new possibilities for application of the pneumowhirl methods for automated assembling, suggesting the use of intermediate sleeve in the pneumowhirl head [2, 19]. The part that has to be orientated is put in the intermediate sleeve, the air stream flows in the space between the pneumowhirl tube and the sleeve's outer wall. The principle scheme of the pneumowhirl head is shown in Fig. 1.

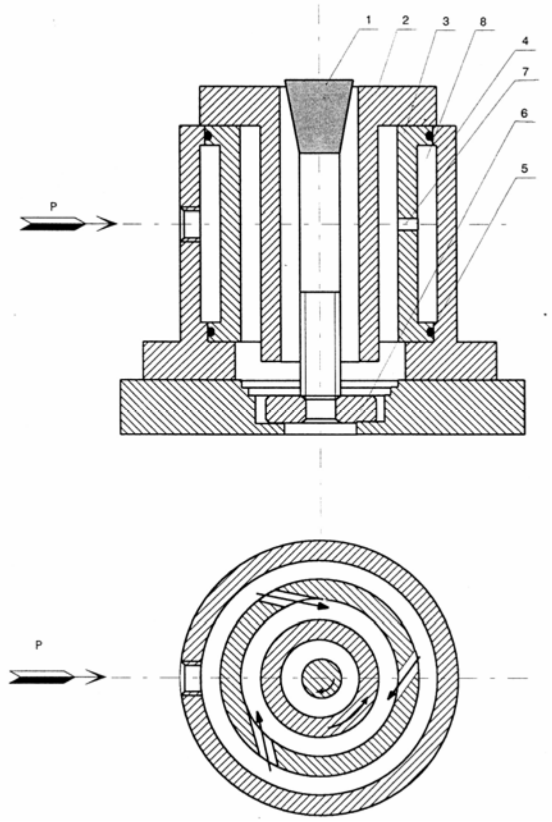


Fig. 1. Basic scheme of the mounting device

It is compound of: assemble part 1(cylindrical body, screw), intermediate sleeve 2, whirl tube 3, mounted through "O" rings 5 in the mounting head 4, assembling part 6 (whole, nut), three tangentially situated nozzles 7 and expanding chamber 8. It is assumed the axes of a part (trunk) – intermediate sleeve – whirl tube – assembling part (nut) practically coincide and they are situated in the centre. When the air stream flows in defined direction of rotating, the intermediate sleeve rotates in the opposite direction and the assembled part (screw) takes the rotating direction of the air stream. After short “search” the part gets into the whole and the assembly is done. The practical researches of the automated mounting of screw joints using such a pneumowhirl head proves the efficiency of the method.

In technical literature is not mentioned the theoretical research of behavior and interaction between parts (pneumatic stream – intermediate sleeve – assembly part) in the pneumowhirl head during the assembly process. The pneumowhirl head, as a subject in dynamic processes, character of motion, factors which influence the work process and possibilities of optimal constructive-technological parameters, is not so well examined.

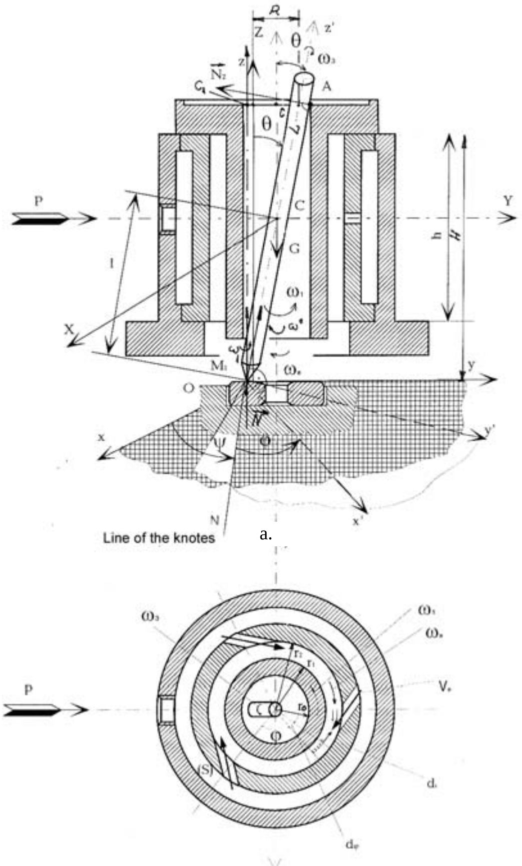
The purpose of this article is to provide a theoretically-analytical research on motion of the elements (part, intermediate sleeve) in the pneumowhirl head during the assembly process. The taken results are based on the dynamic motions and can be considered that in most cases reliably describe the characteristic of the dynamic processes in the pneumowhirl mounting head. They are experimentally proved through filming the motions and is confirmed the practical application of the pneumowhirl method for automating of assembly processes.

3. Angular velocities of rotation in the intermediate sleeve and the part till the moment of separation

In the beginning it is assumed the part is put in the pneumowhirl head and lay on point *O* in the support plane of the assembling part (nut) and the edge point *A* of the intermediate sleeve. With an approximation *the friction in the support plane can be neglected* (point *O*), *and in point A assume there is no sliding between the part and sleeve*. The pressured air is vented in the expanding chamber and from there through the three tangentionally situated nozzles break in the space between the whirl tube and the intermediate sleeve. It obtains a clockwise direction of rotation, assumed from above, with a given angular velocity ω (Fig. 2).

Choosing a fixed coordinate system *Oxyz*, with a beginning in the support point and axis *Oz*, pointed upward (Fig. 2). We fixed a *relative coordinate system Ox'y'z'* to the part with a beginning point *O* and axis *Oz'*, orientated upward according to the axis of the assembly part (Fig. 2). The other two axes *Ox'* and *Oy'* are perpendicular to *Oz’* and rotate along with the part, as the cross line of the plane *Ox'y'* with the static plane is the line of the nodes *ON*. This line is always perpendicular to the plane, defined by the axes *Oz* and *Oz'*, always containing the contact point *A* which is between the part and the intermediate sleeve. The position of this coordinate system and also of the assembly part is determined by the three Euler angles ψ, θ and φ. The angle of precession ψ takes measures from the static axes *Ox* to the line of nodes *ON*. The angle of nutation θ defined by the vertical axes *Oz* and axes of the part *Oz'*. The angle of self rotation φ is measured from the line *ON* to the axes *Ox'*.

The main dynamic task is: *examining the motion of the assembly part, assuming that the initial (support) point O remains fixed and taking into account* *the exerted on it force of weight* $\vec{G}$*, support reaction* $\vec{N}_1$ *in the initial point O, pointed vertically, and the support reaction* $\vec{N}_2$ *in the edge point A, acting normally on the axes of the part.*



a.

b.

Fig. 2. Beginning of part’s motion in the moment of separation from the intermediate sleeve

Due to the interaction of the part with the intermediate sleeve and flowing stream corresponding to the sleeve, the motion of the system *air stream–intermediate sleeve–part* is quite difficult and reciprocally connected. Therefore the main task mentioned above will be separated into several subtasks. *The first subtask is: with a given angular velocity* ω_0 *of the air stream in the whirl tube, the magnitudes and the directions of the angular velocities* $\vec{\omega}_1$ *and* $\vec{\omega}_3$ *of the intermediate sleeve and the part, around its axes, must be defined.*

To solve this sub problem, we apply the theorem for change of the kinetic moment due to the fixed vertical axis *Oz*, according to the observed system.

(3.1) $$\frac{dK_z}{dt} = M_z^{(e)}.$$

Here the external forces' main moment according to the axes *Oz* is equal to zero, that means $M_z^{(e)} = 0$, because of the external forces of the system are the bodies' weight part–intermediate sleeve–air stream and vertical reaction $\vec{N}_1$ in point *O*. Each of these forces has a moment according to the axes *Oz* equal to zero because it is parallel to this axis. Thus the law of preservation of kinetic moment is used and we observe the following equation

(3.2) $$K_z = K_z^b + K_{z1} + K_{z2} = C,$$

where *C* is an integrated constant. Here K_z^b, K_{z1} and K_{z2} are the kinetic moments of the air stream, the intermediate sleeve and the assembly part (screw, trunk), respectively according to axis *Oz*.

If we assume that in the initial moment the system is in state of rest, then C=0 and equation (3.2) becomes

(3.3) $$K_z^b + K_{z1} + K_{z2} = 0.$$

The separate parameters in the equality are calculated. For the *kinetic moment of the air stream* we have

(3.4) $$K_z^b = -\int_{(v)} [\vec{r} \times \vec{v}\,]dm = -\int_{(v)} rv dm\,,$$

where $\vec{r}$ is the radius-vector of an elementary air particle in the windage between the whirl tube and the intermediate sleeve, $\vec{v}$ is the velocity and *dm* is the elementary mass. It is reported that the rotation of the air stream is in a clockwise direction according to +*Oz* (therefore K_z is with negative sign), and the integrating area is the volume *V* of the space (windage) between the whirl tube and the intermediate sleeve, encompassed between the circles with radiuses r_1 and r_2.

Taking into account that

(3.5) $$v = r.\omega,\ dm = \rho dV = \rho hdS = \rho hrd\varphi dr,$$

where ρ is the density of the pressured air, *h* is the height of the whirl tube and $dS = rdrd\varphi$ is the elementary surface of the circular ring with radiuses r_1 and r_2, for the kinetic moment K_z^b (3.4) we obtain

(3.6) $$K_z^b = -\rho h\omega \int_{r_2}^{r_1} r^3 dr \int_0^{2\pi} d\varphi = -\frac{1}{4}\rho h\omega_0 2\pi(r_2^4 - r_1^4) = -\frac{1}{2}M\omega_0(r_1^2 + r_2^2).$$

Here ρ, *h* and ω are constants, and

(3.7) $$M = \pi(r_2^2 - r_1^2)h\rho.$$

is the mass of the whole aerodynamic stream in the windage.

For the *kinetic moment of the intermediate sleeve* we have

(3.8) $$K_{z1} = J_{z1}\omega_1.$$

Here

$$J_{z1} = \frac{1}{2}m_1(r_0^2 + r_1^2)$$

is the axial inertia moment according to *Oz* of the intermediate sleeve with external radius r_1, internal radius r_0, mass m_1, and $\vec{\omega}_1$ is the angular velocity. It is assumed the direction of rotation is counter clockwise according to +*Oz* (i.e. opposite to the air stream) and that is why K_z is with positive sign.

To find the kinetic moment K_{z2} of the part according to vertical axis *Oz*, we determine its angular velocity $\vec{\omega}_3$ according to *Oz'*. To achieve this we accept that in the contact point *A* which is between the part and the intermediate sleeve there is no slip. Then if first we consider it as a point of the sleeve, and second as a point of the part, we can write.

(3.9) $$\vec{v} = \vec{\omega}_1 \times \overrightarrow{CA} = \vec{v}_L + \overrightarrow{\omega_3} \times \overrightarrow{LA}.$$

Here points *C* and *L* (from the axis of the part) are shown in Fig. 2 and they lay in the upper plane of the sleeve. As vectors, each vector addends in this equality, according to the taken directions of rotation, are directed perpendicularly on the drawing, from us towards it. It is equivalent to the scalar equation:

$$\omega_1\ r_0 = \omega_1 R + \omega_3 . LA . \sin(90° - \theta)$$

or

(3.10) $$\omega_1\ r_0 = \omega_1 R + \omega_3 \frac{a}{\cos\theta}\ \cos\theta,$$

from where we find

(3.11) $$\omega_3 = \omega_1 \frac{r_0 - R}{a}.$$

Here a is the radius of the part (screw), and $R = CA$. At $r_0 > R$ the angular velocity $\vec{\omega}_3$ has the assumed in the beginning direction. If $r_0 - R \approx a$, then $\omega_3 \approx \omega_1$. Because the initial support point O is aside from the center of the assembly part, the distance $CL=R$, and the angle θ are changing through a full turn(cycle).This leads to some changes of the angular velocity ω_3 in a small tolerance, i.e. they are significantly small compared to the angular velocity ω_1. Due to this with a relative approximation we assume that angle θ remains almost constant ($\dot{\theta} \approx 0$). This means that the part performs *permanent procession*, during which *the part rotates with constant angular velocity* ω_3 *around its axis Oz' and this axis rotates around axis Oz with constant angular velocity* ω_1,*describing an approximate cone surface with an angle at the top* 2θ.

The projections of the angular velocity vector $\overrightarrow{\omega} = \overrightarrow{\omega_1} + \overrightarrow{\omega_3}$ of the part on the relative axes are

(3.12) $$\omega_{x'} = \omega_1\ \sin\theta . \sin\varphi,\ \omega_{y'} = \omega_1 \sin\theta . \cos\varphi,\ \omega_{z'} = \omega_3 + \omega_1 \cos\theta.$$

Taking into account that the relative coordinate axes *Ox'*, *Oy'* and *Oz'* are main inertia axes for the part, its kinetic moment with respect to *Oz* we present as follows:

$$K_{z2} = \vec{K}_{O2} . \vec{k} = \left(K_{x'} \vec{i}\,' + K_{y'} \vec{j}\,' + K_{z'} \vec{k}\,' \right) . \vec{k} = K_{x'}\, a_{31} + K_{y'}\, a_{32} + K_{z'}\, a_{33}.$$

Here

$$\begin{aligned} a_{31} &= \vec{i}'.\vec{k} = \sin\theta.\sin\varphi, \\ a_{32} &= \vec{j}'.\vec{k} = \sin\theta.\cos\varphi, \qquad (3.13) \\ a_{33} &= \vec{k}'.\vec{k} = \cos\theta, \end{aligned}$$

are pointed the cosines of the relative axes *Ox'*, *Oy'* and *Oz'* in respect to the fixed axis *Oz*. For the projections of $\vec{K}_{O2}$ according to *Ox'y'z'* we observe

$$\begin{aligned} K_{x'} &= J_{x'}.\omega_{x'} = J_{x'}\ \omega_1.\sin\theta.\sin\varphi, \\ K_{y'} &= J_{y'}.\omega_{y'} = J_{y'}\ \omega_1.\sin\theta.\cos\varphi, \qquad (3.14) \\ K_{z'} &= J_{z'}.\omega_{z'} = J_{z'}\ (\omega_3 + \omega_1.\cos\theta), \end{aligned}$$

where we take (3.12). Here $J_{x'} = J_{y'}$ and if the part are cylindrical with a small radius a and length l_1 we have $J_{x'} = J_{y'} = \frac{1}{3} m_2 l_1^2$, and for $J_{z'}$ – $J_{z'} = \frac{1}{2} m_2 a_1^2$, where m is its mass.

Taking into account (3.11), (3.13) and (3.14), the expression for K_z becomes

$$K_z = [\ J_{x'} \sin^2\theta + J_{z'}(\cos^2\theta + \frac{r_0 - R}{a}\cos\theta)]\,\omega_1\,. \qquad (3.15)$$

We will point out that at relatively small complexities of θ (up to 10°-15°), the first addend in (3.15) can be neglected.

We replace (3.6), (3.8) and (3.15) in (3.3) and we have

$$-\frac{1}{2} M\omega_0(r_1^2 + r_2^2) + J_{z1}\,\omega_1 + [J_{x'} \sin^2\theta + J_{z'}\,(\cos^2\theta + \frac{r_0 - R}{a}\cos\theta)]\omega_1 = 0. \qquad (3.16)$$

from here we find

$$\omega_1 = \frac{1}{2}\,\frac{M(r_1^2 + r_2^2)\omega_0}{J_{z1} + J_{x'}\sin^2\theta + J_{z'}(\cos^2\theta + \frac{r_0 - R}{a}\cos\theta)}\,, \qquad (3.17)$$

and from (3.11) for ω_3 we obtain

$$\omega_3 = \frac{1}{2}\,\frac{M(r_1^2 + r_2^2)\frac{r_0 - R}{a}\omega_0}{J_{z1} + J_{x'}\sin^2\theta + J_{z'}(\cos^2\theta + \frac{r_0 - R}{a}\cos\theta)}\,. \qquad (3.18)$$

The obtained expressions *give the magnitudes of the angular velocities of the intermediate sleeve around the vertical axis and of the part around its own axis, respectively.* The positive signs show that *the applied directions of rotation* in the beginning *are correct. The intermediate sleeve rotates opposite to the air stream and the part roll around the intermediate sleeve in the direction of rotation of the air stream.*

4. Separation of the assembly part from the intermediate sleeve

The second subtask states: at what angular velocity of the air stream in the whirl tube the part will separate from the edge of the intermediate sleeve? When the part, lay on the initial support point, roll around the intermediate sleeve without slip to the edge at point *A*, it perform in first approximation one regular (constant) precession. Then the gyroscopic moment of its inertia forces is given [22] with the expression

$$\text{(4.1)} \qquad \vec{L} = J_{z'}\overrightarrow{\omega_3} \times \overrightarrow{\omega_1}\left(1+\frac{J_{z'}-J_{x'}}{J_{z'}}\frac{\omega_1}{\omega_3}\cos\theta\right).$$

As a vector this moment of the inertia forces is directed to the line of the nodes *ON* and has magnitude

$$\text{(4.2)} \qquad L = J_{z'}\,\omega_3\,\omega_1.\sin\theta\left(1+\frac{J_{z'}-J_{x'}}{J_{z'}}\frac{\omega_1}{\omega_3}\cos\theta\right).$$

Here $J_{z'}$ is the inertia moment of the part with respect to its own axis and $J_{x'} = J_{y'}$ are its inertia moments according to the transverse axes of the part through point *O*.

The basic kineto-statical equation describing the motion of the part is

$$\text{(4.3)} \qquad \vec{M}_0^{(e)} + \vec{L} = 0,$$

where $\vec{M}_0^{(e)}$ is the main moment of the external forces, applied on it in respect to the support point *O*. These external forces are: own weight $\vec{G}$, reaction $\vec{N}_1$ in the support point *O* and reaction $\vec{N}_2$ in the edge point *A*. The moment of reaction $\vec{N}_1$ is equal to zero and for the other two moments we have

$$\text{(4.4)} \qquad \vec{M}_0^{(e)}(\vec{G}) = \overrightarrow{OC} \times \vec{G},\ \vec{M}_0^{(e)}.(\vec{G}) = -\,G\,l\sin\theta,$$

$$\vec{M}_0^{(e)}(\vec{N}_2) = \overrightarrow{OA} \times \vec{N}_2,\ \vec{M}_0^{(e)}.(\vec{N}_2) = N_2 L,$$

where $OC = l$ and $OA = L$. As vectors these moments are pointed opposite to each other also on the line of the nodes *ON* . Taking into account that

$$\vec{M}_0^{(e)} = \vec{M}_0^{(e)}(\vec{G}) + \vec{M}_0^{(e)}(\vec{N}_2),$$

after replacement in (4.3) and projection on axis *ON*, we obtain

$$-\,Gl\sin\theta + N_2 L + J_{z'}\omega_3\,\omega_1\sin\theta\left(1 + \frac{J_{z'}-J_{x'}}{J_{z'}}\frac{\omega_1}{\omega_3}\cos\theta\right).$$

From here we find for N_2

$$\text{(4.5)} \qquad N_2 = \frac{1}{L}\left[Gl\sin\theta - J_{z'}\,\omega_3\,\omega_1\sin\theta\left(1 + \frac{J_{z'}-J_{x'}}{J_{z'}}\frac{\omega_1}{\omega_3}\cos\theta\right)\right).$$

Because *the connection in the edge point is one-sided, when* $N_2 \le 0$, i.e. when

$$\text{(4.6)} \qquad Gl\sin\theta - J_{z'}\,\omega_3\,\omega_1\sin\theta\left(1 + \frac{J_{z'}-J_{x'}}{J_{z'}}\frac{\omega_1}{\omega_3}\cos\theta\right) \le 0,$$

The connection is broken and the part is separated from the intermediate sleeve as it starts to set up straight. From here if we divide with $\sin\theta \neq 0$ and take in mind (3.11), we have

$$\omega_1 \geq \sqrt{\frac{Gla}{(r_0-R)[J_{z'}+(J_{z'}-J_{x'})\frac{a}{r_0-R}\cos\theta]}}, \tag{4.7}$$

i.e. the separation from the edge point A will occur at angular velocities of the intermediate sleeve which satisfies this inequality. Taking into account (3.17), we find the angular velocity of the air stream due to which this separation of the part will happen

$$\omega_0 \geq \frac{2[J_{Z1}+J_{X'}\sin^2\theta+J_{Z'}(\cos^2\theta+\frac{r_0-R}{a}\cos\theta)]}{M(r_1^2+r_2^2)} \times \tag{4.8}$$

$$\times\sqrt{\frac{Gla}{(r_0-R)[J_{z'}+(J_{z'}-J_{x'})\frac{a}{r_0-R}\cos\theta]}}.$$

After the separation from the edge point a new level of motion of the part occurs.

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Теоретические аспекты автоматизированной сборки цилиндрических и резбовых соединений пневмовихровым методом (Часть I)

Стефан Бъчваров, Любен Клочков, Тодор Нешков

Технический университет, София

(Резюме)

В работе рассматривается одно из предложенных Д. Левчуком приложение метода Ранка–Хила для автоматизированной сборки цилиндрических и резбовых соединений. Разработана пневмовихровая сборочная головка с междинной втулкой. Проведени соответствующие исследования.