TEKA Kom. Mot. Energ. Roln. – OL PAN, 2009, 9, 172–180

MULTIPARAMETER SYNTHESIS OF NON-CONTACT MACHINE DRIVE

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Summary: A multiparameter dynamic model of non-contact drive was suggested. Analysis of dynamic system of non-contact drive was implemented and evaluation of influence of geometric, force, kinematical parameters on movement mode of asymptotically stable rotary movement of a ring working body (RWB) was performed. Recommendations on efficient choice of non-contact drive for machines of different purpose were made.

Key words: drive system, non-contact drive, parameters.

PREFACE

Creating high-speed and efficient machines of different purpose requires modeling and analysis of dynamic systems, search for algorithms aimed at realization of their structure synthesis as well as developing design procedures and efficiency evaluation concerning synthesis of drives and choosing rational design solutions.

Non-contact drive of working body allows to solve problems such as mechanical contact of moving parts, ratcheting and vibrations, considerable deterioration of contacting surfaces, heating and unproductive capacity loss. However, non-contact drive can only be implemented into machines provided that necessary kinematical and dynamic parameters of movement of ring working bodies (RWB) are ensured – rotation frequency (speed), precise space position of the center of mass, rigidity of non-contact RWB support and sufficient value of rotational moment. A more difficult problem is to maintain invariability or stability of these parameters during effective work as well as their efficient control.

The multiparameter model of non-contact drive containing analytical expressions for the basic unbalance couple and for the resultant vector of motive forces which define dynamics and kinematics of the drive is considered in the paper. The influence of parameters of the model on the mode of asymptotically stable rotary movement of RWB is analyzed, and the recommendations concerning parametric synthesis of a non-contact drive for machines of different purpose are made.

MATHEMATICAL MODEL OF DYNAMIC DRIVE SYSTEM

Parametric synthesis of non-contact drive of machine tools implies developing a mathematical model containing the parameters corresponding to conditions and factors which define the mode of asymptotical RWB movement in non-contact drive [Pavel Nosko, Vladimir Breshev, Pavel Fil].

The previous theoretical and experimental research allowed to determine the exact parameters of dynamic model of non-contact drive changing which results in significant (more than 5%) change of the resultant vector and resultant moment of external motive forces. These parameters are: inner and outer radius of RWB ring, ring thickness, angular velocity of RWB and force field rotation, electrical resistance of RWB material and its displacement from equilibrium position, slope angle of elementary motive forces, characteristic value of force field – module of magnetic induction vector.

Motive forces involved in the dynamic mode are of electrodynamic origin emerge straight on RWB and set it in motion. The resultant moment sets the RWB in motion, and the resulting vector constitutes the restoring resilient force (RRF), it is always directed against RWB displacement and increases together with it. When the RWB is displaced in any direction, the resultant vector like a spring returns the RWB to starting position. Thus the stable plane-parallel RWB motion for idling drive or technologically loaded drive is maintained [Breshev B.E.].

The problem of choosing the values of nine above-mentioned parameters is multivariant and theoretically has an infinite set of solutions. In this case we suggest to determine and justify the ranges and the size of changing for parameters of mathematical model for each type of machines with non-contact drive (actually they mean the RWB parameters if we regard non-contact drive as a dynamic system) according to known technical characteristics of similar machines.

Below are the detailed expressions from the mathematical model concerning the rotational moment $\boldsymbol{M}_{o\tau}$, and the resultant vector – the restoring resilient force (RRF) $\boldsymbol{F}_r$:

$$M_{o\tau} = \frac{\omega_c - \omega_p}{4\rho_{y\partial}} \delta \left[\frac{\pi}{2} \sin\psi \; B^2 (R_{PH}^4 - R_{PB}^4) + \pi \sin\psi \; B^2 (R_{PH}^2 - R_{PB}^2) \; e^2 \right], \tag{1}$$

$$F_r = \frac{\omega_c - \omega_p}{4\rho_{y\partial}} \delta \; \pi \cos\psi \; B^2 (R_{PH}^2 - R_{PB}^2) \; e, \tag{2}$$

where: $\boldsymbol{\omega}_c$ – angular velocity of force field rotation,

$\boldsymbol{\omega}_p$ – RWB angular velocity,

$\boldsymbol{\rho}_{y\partial}$. – electric resistivity of RWB material,

$\boldsymbol{\Psi}$ – slope angle of elementary motive force regarding radial direction,

$\boldsymbol{B}$ – force filed characteristic (module of magnetic induction vector),

$\boldsymbol{e}$ – RWB displacement from the initial equilibrium position,

$\boldsymbol{\delta}$ – thickness of RWB ring,

$\boldsymbol{R}_{PH}$ – outer RWB radius,

$\boldsymbol{R}_{PB}$ – inner RWB radius.

The above-mentioned parameters are divided into several groups for the benefit of the following analysis:

- geometrical parameters: $\boldsymbol{R}_{PH},$ $\boldsymbol{R}_{PB}$ и $\boldsymbol{\delta}$;
- parameter of RWB position – displacement $\boldsymbol{e}$, which corresponds to the undisturbed rotation in the equilibrium position (when the RWB center of mass coincides with the axis of symmetry of working space and field of motive forces);
- parameters of force interaction: characteristic $\boldsymbol{B}$ and angle $\boldsymbol{\Psi}$;
- parameters of motion: $\boldsymbol{\omega}_p$ и $\boldsymbol{\omega}_c$;

- parameter which characterizes physical property of RWB material – $\boldsymbol{\rho_{yd}}$.

The extent of influence of each parameter on RRF value $\boldsymbol{F_r}$. and $\boldsymbol{M_{o\tau}}$ is determined, the control limits according to application of non-contact drive in machines of various purpose are defined.

Geometrical parameters. Outer $\boldsymbol{R_{PH}}$ and inner $\boldsymbol{R_{PB}}$ RWB radiuses characterize not only the dimensions, moment of inertia, linear velocity of points, but primarily – the values of $\boldsymbol{M_{o\tau}}$, and $\boldsymbol{F_r}$, which set RWB in stable rotary movement in non-contact drive.

In order to explore the relation $\boldsymbol{M_{0\tau}} = f(\boldsymbol{R_{PH}})$ we assign fixed values to all parameters from (1), beside $\boldsymbol{R_{PH}}$. These values comply with experimental ones obtained for working models of dynamic pump and machine for cutting monocrystals with non-contact drive. Changing $\boldsymbol{R_{PH}}$ persistently within the range of 0,16…0,22m, we calculate $\boldsymbol{M_{0\tau}}$ for several values of the second geometrical parameter – $\boldsymbol{R_{PB}}$.

Fixed values of parameters and corresponding dependences $\boldsymbol{M_{0\tau}} = f(\boldsymbol{R_{PH}})$ in accordance with (1) are listed in Table 1.

Table 1. Parameters values and considered dependencies $\boldsymbol{M_{0\tau}} = f(\boldsymbol{R_{PH}})$

Ψ, grad.	δ, mm	ρ_{yd}, Om m	ω_p, sec^{-1}	ω_c; sec^{-1}	e_x, m	B, Tl.	R_{PB}, m	$M_{0\tau} = f(R_{PH})$
45	0,00075	$1{,}75\cdot10^{-8}$	1320	1500	0,03	0,2	0,09	$M_{0\tau}$ =942,47779 (R_{PH}^4 – –0,00007) + 1,69646 (R_{PH}^2 – –0,00810)
45	0,00075	$1{,}75\cdot10^{-8}$	1320	1500	0,03	0,2	0,11	$M_{0\tau}$ =942,47779 (R_{PH}^4 – 0,00015) + 1,69646 (R_{PH}^2 – –0,01210)
45	0,00075	$1{,}75\cdot10^{-8}$	1320	1500	0,03	0,2	0,13	$M_{0\tau}$ =942,47779 (R_{PH}^4 – –0,00028) + 1,69646 (R_{PH}^2 – – 0,01690)
45	0,00075	$1{,}75\cdot10^{-8}$	1320	1500	0,03	0,2	0,15	$M_{0\tau}$ =942,47779 (R_{PH}^4 – –0,00051) + 1,69646 (R_{PH}^2 – –0,02250)

The obtained relations $\boldsymbol{M_{0\tau}} = f(\boldsymbol{R_{PH}})$ for RWB with different $\boldsymbol{R_{PB}}$ are graphically shown in Fig.1. Equal step of increment is chosen for $\boldsymbol{R_{PB}}$.

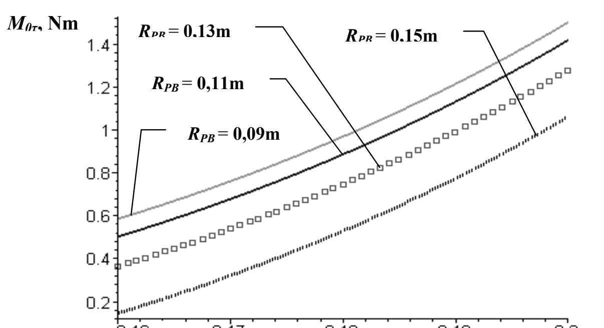

Fig. 1. Dependence $\boldsymbol{M_{0\tau}} = f(\boldsymbol{R_{PH}})$ for RWB with different $\boldsymbol{R_{PB}}$

Analytical expression (2) for $\boldsymbol{F_r}$ include parameters, similar to $\boldsymbol{M_{0\tau}}$ expression, since the origin of rotational moment and RRF is the same. Dependence $\boldsymbol{F_r} = f(\boldsymbol{R_{PH}})$ is studied in the same manner as $\boldsymbol{M_{0\tau}} = f(\boldsymbol{R_{PH}})$. Fig. 2 shows the results of calculation of the dependence $\boldsymbol{F_r}$=$f(\boldsymbol{R_{PH}})$ according to (2).

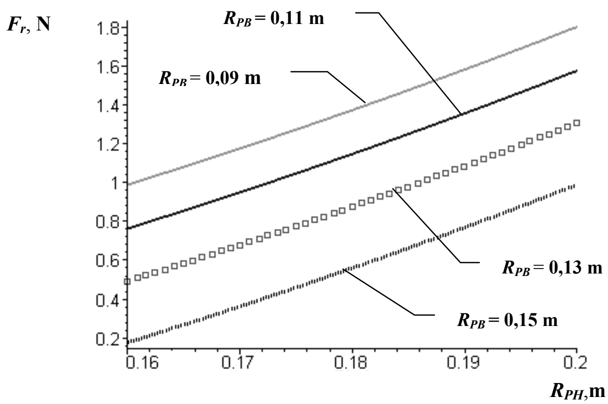

Fig. 2. Dependence $\boldsymbol{F_r} = f(\boldsymbol{R_{PH}})$ for RWB with different $\boldsymbol{R_{PB}}$

The analysis of obtained dependences (see Fig.1. и Fig.2.) shows that the increase of $\boldsymbol{R_{PB}}$ leads to decrease of $\boldsymbol{M_{0\tau}}$ и $\boldsymbol{F_r}$ working on RWB; this is related to the reduction of area where potential forces act (and therefore capacity as well). If reduction of RWB ring is necessary due to some technological or other reasons, then in order to retain the values of $\boldsymbol{M_{0\tau}}$ и $\boldsymbol{F_r}$ other parameters should be changed, for example the thickness $\boldsymbol{\delta}$.

Functional relations between $\boldsymbol{F_r}$, $\boldsymbol{M_{0\tau}}$ and RWB thickness $\boldsymbol{\delta}$, are linear, according to (1), (2). In the absence of conditions on $\boldsymbol{\delta}$ (which is true in machines for cutting monocrystals) as well as limitations on RWB mass (strictly limited in gyroscopic mechanisms), changes of $\boldsymbol{\delta}$ allow to control $\boldsymbol{F_r}$ и $\boldsymbol{M_{0\tau}}$ efficiently. In this way the necessary proportion of RWB dimensions ($\boldsymbol{R_{PH}}$ and $\boldsymbol{R_{PB}}$, $\boldsymbol{\delta}$), linear velocity of its points, $\boldsymbol{F_r}$ и $\boldsymbol{M_{0\tau}}$ can be reached. In other words, the stability of RWB movement, acceptable dimensions of non-contact drive and mechanical characteristics are maintained.

RWB position parameter. The parameter of ring working body position in non-contact drive is the displacement $\boldsymbol{e}$ of its centre of mass relative to starting position – central equilibrium position, where $\boldsymbol{F_r}$, according to (1), works for 0, but $\boldsymbol{M_{0\tau}}$ continues to act (2). Rotation in starting position corresponds to the ideal case when all the radial forces are balanced or, in other words, RWB is in an undisturbed movement. In case of real functioning of the machine, perturbations inevitably occur; they result from the irregularity of resistance forces and temperature, lack of manufacture precision, deformations, the irregularity of technical load etc. Thus, the "ideal" central position of RWB can be reached as momentary one with the displacement $\boldsymbol{e} = 0$. Practically, during rotation the RWB centre of mass is situated at some distance from the central position or oscillates around it.

The limits of possible RWB displacement during rotation in a force field are defined theoretically as the difference between inner radius of force field $\boldsymbol{R_{CB}}$ and working body $\boldsymbol{R_{PB}}$, and then are extended on the basis of experimentally based assumptions. For example, for the experimental non-contact drive device maximal calculated displacement equals to 0,01 m, while maximal practical one – 0,03 m (for $\boldsymbol{R_{CB}}$ = 0,1 м and $\boldsymbol{R_{PB}}$ = 0,11 м), because in real conditions the action of force field exceeds the limits of $\boldsymbol{R_{CB}}$ in the dynamic model.

The analysis of dependences $\boldsymbol{F_r}$=$f(\boldsymbol{e})$ и $\boldsymbol{M_{0\tau}}$=$f(\boldsymbol{e})$ was performed in the same way; the influence of geometrical parameters was studied using $\boldsymbol{e}$ as the persistently changing parameter. Dependences $\boldsymbol{M_{0\tau}} = f(\boldsymbol{e})$ и $\boldsymbol{F_r}$=$f(\boldsymbol{e})$ are graphically shown in Fig.3 and Fig.4.

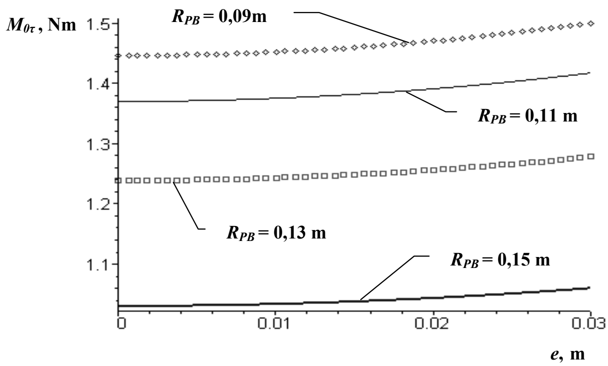

Fig. 3. Dependences $M_{0\tau} = f(e)$ for RWB with different inner radius

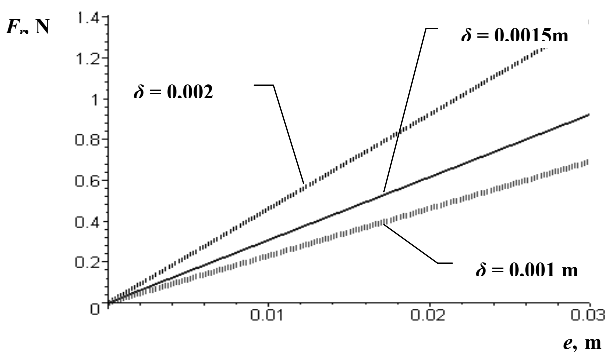

Fig. 4. Dependence $F_r = f(e)$ for RWB of different thickness

For evaluating the influence of geometrical RWB parameters and displacement $\boldsymbol{e}$, the dependence $M_{0\tau} = f(e)$ was calculated for RWB with different R_{PB}, while functional dependence $F_r = f(e)$ – for three RWB with different δ. When $\boldsymbol{e}$ increases, the value of $M_{0\tau}$ slightly increases too – approximately by 2…3%. In respect of efficient work, retaining of $M_{0\tau}$ level is a positive property of non-contact drive, and in respect of stability it is fundamentally important – retaining the value of $M_{0\tau}$ for working body of the machine during displacement maintains the stability of rotational speed and useful power during work. Thus the stability of mechanical characteristic of non-contact drive at acceptable RWB displacement is maintained. Dependences of F_r from $\boldsymbol{e}$ for RWB with different thickness – δ are linear; this is technically convenient for controlling and measuring the RWB reactions.

Parameters of force interaction. Such parameters are the characteristic of force field $\boldsymbol{B}$ (in fact it is the coefficient of proportionality) and angle of slope Ψ of elementary force to radial direction in the point of application.

Studying the relation $M_{0\tau} = f(B)$ we varied the argument of the function in the range (0,1…0,6 Tl) which is acceptable for modern drives. The experimental device had B = 0,16…0,2 Tl. The values that we had fixed were R_{PB} = 0,110 m, R_{PH} = 0,156 m, and the values of others parameters were set according to Table1. Fig. 5 graphically illustrates the dependence $M_{0\tau} = f(B)$.

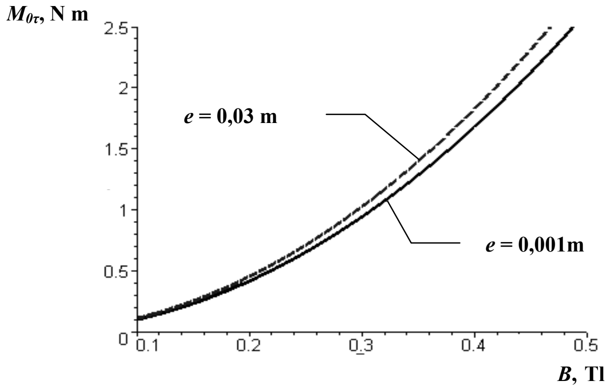

Fig. 5. Dependences $M_{0\tau} = f(B)$ with maximal and minimal e

Dependence F_r=f(B) is of the same kind, since the square factor B is included in (1) and (2). Fig. 5 clearly shows the quadratic nature of the dependence $M_{0\tau} = f(B)$ and slight (0,5…5%) influence of displacement e on $M_{0\tau}$.

The second parameter of force interaction is the slope angle Ψ of elementary motive forces.

Reduction of Ψ, under other stable conditions, results in an increase of RWB stability, namely the increase of RRF. If the load is proportional and symmetric (for example, in dynamic pumps), then there is a chance to increase Ψ, which leads to slight reduction of RRF, but to an increase of $M_{0\tau}$.

Parameters of rotation and RWB material. The dependence of ω_p on $M_{0\tau}$. for RWB with different $\rho_{y\partial}$ is studied. For that the expression in square brackets from formula (1) we denote as A. All variables in A are assigned fixed values: R_{PH}=0,156m; R_{PB}=0,110m; B=0,2Tl; e=0,03m; ω_c=80πc^{-1}; ψ=π/4, δ=0,001m. Then:

$$A = 0,467855696 \cdot 10^{-5} \pi \sqrt{2}.$$

Using A, we transform the expression (1) into ω_p=f ($M_{o\tau}$):

$$\omega_p = \omega_c - \frac{4 \rho_{y\partial} M_{\sigma\tau}}{A\,\delta}. \tag{3}$$

The calculations were performed according to (3) for two RWB made from copper ($\rho_{y\partial}$= 1,75·10^{-8} Om m) and aluminium ($\rho_{y\partial}$=2,9·10^{-8} Om m). At that $M_{o\tau}$ was persistently changed within the range of 0,01 Nm to 1,0 Nm, which correspond with experimentally obtained values $M_{o\tau}$ for thin ring plates. The results of calculations show an influence of $M_{o\tau}$ и $\rho_{y\partial}$ on RWB rotation speed.

For convenience of comparing the results of calculations with experimental results and the following analysis ω_p (sec^{-1}) was converted to rotational speed n (rpm).

The derived dependence n=f ($M_{o\tau}$) for copper and aluminium RWB is graphically shown in Fig. 6.

The results of calculations (Fig.6) and experimental data *[Eroshin, Nevzlin, Breshev]* show that an increase of moment of resistance (it is equal to $M_{o\tau}$ in steady mode) leads to a reduction of RWB rotation speed, which is explicable and is common for the majority of drives.

Copper and aluminium RBW without load have one rotation speed – 2400 rpm (see Fig.6), while a similar load in the form of moment of resistance results in a more significant reduction of n for aluminium RWB.

If technological, structural, strength or other reasons require to use aluminium RWB instead of solid copper, it is necessary to adjust other parameters from (1) and (3) in order to obtain the required relation between $\boldsymbol{n}$ and $\boldsymbol{M}_{o\tau}$ (mechanical characteristic of non-contact drive).

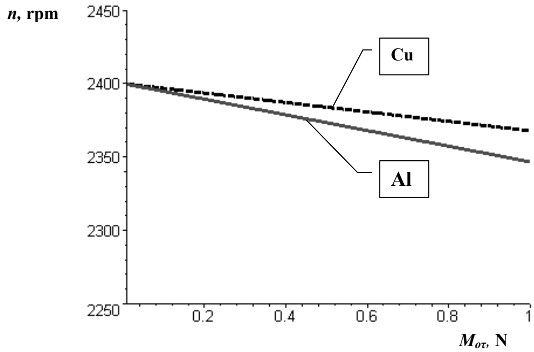

Fig. 6. Dependence $\boldsymbol{n}=f\,(\boldsymbol{M}_{o\tau})$ for copper and aluminium RWB

Use of non-contact RWB drive in machines of different purpose requires maintaining appropriate kinematical and dynamic characteristics of the drive – RWB rotation speeds, acceptable displacements, rotational RWB moments etc.

Table 2 shows the limits of variation for the parameters of non-contact drive discussed above for application in machines of different purpose. They are obtained by comparison of parameters of similar machines, the results of experimental study of non-contact RWB drive and calculations based on the mathematical model (1) and (2).

Table 2. Parameters of non-contact RWB drive for machines of various purpose

Application of non-contact RWB drive	$\boldsymbol{\delta}$, m	$\boldsymbol{\omega_c}$, secc^{-1}	$\boldsymbol{\omega_p}$, sec^{-1}	$\boldsymbol{\rho_{y\partial}}$, Om m	$\boldsymbol{R_{PH}}$, m	$\boldsymbol{R_{PB}}$, m	$\boldsymbol{B}$, Tl	$\boldsymbol{\Psi}$, grad	$\boldsymbol{e}$, m
rotary pumps	0,002-0,008	85-400	78,5-314,2	$0{,}175\cdot10^{-7}$ or $0{,}29\cdot10^{-7}$	0,1-0,6	0,1-0,5	0,1-0,4	55-70	up to 0,0005
peripheral pumps	0,004-0,01	85-200	78,5-157,1	$0{,}175\cdot10^{-7}$ or $0{,}29\cdot10^{-7}$	0,1-0,6	0,1-0,5	0,1-0,4	55-70	up to 0,0005
machines for cutting mono-crystals	0,0003-0,0008	90-800	83,7-628,3	$0{,}175\cdot10^{-7}$	0,150 - 1 and more	0,110 0,75 and more	0,2-0,6	45-55	0,02-0,06
gyroscopic mechanisms	0,002-0,006	350-1350	314,2-2047	$0{,}175\cdot10^{-7}$	0.08-0,2	0,05-0,15	0,4-0,6	50-60	0,0001
Machines for working in isolated capacity	0,002-0,04	35-135	31,4-104,7	$0{,}175\cdot10^{-7}$ or $0{,}29\cdot10^{-7}$	0,1-0,5	0,7-0,35	0,1-0,2	50-60	0,005-0,06

Thus, working wheels of rotary and peripheral pumps typically have the rotation speed from 750 rpm to 3000 rpm, approximately proportional work load on the circumference and surface area of RWB, relatively small (up to 0,0005 m) displacement of the wheel from central position, the material used for construction may be copper or aluminium. The given parameters correspond to existing construction of pumps and can be realized in non-contact drive, which is confirmed by experimental research *[Eroshin, Nevzlin, Breshev]*.

For gyroscopic mechanisms achieving high speed of rotation is fundamental – from 3000 rpm to 20 000 rpm (314,2…2047 sec^{-1}), rotation takes place without technological load with minimal resistance forces because they result in rotor “drift”. The experimental machine with non-contact drive allowed to obtain the frequency of ring rotor more than 4000 rpm without technological load.

In the machines for cutting monocrystals speed of RWB rotation is significantly lower – from 800 to 4000 rpm, but at the same time, RWB is working in displaced position (0,02…0,06m) due to asymmetry of technological load applied along its inner cutting edge in a limited sector – the line of contact with the processed object. Minimal thickness of the instrument (0,0003…0,0008 m) can be reached due to an increase of $\boldsymbol{R}_{PH}$, and reduction of $\boldsymbol{R}_{PB}$, obtaining sufficient $\boldsymbol{F}_r$, $\boldsymbol{M}_{0\tau}$ and high linear speeds in regard to inner cutting edge (40…70 m/s). This allows to choose more optimal cutting modes and to process monocrystal with diameter bigger than 0,3 m, which is essential nowadays. Besides, an increase of dimensions of the cutting instrument results in a better economical efficiency of the non-contact drive, since multiple reduction of machine mass is reached – by 6…10 times, and power consumption is reduced by 1,5…3 times. The working model of the machine with non-contact drive performed test cutting of a monocrystal at the rotation speed 900 rpm и $\boldsymbol{e}$ = 0,025m.

For RWB of separators and impellers $\boldsymbol{e}$ can be different (0,005…0,06 m) – depending on the kind of work load and operational rotation speeds are relatively low: from 300 rpm to 1000 rpm, when $\boldsymbol{\delta}$ may change in a wide range (0,002…0,04m) for maintaining sufficient $\boldsymbol{F}_r$ and $\boldsymbol{M}_{0\tau}$. This allows the rotating RWB to move additionally along the inner surface of the capacity according to the drive movement without mechanical contact with the latter.

CONCLUSION

1. A dynamic system of a non-contact RWB drive was suggested and a corresponding mathematical model allowing to perform multiparameter synthesis of a non-contact RWB drive was elaborated.
2. Functional dependences between geometrical, power and kinematical parameters of the model of non-contact drive were analyzed and their limits of variation in the process of multiparameter synthesis of non-contact drive for machines of different purpose were suggested.
3. The application of non-contact drive allows to significantly reduce mass, dimensions, power consumption and cost price of machines.

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WIELO-PARAMETROWA SYNTEZA BEZKONTAKTOWEGO NAPĘDU DLA MASZYN

Streszczenie. Zaproponowano wieloparametrowy, dynamiczny model bezkontaktowego napędu. Przeprowadzono analizę dynamicznego systemu bezkontaktowego napędu oraz ocenę wpływu parametrów geometrycznych, siły, oraz kinematycznych na asymptotycznie stały ruch obrotowy RWB. Przedstawiono możliwości dobrego wyboru bezkontaktowego napędu dla wieloczynnościowych maszyn.

Słowa kluczowe: system napędu**,** napęd bezkontaktowy, parametry.