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ELECTRODYNAMICS OF HIGH-PRECISION ITERATIVE FEED ELECTRIC DRIVE OF MACHINING CENTER WITH INERTIAL LOAD

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The kinematical diagram and refined mathematical model of steady motion in machining mode of high-precision iterative multichannel differential-geared electric feed drive of machining center with substantially inertial working tool are presented. The structural-algorithmic diagram of a three-channel control system of an electric drive, represented by various options for implementing an iterative algorithm for the interaction of control channels is given. Concretization of computer model is completed to simulation of movements of iterative two- and three-channel electric drive with subordinated adjustment of control channels, destined for displacement of working tool feed mechanism in face milling mode. Comparative assessment in time and frequency areas of quality indicators to improve the feed accuracy using the proposed multichannel electromechanical system is completed. Comparison is made with similar on purpose, but different on speed of operation, modern single-channel gearless feed electric drives, which traditionally used on heavy metal cutting machines and machining centers. It is shown that in compensated two- and three-channel electric drive compared to even broadband single-channel asynchronous feed electric drive with frequency-current vector control a significant increase not only in speed of operation, but also in the dynamic accuracy of feed control practically in the entire range of working tool movements can be achieved. It is determined that iterative three-channel electric drive potentially provides a level of quality control of the working tool, unattainable not only in the corresponding traditional single-channel electric feed drives of various types, but in a similar construction two-channel differential-reducer feed electric drive. References 10, figures 5, table 1.

Key words: iterative multichannel electric drive, differential-geared electric drive, bandwidth, static and dynamic accuracy.

Introduction. Raise static accuracy and, especially, dynamic accuracy of inertia working tools (WT) feed mechanisms (FM) servo electric drives (ED) of heavy cutting machines and machining centers (MC) is one of the important problems facing to designers of program-controlled ED of machining industrial facilities [1, 2]. The multichannel electric drives of FM designed by an iterative [3] or close to it [4-7] principles have considerable potential advantages on dynamic indexes of WT position control quality compared with traditional one-channel feed ED of machines and MC [8].

Formulation of the problem. Iterative multichannel FM ED with summing mechanical differentials (MD) under condition of compensation in such drives of a negative dynamical interference of channels (DIFC) on loading have all properties of iterative high-precision control systems [3]. Thus, in control channels of multichannel feed ED can be applied well completed and unified typical tunings of an electrodynamics, for example, by a principle of subordinated control systems (SCS) [8].

It is established in [8], that speed and accuracy of iterative multichannel feed ED including ED with MD and typical tuning of channels, depend not so much on torque overload capacity, as from bandwidth of the drive of final precise control channel. Comparative raise of speed and efficiency of corresponding multichannel differential FM ED will be various depending on type of a drive power part of precise channel. Additional decrease of control processes regulation time by multimotor inertia FM with MD is possible by including to differential drive mechanism (DM) the readjusted raising gearbox (RRG) and excluding transmission.

It is shown in [9], that compensated multichannel differential-geared feed ED with RRG and SCS-adjustment of channels with reference to feed of heavy cutting machine WT with numeric control (NC) realizes potential advantages of iterative ED on speed and accuracy of control. It is established, that coordinated use of possibilities of RRG and NC system in each calculated zone of machine WT displacements allows adjusting effectively a mode of series-parallel interacting of main and refinement drives of multimotor FM without an essential modification of control channels typical tuning and DM design. It is necessary for providing of as much as possible accessible control quality of multichannel differential-geared feed ED in all range of WT feed. Results of computer simulation presented in [9], have shown, that iterative three-channel

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FM ED with RRG potentially provides control speed operation of machine WT feed, which unattainable not only by traditional one-channel direct-drive feed ED of various types, but also by similar on construction double-channel differential-geared FM ED.

At the same time, problems of potentially accessible raise of inertia WT feed control accuracy by means of iterative multichannel FM ED with RRG and typical tuning of channels demand the further analysis, concretization and a quantitative estimation. Thereby the comparative estimation of control accuracy indexes of such multichannel feed ED with the broadband precise channel and modern one-channel direct-drive FM ED with control system SCS-adjustment and various types of drive power part is of interest: on the basis of DC actuating motors (AM) (PWM-DC motor type) and AC motors (FC-IM type). In this sense, such results are logical prolongation and development of results obtained in [9].

The paper purpose is deriving of the specified mathematical model of three-motor drive (taking into account DIFC on loading) and a comparative estimation of control accuracy raise potential efficiency of compensated iterative two- and three-channel differential-geared FM ED with RRG and typical tuning of control channels with reference to inertia WT feed of NC WorkCentre of «Horizontal machining centre ИР1600ПМФ4» type (machine mass of 85 tons) [10].


Fig. 1

Material of researches. The high precision WorkCentre ИР1600ПМФ4 with a program control contour-positional system and tool automatic change is made with console less twin-spindle machine head which located into a longitudinal-mobile rack, moved on a skid (Fig. 1). Skids, rack and the spindle head have lateral movement on the frame (axis *X*, on distance to S_{WT}=3200 mm).

Proposed iterative multichannel differential-geared feed ED includes for observed WorkCentre (on axis *X*) first channel (main) К-1, second (refinement) К-2 and the third (precise) К-3 angle control channels with corresponding subordinated speed loops which have been adjusted on a symmetric optimum. Variants (*a* and *b*) of the generalized structurally-algorithmic scheme of a three-channel differential-geared FM ED control system with system of differentials MD1-MD2, RRG, the coupling muff CM and the load toque accounting: M_{l1}, M_{l2}, M_{l3}, converted to outputs of corresponded control open loop channels are displayed on Fig. 2. In addition are marked out on figure: $i_{\mathrm{RRG},1+2+3}$ and C_{LS} – RRG reduction ratio and a transfer ratio of ball screw lead screw (LS) ; $R_i^*(p)$ (i=1,2,3) – differential operators of separate drives position open loops taking into account corresponding control and actuating devices; $W_{T_l,i}(p)$ and $E_{\mathrm{c},i}(p)$ (i=1,2,3) – differential operators of speed loops on the loading torque $T_{l,\mathrm{i}}$ and errors of separate drives speed loops; $p=d/dt$ – differentiation operator on time. Both structures (Fig. 2 *a*, *b*) are equivalent from the point of view of properties of observed iterative three-channel system.

It is supposed, that electric drives of main К-1 and refinement К-2 channels of double-channel differential-geared FM ED, included in three-channel WT feed control system, are designed based on typical machine transistor DC ED with power parts of PWM-DC motor type. In this case modern modifications of widely known deeply regulated kit DC ED of Mitsubishi Electric series MR-J2S and MR-J3, for example, model MR-J3-DU37KA can be used. As M1 AM of main drive and M2 of refinement drive of double-channel FM ED with RRG is offered to be used great torque reverse DC motors with permanent magnets of series ПВ type ПФВ160С ($P_{nom,1}$=7,5 kW; $T_{nom,1}$=143,2 Nm) and series ПВ type ПБВ160М ($P_{nom,2}$ = 4 kW) (Ukraine).

Additional third precise channel К-3 in three-channel differential-geared WT feed ED it is offered to design based on an AC-drive. Thus, the servodrive of precise channel К-3 can be realized based on induction motor M3 with the squirrel cage rotor (a slip-ring motor), matching on the torque and power to AM of base ED. For example, ABB corporation IM type M3AA180MLA ($P_{nom,3}$ = 11 kW; $T_{nom,3}$ = 143,7 Nm) or Siemens IM type 1LA5186-8AB ($P_{nom,3}$ = 11 kW; $T_{nom,3}$ = 144,9 Nm) are suitable for WorkCentre ИР1600ПМФ4. For M3 control it is offered to use broadband kit AC ED (FC-IM type) with frequency-current vector control on the basis of a modular frequency converter (FC) corporation Invertek Drives series

Optidrive Plus 3GV models OPD-52220-IN, 200-240 V, 3AC ($P_{nom,\mathrm{FC}} = 22$ kW) or Siemens series Sinamics G120 model Sinamics G120, 380-480 V, 3AC ($P_{nom,\mathrm{FC}} = 30$ kW).

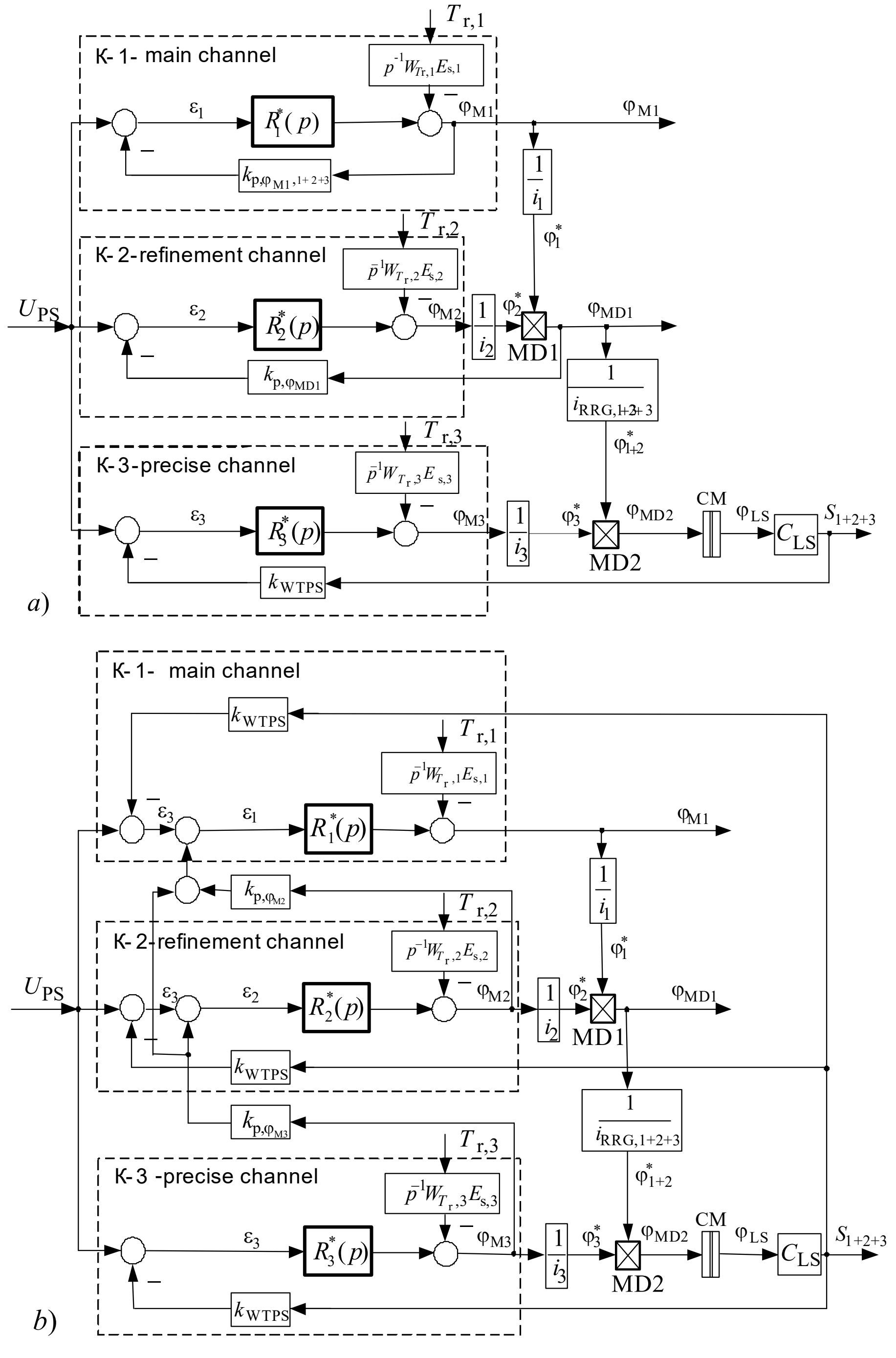

Fig. 2

Comparison is made with analogous to destination typical one-channel (autonomous) direct-drive feed ED of PWM-DC motor and FC-IM type. At simulation of electrodynamics characteristics in one-channel ED as WorkCentre FM drive AM are used accordingly great torque DC motor with permanent magnets ПФВ160S type and IM M3AA180MLA type.

The simplified design scheme of three-motive FM with RRG for three-channel differential-geared WorkCentre WT feed ED is observed in [9]. The matching kinematical scheme of three-channel differential-geared ED with three-motive WT FM (a working rack with a sled) is resulted on Fig. 3 where gear ratios are marked out: i_1=1,9988, i_2=2,0004, i_3=2,924584; i_{MD1}=i_{MD2}=2; $i_{\mathrm{RRG,1}}$=0,125075, $i_{\mathrm{RRG,1+2}}$=0,5, $i_{\mathrm{RRG,1+2+3}}$=1; C_{LS}=3,1831·10^{-3} m/rad. The operating principle of three-motive FM with RRG is easy for understanding from figure taking into account given designations (in corresponding iterative double-channel feed ED with RRG are not used motor M3 and gear ratio $i_{\mathrm{RRG},1+2+3}=1$).

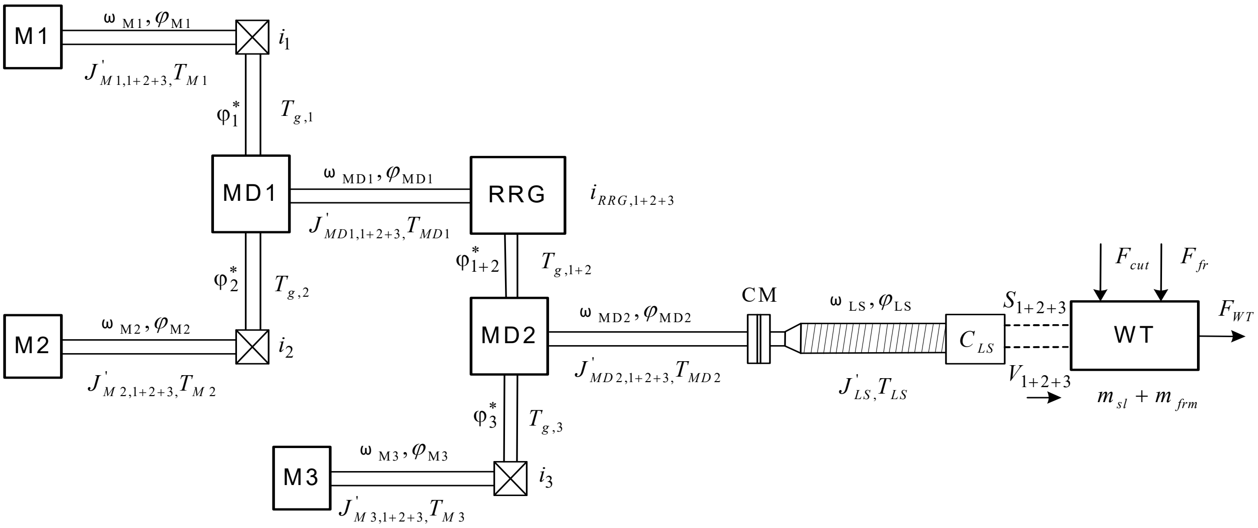

Fig. 3

The specified mathematical model of three-channel FM ED with RRG in steady modes of the metal working (face milling), obtained from Fig. 3 at an assumption of absolute stiffness of mechanical links of a drive kinematic scheme and static character of the reactive load torques on motor shafts, looks like:

$$F_{WT}(t) - m'_{WT,SN} p^2 S_{WT}(t) - F'_{r,WT,SN} = 0\,; \tag{1}$$

$$S_{WT}(t) = S_{1+2+3}(t) = C_{LS}\varphi_{LS}(t) = C_{LS}\varphi_{MD2}(t) = \frac{t_{\text{в}}}{2\pi}\varphi_{MD2}(t)\,; \tag{2}$$

$$\begin{cases} \varphi_{MD2}(t) = \dfrac{\varphi_{1+2}^*(t) + \operatorname{sign}\varphi_3^* \cdot \varphi_3^*(t)}{i_{MD2}} = \dfrac{\varphi_{MD1}(t)}{i_{RRG,1+2+3}\, i_{MD2}} + \operatorname{sign}\varphi_{M3}\dfrac{\varphi_{M3}(t)}{i_3 i_{MD2}} = \\ \qquad = \dfrac{\varphi_{MD1}(t)}{2 i_{RRG,1+2+3}} + \operatorname{sign}\varphi_{M3}\dfrac{\varphi_{M3}(t)}{2 i_3}; \\ \varphi_{MD1}(t) = \dfrac{\varphi_1^*(t) + \operatorname{sign}\varphi_2^* \cdot \varphi_2^*(t)}{i_{MD1}} = \dfrac{\varphi_{M1}(t)}{2 i_1} + \operatorname{sign}\varphi_{M2}\dfrac{\varphi_{M2}(t)}{2 i_2}; \end{cases} \tag{3}$$

$$\begin{cases} T_{M1}(t) - J'_{\Sigma,1} p^2 \varphi_{M1}(t) - \operatorname{sign}\varphi_{M2} \cdot J_{1-2} p^2 \varphi_{M2}(t) - \operatorname{sign}\varphi_{M3}\dfrac{J_{1-3}}{\eta_{s.g}\eta_{MD}} p^2 \varphi_{M3}(t) - T_{r,1} \cong 0; \\ T_{M2}(t) - J_{2-1} p^2 \varphi_{M1}(t) - \widetilde{J}'_{\Sigma,2} p^2 \varphi_{M2}(t) - \operatorname{sign}\varphi_{M3}\dfrac{J_{2-3}}{\eta_{s.g}\eta_{MD}} p^2 \varphi_{M3}(t) - T_{r,2} \cong 0; \\ T_{M3}(t) - J_{3-1} p^2 \varphi_{M1}(t) - \operatorname{sign}\varphi_{M2} \cdot J_{3-2} p^2 \varphi_{M2}(t) - \widetilde{J}'_{\Sigma,3} p^2 \varphi_{M3}(t) - T_{r,3} \cong 0, \end{cases} \tag{4}$$

where

$$F'_{r,WT,SN} \cong C_{LS}^{-1}\eta_{\mathrm{s}} T_{r,1+2+3,MD2} = \frac{2\pi\eta_s T'_{r,1+2+3,MD2}}{t_{\text{в}}}\,; \tag{5}$$

$$T'_{r,1} = \frac{T'_{r,1+2+3,MD2}}{4 i_{RRG,1+2+3}\, i_1 \eta_{s.g}^2 \eta_{MD}^2}; \qquad T'_{r,2} = \frac{T'_{r,1+2+3,MD2}}{4 i_{RRG,1+2+3}\, i_2 \eta_{s.g}^2 \eta_{MD}^2}; \qquad T_{r,3} = \frac{T'_{r,1+2+3,MD2}}{2 i_3 \eta_{s.g}\eta_{MD}};$$

$$T'_{r,1+2+3,MD2} = 0{,}8T'_{r,w,MD2} = \\ = 0{,}8\frac{3t_{\text{в}}\left\{kF_h + \left[\left(m_{sl} + m_{fr}\right)g + F_y\right]f_{rol}\right\} + 2\pi F'_f\left(0{,}032t_{\text{в}} + 2{,}21\cdot 10^{-7}k_{\text{п}}d_{\text{п}}\right)}{6\pi\eta_{\text{в}}}; \tag{6}$$

$$J'_{\Sigma,1} = J'_{M1,1+2+3} + \frac{4J'_{MD1,1+2+3}i^2_{RRG,1+2+3}\eta_{s.g}\eta_{MD} + J'_{MD2,1+2+3}}{16i^2_{RRG,1+2+3}i_1^2\eta^2_{s.g}\eta^2_{MD}};$$

$$\tilde{J}'_{\Sigma,2} = J'_{M2,1+2+3} + \operatorname{sign}\varphi_{\text{M}2}\frac{4J'_{MD1,1+2+3}i^2_{RRG,1+2+3}\eta_{s.g}\eta_{MD} + J'_{MD2,1+2+3}}{16i^2_{RRG,1+2+3}i_2^2\eta^2_{s.g}\eta^2_{MD}};$$

$$\tilde{J}'_{\Sigma,3} = J'_{M3,1+2+3} + \operatorname{sign}\varphi_{\text{M}3}\frac{J'_{MD2,1+2+3}}{4i_3^2\eta_{s.g}\eta_{MD}};$$

$$J_{1-2} = J_{2-1} = \frac{4J'_{MD1,1+2+3}i^2_{RRG,1+2+3}\eta_{s.g}\eta_{MD} + J'_{MD2,1+2+3}}{16i^2_{RRG,1+2+3}i_1i_2\eta^2_{s.g}\eta^2_{MD}};$$

$$J_{1-3} = J_{3-1} = \frac{J'_{MD2,1+2+3}}{8i_{RRG,1+2+3}i_1i_3\eta_{s.g}\eta_{MD}}; \qquad J_{2-3} = J_{3-2} = \frac{J'_{MD2,1+2+3}}{8i_{RRG,1+2+3}i_2i_3\eta_{s.g}\eta_{MD}}; \tag{7}$$

$$J'_{MD1,1+2+3} = \frac{J'_{MD2,1+2+3}}{i^2_{MD2}i^2_{RRG,1+2+3}} + \frac{J_{s.g.MD2} + J_{\Sigma g.RRG}}{i^2_{RRG,1+2+3}} + J_{\Sigma d.g.RRG} + J_{s.MD1}; \quad J_{s.MD1} = 1{,}5J_{s.MD2};$$

$$J'_{MD2,1+2+3} = \frac{8(m_{sl} + m_{fr})t_{\textit{в}}^2 + \pi^3 d^4_{LS}l_{LS}\gamma}{32\pi^2} + J'_{CM,1+2+3,MD2} + J_{s.MD2}; \quad J'_{CM,1+2+3,MD2} = 0{,}1J_{M1};$$

$$J_{s.g.MD2} = J_{s.g.MD1} = \frac{\pi h_{fr}\left(R^5_{s.g} - r^5_{s.g}\right)\gamma}{10(R_{s.g} - r_{s.g})};$$

$$J_{\Sigma d.g.RRG} = \frac{\pi\left[\left(D^4_{s,1} - d^4_{s,1}\right)l_{s,1} + \left(D^4_{s,2} - d^4_{s,2}\right)l_{s,2} + \left(D^4_{s,3} - d^4_{s,3}\right)l_{s,3}\right]\gamma}{32};$$

$$J_{\Sigma g.RRG} = \frac{\pi\left[\left(D_1^4 - d_1^4\right)l_1 + \left(D_2^4 - d_2^4\right)l_2 + \left(D_3^4 - d_3^4\right)l_3\right]\gamma}{32}; \tag{8}$$

$$\operatorname{sign}\varphi_{M2} = \begin{cases} +1 & \text{with coincident rotation of M2 relatively M1;} \\ \text{-}1 & \text{with opposite rotation of M2 relatively M1;} \end{cases}$$

$$\operatorname{sign}\varphi_{M3} = \begin{cases} +1 & \text{with coincident rotation of M3 relatively MD1;} \\ \text{-}1 & \text{with opposite rotation of M3 relatively MD1.} \end{cases} \tag{9}$$

Let us note that precise execution of drives motion equations in (4) corresponds to the steady-state static operating modes of three-channel ED.

In equations (1) – (9) and in Fig. 2 indicate: F_{WT} and S_{WT} are the resulting axial feed force and the corresponding machine WT movement (feed); kF_h and F_y are the horizontal (X-axis) and loading (along the vertical Y-axis of the spindle) components of the steady-state value of the circumferential cutting force F ($kF_{h,\max}\approx 25500$ N; $F_{y,\max}\approx 34425$ N); k is the safety factor, taking into account the distortions in the FM, $k = 1 \div 1{,}2$; F'_f is the total axial feed force, reduced to SN and determined by the forces kF_h, F_y and rolling friction force of WT sliding carriage: $F'_f = kF_h + (m'_{WT,SN}g + F_y)f_{rol}$, $f_{rol}\approx 0{,}01$ ($F'_{f,\max}=30000$ N); $F'_{r,WT,SN}$ is the steady-state load resistance force during feeding (in metal working mode), created by WT on the LS axis and reduced to SN; T_{M1}, T_{M2}, T_{M3} and T_{MD1}, T_{MD2} are the torques developed by M1, M2, M3 and differentials MD1, MD2 when they work together; $T_{rc,i}$ (i = 1, 2, 3) and $T_{rc,1+2}$ are the reactive torques on shafts, respectively, M1, M2, M3 and RRG; $T'_{r,w,MD2}$ is the steady-state torque of load resistance (in the metalworking mode), created by machine WT moving and reduced to MD2 shaft (determined by the rolling frictional forces of the work rack supports along the frame guides, friction in a screw-nut pair and friction in the bearings of the LS supports, as well as the components of the cutting force F) ($T'_{r,w,MD2,max}$≈139,944 Nm); $T'_{r,i}$ (i = 1, 2, 3) are the load resistance torques, reduced to the shafts, respectively, M1, M2, M3 ($T'_{r,1,max}$≈15,028 Nm; $T'_{r,2,max}$≈15,016 Nm; $T'_{r,3,max}$≈19,828 Nm;); φ_{M1}, φ_{M2}, φ_{M3}, φ_{MD1}, φ_{MD2} and φ_{LS} are the angles of rotation of shafts M1, M2, M3, differentials MD1, MD2 and LS; $m'_{WT,SN}$ is the mass of WT reduced to SN: $m'_{WT,SN}=m_{sl}+m_{fr}=45000$ kg; $J'_{MD1,1+2+3}$, $J'_{MD2,1+2+3}$ and $J'_{M1,1+2+3}$, $J'_{M2,1+2+3}$, $J'_{M3,1+2+3}$ are the moments of inertia of DM, reduced, respectively, to the shafts of the differentials MD1, MD2 and to shafts of M1, M2, M3 when they work together as part of a three-channel ED (at $i_{RRG,1+2+3}=1$): $J'_{M1,1+2+3}$=0,284573 kgm^2, $J'_{M2,1+2+3}$=0,332434 kgm^2, $J'_{M3,1+2+3}$=0,240153 kgm^2; J_{M1} and $J_{s,MD2}$ are the own moments of inertia of the motor M1 and the output shaft MD2: J_{M1}=0,194 kgm^2, $J_{s,MD2}$=0,015 kgm^2; $J_{\Sigma d.g.RRG}$, $J_{\Sigma g.RRG}$, $J_{s.g.MD2}$ and $J'_{CM,1+2+3,MD2}$ are the moments of inertia of the DM, elements: the driving gears of the RRG, driven gears of the RRG, MD2 first sun gear and reduced one of CM; γ is the density of gear material, for steel $\gamma=7{,}8\cdot10^3$ kg/m^3; g is the acceleration of gravity; $\eta_{s.g.}$, η_{MD} and η_s are the efficiency of a spur gear reducer, bevel MD and a screw-nut type helical gear: $\eta_{s.g.}$=0,985, $\eta_{MD.}$=0,98, η_s =0,85.

The generalized functional diagrams of three-channel FM ED with RRG and compared single-channel gearless feed EDs of the PWM-DCM type and the FC-ID type are presented in [9].

Mathematically taking into account the influence of DIFC cross connections on the load on the movement of iterative ED is determined by the system of equations (4) taking into account (6) – (9).

Research results. Computer simulation of electrodynamics of iteration multichannel FM ED with RRG and compared single-channel feed ED is carried out on the basis of the developed mathematical models of the drives motion, in particular the model (1) – (9), taking into account the corresponding structural-algorithmic schemes (Fig. 2, *a*), technical characteristics of the machine ИР1600ПМФ4 and requirements for ED with SCS-adjustment. For all cases, the machine WT feed was simulated in the mode of product face milling (WT position overshoot is not allowed) at the maximum static load of the feed drive. Comparative diagrams for calculating the ED electrodynamics characteristics are shown in Fig. 4 and 5, and the results of a comparative assessment of the obtained drives quality characteristics are in Table.

Given WT zone and displacement	Phase lag decrease in three-channel ED in comparison with one-channel ED (with various types of drives) and with double-channel machine WT feed ED at working off operating sinusoids $U_{PS}(t)=U_{PS,max}\sin2\pi ft$ ($U_{PS,max}$=var, f=var), times					
S_{S} **(0,1 μm)**	30 Hz			364 Hz		
	One-channel ED type		Double-channel ED	One-channel ED type		Double-channel ED
	PWM-DCM	FC-IM		PWM-DCM	FC-IM	
	45,7	**1,35**	**2,97**	**–**	**1,54**	**2,36**
S_{S} **(0,001 mm)**	27,5 Hz			160 Hz		
	One-channel ED type		Double-channel ED	One-channel ED type		Double-channel ED
	PWM-DCM	FC-IM		PWM-DCM	FC-IM	
	14	**1,463**	**3,26**	**2,95**	**1,17**	**1,48**
S_{M} **(0,02 mm)**	31 Hz			55 Hz		
	One-channel ED type		Double-channel ED	One-channel ED type		Double-channel ED
	PWM-DCM	FC-IM		PWM-DCM	FC-IM	
	5,39	**3,21**	**1,135**	**1,355**	**1,234**	**1,209**
S_{L} **(20 mm)**	1 Hz			1,6 Hz		
	One-channel ED type		Double-channel ED	One-channel ED type		Double-channel ED
	PWM-DCM	FC-IM		PWM-DCM	FC-IM	
	6,27	**4,69**	**1,416**	**1,31**	**1,185**	**1,139**

On Fig. 4 and 5 are marked out: by digits «1», «2» and «3» – drives performances graphs of basic К-1, refinement К-2 and precise К-3 control channels operating at iterative mode; by digits «1+2», «1+2+3» and «1DCM», «1IM» – performances graphs of optimized two- and three-channel differential-geared ED and compared one-channel (autonomous) ED with a power part accordingly PWM-DCM type and FC-IM type; by digits «1+2*» – performances of double-channel ED, operating as a part of optimized three-channel differential-geared ED. In table are specified: S_{S}, S_{M} and S_{L} are the zones matching to small, middle and large displacements of WorkCentre WT. Zones of displacements are calculated separately for each variant of a feed drive.

Results of computer researches have displayed considerable potential advantages of iterative multichannel FM ED with RRG not only on comparative decrease of transients time on WT position (first of all, at the most responsible static modes) [9], but also on WT moving control accuracy at feed dynamic regimes that is expected for iterative systems. High dynamic and precise indexes of three-channel feed ED are caused by essential relative expansion of its bandwidth at operation in the most responsible WT feed range (until S_{WT}=20 mm).

Fig. 4 shows comparative frequency characteristics of compensated three-channel ED and optimized double-channel and one-channel (autonomous) feed ED of PWM-DCM type and FC-IM type at working off of sinusoidal inputs of given amplitude in a zone small (*a*, *b*), middle (*c*) and large (*d*) WT displacements: *a* – S_{WT}=0,1 μm; *b* – S_{WT}=0,001 mm; *c* – S_{WT}=0,02 mm; *d* – S_{WT}=20 mm. Researches have shown, that already in a zone of average displacements (0,02 mm ≤ S_{WT} < 0,1 mm) expansion of a bandwidth of double-channel ED in comparison with both types one-channel ED is ensured: for ED of PWM-DCM type – not less than over 1,4 times and for ED of IM type – not less than over 1,2 times. On the first section of a large displacements zone (0,1 mm ≤ S_{WT} < 20 mm) comparative expansions of a bandwidth of double-channel ED are accordingly: over 1,38 times and over 1,27 times.

At the same time, it is established, that in a zone of small displacements (until S_{WT}=0,001 mm) a reproduced bandwidth of three-channel ED can be not less than $\omega_{b,1+2+3}$=1060 rad/s (168,7 Hz), that provides bandwidth expansion of three-channel ED not less than over 1,4 times even in comparison with broadband one-channel ED of FC-IM type. In comparison with similar double-channel feed ED with RRG its bandwidth extends on the specified section more than over 2,5 times. Indexes of admissible expansion three-channel ED bandwidth (in comparison with direct-drive one-channel feed ED of both types) sequentially increase in a zone of middle displacements and on the first section of a zone of the large WT displacements.

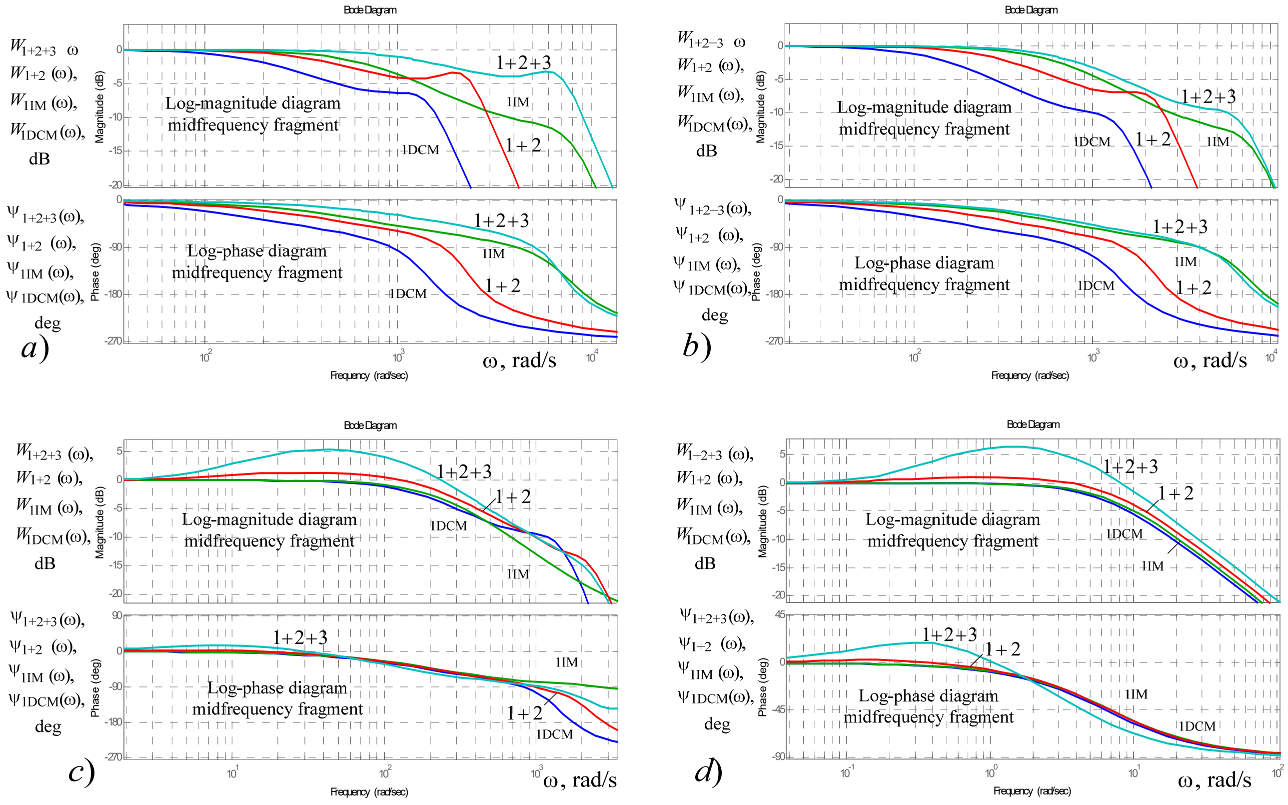

Fig. 4

The greatest effect of control accuracy raise by means of proposed multichannel differential-geared feed ED can be attained at working off varying refinement stimulus (Fig. 5 and Table). For example, at working off a signal of fixed acceleration $U_{PS}(t)=0,2t^2$ [V] ($S_G(t)=0,064t^2$) position error (at feed S_{WT}=500 mm) for three-channel drive is only $\varepsilon_{y,1+2+3}$=0,22 mm. There are analogous errors of double-channel ED $\varepsilon_{y,1+2}$=5,15 mm and one-channel ED of PWM-DCM type $\varepsilon_{y,DCM}$=143,76 mm and FC-IM type $\varepsilon_{y,IM}$=53,32 mm, that ensures three-channel ED accuracy advantage over 23,4 times, 653,5 times and 242,4 times accordingly.

Potential accuracy possibilities of multichannel feed ED are manifested in the fullest measure at working off of more complicated small amplitude sinusoidal signals (within $0<S_{\text{WT}}\leq 20$ mm) (see Fig. 5 and Table). On Fig. 5 working off graphs (at steady modes) of sinusoidal signal $U_{\text{PS}}(t)=U_{\text{PS,max}}\sin 2\pi ft$ ($U_{\text{PS,max}}$=var, f=var) by compensated three-channel ED and compared one-channel (autonomous) feed ED in the given WT displacements zones are resulted: a – S_{S}=0,1 μm (f=30 Hz; 364 Hz); b – S_{S}=0,001 mm (f=27,5 Hz; 160 Hz); c – S_{M}=0,2 mm (f=31 Hz; 55 Hz); d – S_{L}=20 mm (f=1 Hz; 1,6 Hz). Comparative estimation results of operating sinusoids working off accuracy by compensated three-channel machine WT feed ED are presented in Table.

For example, a diminution of a phase lag in three-channel ED at S_{WT}=20 mm and f=1 Hz are: in comparison with one-channel ED of PWM-DCM type – over 6,27 times; in comparison with one-channel ED of FC-IM type – over 4,69 times, in comparison with double-channel ED – over 1,416 times. When oscillations frequency raises, accuracy are diminished, remaining thus more than one (Table).

In summary we will note, that negative effect of DIFC on loading (without connection CCL) noticeably affects on control quality of multichannel differential-geared FM ED only in a zone small, middle and, fractionally, the large WT displacements ($0<S_{\text{WT}}\leq 50$ mm). CCL introduction into feed range $50<S_{\text{WT}}\leq 3200$ mm for raise of control operation speed at static modes is not necessary as practically does not effect on position transients quality in multichannel ED. Connection CCL to system at reproduction of sinusoidal specified stimulus by multichannel ED may be useful at working off of high-frequency sinusoids (f >50÷100 Hz) and only in a zone of small WT displacements (amplitude until S_{WT}=0,02 mm).

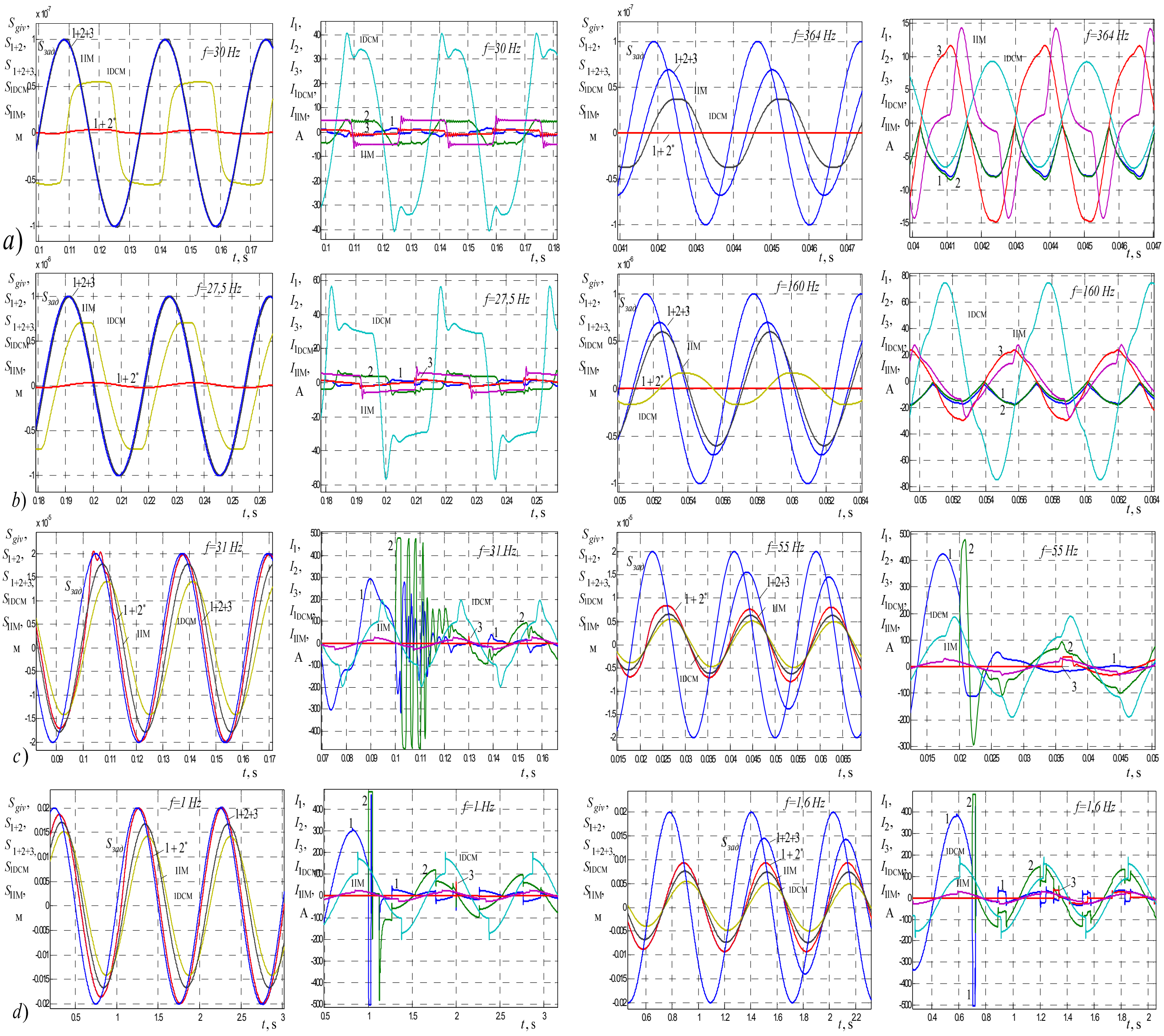

Fig. 5

Conclusions. **1**. The kinematic scheme is obtained and the specified mathematical model of the steady drive moving (taking into account DIFC on loading) of iterative three-channel feed ED on the basis of three-motor FM with RRG for WorkCentre with an inertia loading is presented.

2. On an example of a comparative estimation of potential efficiency of double-channel feed ED with channels feeds on base of large torque DCM and three-channel feed ED with the IM drive of the third, precise control channel it is established: at operation at the most responsible zone of small, medium and, fractionally, large machine WT displacements ($0<S_{WT}\leq 20$ mm) operation speed and a dynamic accuracy of iterative feed ED, including proposed FM ED with RRG, depend both from torque overload capacity, and from drive bandwidth of the last (precise) channel of a multichannel control system. Therefore, it is recommended at selection of the drive power part type of last, precise channel of iterative feed ED to prefer asynchronous ED on the basis of IM and frequency-current vector control.

3. It is established, that the greatest effect of control accuracy raise by means of iterative three-channel differential-geared feed ED of machine WT is attained at working off varying reference signals. When working out signals of constant speed and constant acceleration, the accuracy of three-channel ED in comparison with corresponding modern one-channel feed ED of various types can be raised over 10 times at working off a fixed speed and fixed acceleration signals, and – over some times at working off sinusoidal signals (see table). Thus, depending on the given amplitude of WT sine-wave oscillations the accuracy of three-channel ED in comparison with analogous on design double-channel feed ED can be raised to 1,14 ÷ 3,26 times.

4. When informational-measuring system of heavy cutting machines iterative multichannel feed ED has devices with demanded precision resolution, then quality of control (operation speed and accuracy) can be implemented, satisfying to the highest technical requirements and unattainable in traditional one-channel feed ED. The assumption that for effective functioning of proposed three-channel differential-geared FM ED with RRG and with essentially inertia loading AM power of the second, refinement DC-drive should be not less than 50 ÷ 75 %, and AM power of the third, precise AC-drive – not less 100 % from main (base) ED motor power is confirmed.

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ЕЛЕКТРОДИНАМІКА ВИСОКОТОЧНОГО ІТЕРАЦІЙНОГО ЕЛЕКТРОПРИВОДА ПОДАЧІ ОБРОБНОГО ЦЕНТРА З ІНЕРЦІЙНИМ НАВАНТАЖЕННЯМ

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Наведено кінематичну схему і подано уточнену математичну модель усталеного руху в режимі металообробки високоточного ітераційного триканального диференціально-редукторного електропривода подачі обробного центра із суттєво інерційним робочим органом. Наведено структурно-алгоритмічну схему триканальної системи керування електропривода, яка подана різними варіантами реалізації ітераційного алгоритму взаємодії каналів керування. Конкретизацію комп'ютерної моделі виконано стосовно до моделювання рухів ітераційного дво- та триканального електропривода з підпорядкованим налаштуванням каналів керування, призначеного для переміщення механізму подачі робочого органу в режимі торцевого фрезерування. Виконано порівняльну оцінку у часовій та частотній царинах показників якості підвищення точності керування подачею із застосуванням запропонованої багатоканальної електромеханічної системи. Порівняння проводиться з аналогічними за призначенням, але різними за швидкодією, сучасними одноканальними безредукторними електроприводами подачі, які традиційно застосовують на важких металорізальних верстатах та обробних центрах. Показано, що в компенсованому дво- та триканальному електроприводі у порівнянні навіть з широкосмуговим одноканальним асинхронним приводом подачі з частотно-струмовим векторним керуванням може бути досягнуто суттєве підвищення не тільки швидкодії, але й динамічної точності керування подачею практично в усьому діапазоні переміщень робочого органу. Встановлено, що ітераційний триканальний електропривод потенційно забезпечує рівень якості керування робочим органом, недосяжний не тільки за допомогою відповідних традиційних одноканальних електроприводів подачі різних типів, але й за допомогою аналогічного за побудовою двоканального диференціально-редукторного електропривода подачі. Бібл. 10, рис. 5, табл. 1.

Ключові слова: ітераційний багатоканальний електропривод, диференціально-редукторний електропривод, смуга перепуску, статична і динамічна точність.

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