ISSN 0005-1179, Automation and Remote Control, 2014, Vol. 75, No. 1, pp. 129–138. © Pleiades Publishing, Ltd., 2014.
Original Russian Text © L.I. Martinova, R.L. Pushkov, N.V. Kozak, E.S. Trofimov, 2011, published in Avtomatizatsiya v Promyshlennosti, 2011, No. 5, pp. 30–35.

Solution to the Problems of Axle Synchronization and Exact Positioning in a Numerical Control System

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Received March 5, 2011

Abstract—This paper considers the architecture and design specifics for the subsystems of axle synchronization and exact positioning in an open modular numerical control system. The authors present practical results of solving these problems for gear-hobbing machines and a coordinate measuring machine. Finally, the features of motion control are identified and analyzed for working machines with portal axle displacement actuators.

DOI: 10.1134/S000511791401010X

1. INTRODUCTION

A major requirement to metal-cutting machines dictated by their purpose concerns the relative displacement accuracy of a tool and workpiece. This predetermines the shaping of a manufactured product, as well as causes errors in dimensions, shape and location of processed surfaces [1, 2].

The relative displacement accuracy of a tool and workpiece depends on kinematic displacement accuracy and positioning accuracy (how precisely a cutting tool advances to a functional point with given coordinates during processing). This concept implies that (1) a functional point can be reached from any side and (2) the working tool of a machine stably advances to a given functional point in the case of several iterations. The accuracy of angular (dividing) displacements represents a special case of positioning accuracy. The above-mentioned requirements mostly apply to coordinate machines (particularly, multiprocessing machines) when a cutting tool must advance to a functional point with given coordinates during processing.

Metal processing comprises several shaping processes, where a processed surface results from the kinematic coupling between the displacement of a tool and workpiece (e.g., processing of gear wheels, helical surfaces, screw threads, etc.). To produce such surfaces, a working machine must coordinate the motion of a workpiece and tool. In the case of gear wheel manufacturing, the so-called gearing takes place (for instance, the running-in of a gear rack and workpiece disc is reproduced).

The coordination accuracy of these motions is known as kinematic accuracy or running-in accuracy. In common machines, kinematic accuracy is guaranteed by rigid kinematic coupling realized through a mechanical gearbox. This solution seems very inflexible, since even small changes in product nomenclature consume much time for changeover operations. In numerical control machines of the *Hi-End* class (they are remarkable for large computational power), the problem is treated at the numerical control level involving no adjustable change gearbox. The matter consists in implementing the additional functionality of "axle synchronization" (for axles controlled by high-precision follow-up drives). Such approach ensures high kinematic accuracy, while machine setup comes to simple change of a control program.

However, using follow-up drives as machine axle drives with closed-loop control circuit causes two types of errors reducing the accuracy of actuator displacements:

—errors in different elements of axle drives and an actuator (that are not covered by the feedback control system); these errors get revealed mostly in feedback control systems with rotary measuring transducers (MTs);

—errors in the displacements or rotation angle of machine's electric actuators obtained by a measuring transducer.

A numerical control system performs exact axle positioning of a working machine (including a desired location of a tool with respect to a workpiece) owing to synchronous drive control. Here the system performs one of the following tasks:

—drives' synchronization for one-coordinate motion;

—synchronization of several axles for composite coordinated motion.

The first problem arises in portal working machines, extended conveyors, printing machines and packing machines, where one-coordinate motion (an actuator or a workpiece) is implemented at least by two motors. In the case of portal working machines, such solution follows from the need for designing a rigid structure, decreasing possible errors caused by power transmissions and deformations, etc.

In the case of printing machines, rolling mills and conveyor machines, synchronous operation of several motors is necessary due to the length of conveyor proper or a processed material (paper, film, fabric, and so on) running on a series of rollers. Previously, the motion synchronization problem was treated mechanically (e.g., by means of V-belt drives or gear drives). Solution of this problem at the numerical control level allows to eliminate mechanical synchronization, thus leading to higher reliability and performance and lower operating costs. *Bosch Rexroth* company applies electronic line shafting (ELS); this technology realizes multi-axle motion synchronization, as well as improves the performance of packing machines, conveyor machines and printing machines. In particular, ELS guarantees the ink spot accuracy of 0.01 mm under the printing speed of over 48 km/h [3].

Synchronization of several axles becomes essential for machining of intricate-profile surfaces or organization of coordinated operations by different actuators of a working machine. In such situations, axle synchronization generally employs a master drive (similarly to gear milling by a hobbing cutter). A numerical control system makes it possible to remove a reduction gearbox with a variable ratio. Furthermore, a numerical control system appreciably perfects the accuracy of axle coordination and positioning.

2. SOLUTION TO THE AXLE SYNCHRONIZATION PROBLEM IN MODERN NUMERICAL CONTROL SYSTEMS BY LEADING SUPPLIERS

Each supplier of numerical control systems suggests an individual solution to the axle synchronization problem, since there exist no conventional standards in this field [4].

Numerical control systems by Fanuc, series 30i–32i. Here axle synchronization is implemented through electric gear boxes (EGBs). An axle defining displacement is called a driving axle (a leading axle). An axle whose displacement is synchronized with a leading axle is called a driven axle. For instance, consider synchronization between workpiece displacement and tool rotation; the latter serves as driving axle motion, whereas the former represents driven axle motion. In Fanuc systems, a leading axle is a mainspindle, whereas a driven axle is axle C.

Axle synchronization is activated/deactivated using G81/G80 commands:

G81 $T\ldots[L\ldots][Q\ldots P\ldots]$ .... ; axle synchronization activation;

G80 .... ; axle synchronization deactivation.

G81 command possesses the following parameters:

T—the number of teeth, pcs	1...1000
L—the number of cutter starts, pcs	−21...21
Q—module, mm	0.1...25.0
P—gradient angle, °	−90.0...90.0

For the parameter L, the signs "+" or "−" designate workpiece axle rotation in the positive or negative direction, respectively. The value of L being missed, we have $L = 1$ by default. The parameters Q and P are specified for helical gears.

Helical gear cutting calls for coordinated rotation of a workpiece and cutter (to obtain an involute profile). Moreover, it is necessary to guarantee additional turn motion of a workpiece to obtain a tooth length profile (a helical curve). The additional turn value a_c depends on the current displacement with respect to axle Z and satisfies the formula

$$a_c = Z \times \sin(P)/\pi \times T \times Q.$$

To increase computational accuracy, the axle synchronization factor K is defined as a vulgar fraction. The numerator K_n and the denominator K_d acquire the form

$$K_n = L \times \beta,$$
$$K_d = T \times \alpha,$$

where T gives the number of teeth; L stands for the number of cutter starts; α is the number of increments per 1 revolution of driving axle sensor; and finally, β means the number of increments per 1 revolution of driven axle sensor.

The following sequence of operations runs in activated synchronization mode:

—during G81 command execution, a driven axle is accelerated up to synchronization speed (acceleration rate is defined in machine parameters). As a driven axle reaches synchronization speed, G81 command is completed;

—G80 command serves to deactivate synchronization mode. To avoid tool damages or workpiece damages, this command must be executed after tool withdrawal. During G80 command execution, a driven axle is decelerated (again, deceleration is expressed through machine parameters). As a driven axle has zero speed, this command is completed.

A program with axle synchronization

```
N0010 M19             ; tool axle orientation specification
N0020 G28 G91 C0      ; workpiece axle checking
N0030 G81 T20 L1      ; synchronization activation (18°-turn
                      ; of a workpiece per 1 cutter revolution)
N0040 S300 M03        ; tool rotation speed specification
N0050 G01 X... F...   ; displacement along axle X (penetration)
N0060 G01 Z... F...   ; displacement along axle Z (processing)
...
N0100 G01 X... F...   ; tool withdrawal
N0110 M05             ; tool rotation stop
N0120 G80             ; synchronization deactivation
N0130 M30
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Numerical control systems by RexrothBosch, series IndraMotion MTX. These systems provide a more universal solution to the axle synchronization problem. Driving axles, driven axles, as well

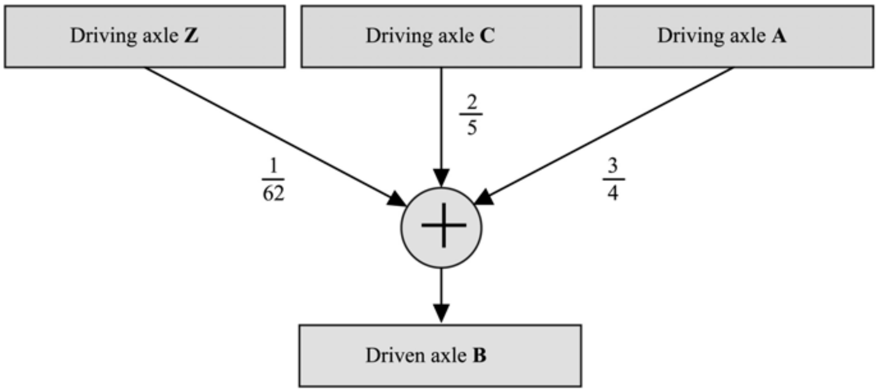


Fig. 1. Axles in Rexroth Bosch systems.

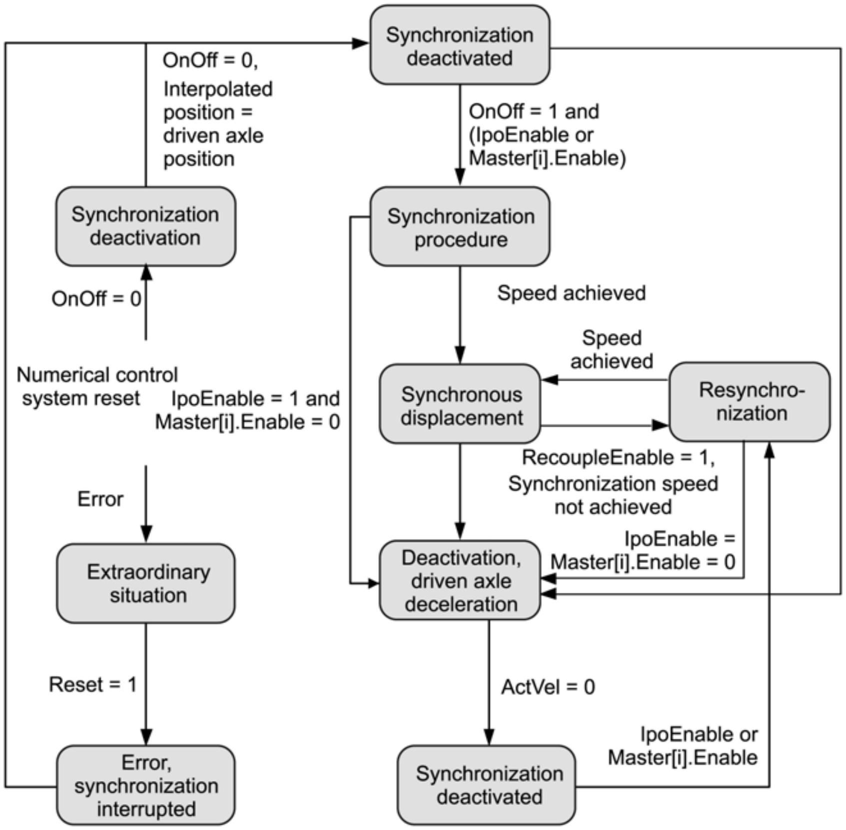


Fig. 2. The state graph of the system during axle synchronization.

as their synchronization factors are defined by system parameters. In addition, it is possible to specify several leading axles for a driven one (e.g., see Fig. 1).

A control program admits assigning cascade relationships for different axles (an axle has a leading axle and simultaneously represents a driving axle for another axle).

Axle synchronization is deactivated during numerical control system start. Later, it is controlled by some system variables adjusted in a control program (the maximal speed of a driven axle, maximal acceleration rate, a logical parameter responsible for synchronization activation/deactivation, etc.).

Figure 2 demonstrates the state graph of the system in the course of axle synchronization.

While computing the position of a driven axle, the program accounts synchronization factors and displacement coefficients for all driving axles.

Numerical control systems by Siemens, series Sinumerik SolutionLine (840Dsl). These systems use the so-called ElectronicGearbox (EG) technology for tooth cutting. It allows to calculate the motion of a driven axle based on the motions of driving axles (maximum 5). The displacements of a driven axle and each leading axle get coupled through synchronization factors. Axle motion synchronization can be performed taking into account (a) the current value of a driving axle or (b) a given value. Cascade synchronization appears possible, as well (a driven axle becomes a driving axle for another axle).

Axles to-be-synchronized are assigned prior to synchronization activation. *This procedure is performed by EGDEF command (driven axle, driving axle 1, synchronization type 1, ...).* Here synchronization has the following types: 0—calculation based on the current position of a driving axle, 1—calculation based on a given position of a driving axle.

Synchronization can be activated in several modes. Let us consider two of them:

$$EGON(FA,\ BCM,\ LA1,\ Z1,\ N1,\ \ldots) \quad \text{and}$$
$$EGONSYN(FA,\ BCM,\ SynPosFA,\ LA1,\ SynPosLA1,\ Z1,\ N1,\ \ldots).$$

Mode syntax involves the following notation: *FA*—a driven axle; *LAi*—a driving axle; *Zi*—the numerator of the synchronization factor for axle i; *Ni*—the denominator of the synchronization factor for axle i; *SynPosFA*, *SynPosLAi*—the synchronization positions of the driven and driving axles (synchronization mode is activated as the axles advance to these positions); *BCM*—transition to a next command (namely, *NOC*—immediate control transfer to a next command, or *FINE*, *COARSE*, *IPOSTOP*—control transfer to a next command depending on some condition). These modes differ in synchronization accuracy.

In *EGON* mode, axle synchronization runs immediately. In *EGONSYN* mode, first axles reach given positions, and synchronization starts then.

In the general form, the position of a driven axle is calculated by

$$FA_{cal} = SynPosFA + \Sigma((LA_i - SynPosLA_i) \times CF_i),$$

where $SynPosFA$ and $SynPosLA_i$ designate the synchronization position of a driven axle and leading axles, respectively; FA_{cal} stands for the calculated position of a driven axle; LA_i means the given or current position of a driving axle; and finally, CF_i corresponds to the coupling factor for axle i.

3. AXLE SYNCHRONIZATION MODULE WITHIN NUMERICAL CONTROL SYSTEM CORE ARCHITECTURE

The geometric task architecture of PCNC systems [5] provides for an interpreter which receives a control program and outputs an IPD code for an interpolator. The latter generates control commands for machine's electric actuators [6].

Axle synchronization implies extending the functional capabilities of an interpolator by adding a dedicated operation mode. In this mode, axle control commands enter a special synchronization block which contains coupling factors for axles. The block generates synchronous motion commands for axles (see Fig. 3).

Axle motion synchronization can be "rigorous" or "adjustable." Rigorous synchronization implies synchronization parameters tuning through machine parameters at the start-up stage of numerical control system design (subsequently, it is impossible to modify synchronization parameters from a control program). For instance, such synchronization mode can be applied in portal machines, where asynchronous motion may cause machine jamming.

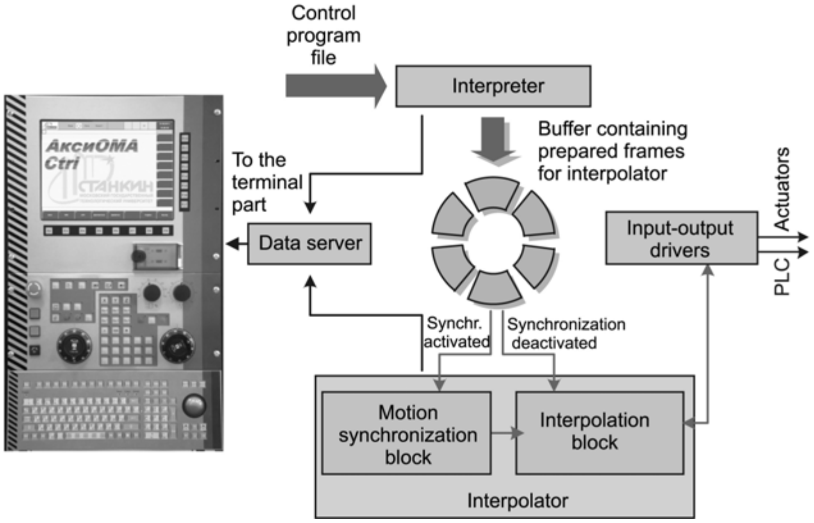


Fig. 3. The classical geometric task architecture.

In the adjustable synchronization mode of axle motion, synchronization factors are defined by a control program. Subsequently, synchronization mode is activated or deactivated by a special command.

4. CONTROL PROGRAM DEVELOPMENT LANGUAGE: EXTENSION SUBJECT TO THE REQUIREMENTS OF AXLE SYNCHRONIZATION PROBLEMS

Consider the control program development language embedded in *AksiOMA Kontrol*; this numerical control system was designed at Moscow State University of Technology (STANKIN). Here parameter specification and synchronization mode activation/deactivation are organized via special commands, i.e., G-commands and M-commands [7]. Synchronization mode activation and deactivation are performed by functions M902 and M903, respectively. During first activation of synchronization mode, axle couples are not defined. In this case, axles move as if axle synchronization is still not activated. As axle synchronization mode is deactivated, the synchronization block captures axle couples and use them in next synchronization procedure. Synchronization parameters are defined by G583 command <*driving axle*><*driven axle factor*>.

For instance, G583 $X0$ $Y0.5$ means that axle X acts as a driving axle in synchronization mode (and axle Y represents a driven axle with the coupling factor of 0.5). In other words, G01 G91 $X100$ command synchronously moves axle Y by 50 units (this frame is analogous to frame G01 G91 $X100$ $Y50$).

It is possible to define several driving axles for one driven axle; in this case, the displacements of a driven axle are summed up. In the example below, frame N120 specifies the displacement of axle Y by 54 units:

N100 G583 $X0$ $Y0.5$,
N110 G583 $Z0$ $Y0.2$,
N120 G01 G91 $X100$ $Z20$;
$100 \times 0.5 + 20 \times 0.2 = 54.$

The language enables the cascade definition of axle synchronization, when a certain axle is a driving axle for one axle and a driven axle for another [8]. Here is the corresponding example:

$$\begin{aligned}&\text{N100 G583 } X0\ Y0.5,\\&\text{N110 G583 } Y0\ Z0.2,\\&\text{N120 G01 G91 } X100.\end{aligned}$$

In frame N120, axle Y moves by $100\times0.5 = 50$ units, whereas axle Z moves by $50\times0.2 = 10$ units. Parameter-free command G584 eliminates existing data on axle couplings.

5. AXLE SYNCHRONIZATION ACCURACY TESTING BY EMBEDDED NUMERICAL CONTROL SYSTEM TOOLS

Consider the accuracy testing process for axle synchronization in the case of a portal machine with two drives and one axle. An oscilloscope embedded in a numerical control system [9] displays output signals of both drives, their discrepancy and maximal discrepancy. An operator can monitor the values and discrepancy of these signals at any instant by a moving cursor.

During axle synchronization in a gear hobbing machine, it is necessary to control the relationship of cutter speed, workpiece speed and the amount of advance. For this, the system displays the output signals of tool drive and workpiece drive, as well as their ratio and advance rate (see Fig. 4). Automatic zooming makes signals fit into the screen size. By choosing a signal, an operator observes the real scale of an active signal. A moving cursor enables to follow the values of signals and their discrepancies at any time instants.

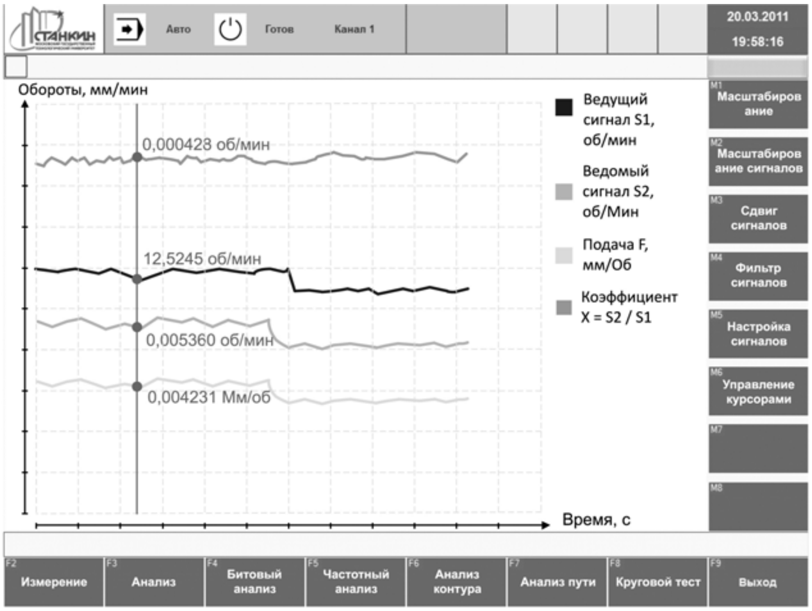


Fig. 4. Drive synchronization testing for a gear-hobbing machine.

6. PRACTICAL SOLUTION OF THE AXLE SYNCHRONIZATION PROBLEM: THE EXAMPLE OF A GEAR-HOBBING MACHINE

Let us analyze the process of plain gear cutting by a hobbing cutter in a gear-hobbing machine (see Fig. 5). This requires two shaping motions, namely, the main motion $\mathit{\Phi}_v(B_1B_2)$ (which co-

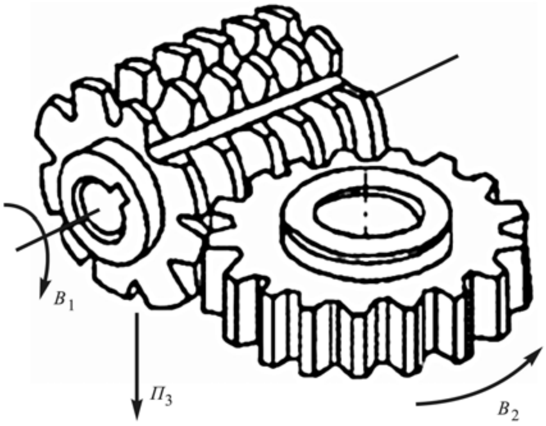


Fig. 5. Plain gear cutting.

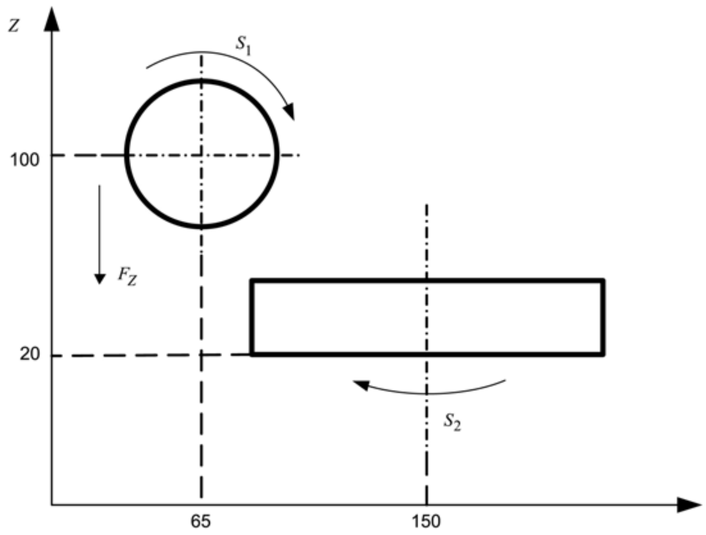


Fig. 6. The cut-map for a plain gear.

ordinates the rotations of a cutter and workpiece and forms an involute profile) and the advance motion $\Phi_s(\Pi_3)$ (which creates the straight-line profile along tooth length).

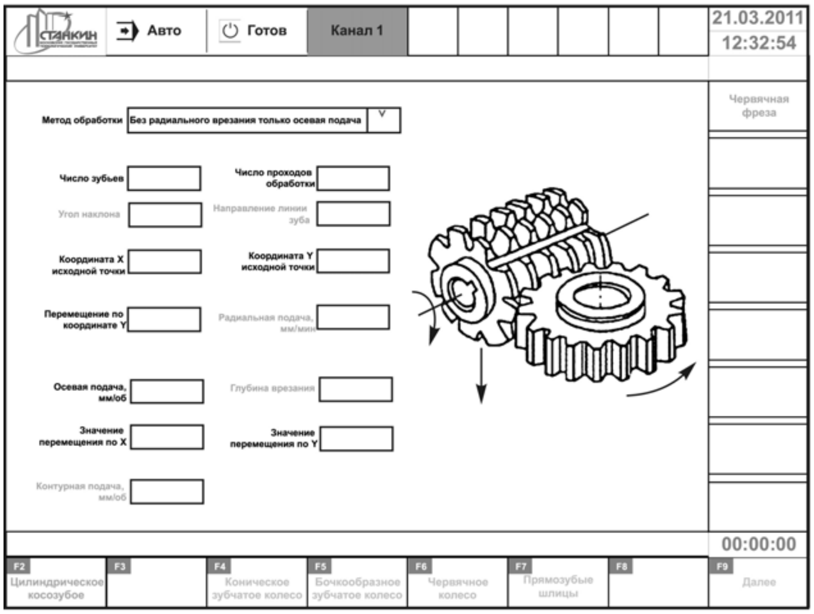
The rotations of a workpiece and cutter in the main shaping motion are coordinated through the following relationship [10]:

1 cutter revolution → k/z workpiece revolutions,

where k means the number of cutter starts; z indicates the number of teeth in a hobbed gear.

Consider a numerical example. It is required to process a gear with the following parameters: $m = 3$ mm, $z = 33$, $k = 2$, the width of teeth row equals 30 mm. Machining employs a hobbing cutter with the diameter $d_{cut} = 85$ mm. The simplified cut-map of the process is illustrated by Fig. 6.

In this cut-map, we have cutting modes $S1 = 100$ rpm, $S2 = (2/33)\times S1 = 6.061$ rpm, the advance rate along axle Z makes up 15.15 mm/min.



Метод обработки: Без радиального врезания только осевая подача

Fig. 7. A dialog box of the user interface in the gear hobbing numerical control system.

Control program type

```
G00 X65 Z100            ; tool advance
M902                    ; axle synchronization mode activation
G584                    ; synchronization parameters reset
G583 S1 = 0 S2 = 0.061  ; synchronization factor specification
S1 = 100 M3             ; axle S1 start, axle S2 has synchronous rotation
G91 G01 F15.15 Z-90     ; advance
S1 = 0 M5               ; axle rotation stop
M903                    ; synchronization deactivation
G00 X-40                ; tool withdrawal
G00 Z90
```

Typical gear surface processing is implemented as hobbing cycles. An operator exploits a user interface consisting of several dialog boxes (Fig. 7). By switching between these boxes, an operator specifies different parameters of processing, workpiece parameters and tool parameters in dialog mode. Subsequently, these parameters serve to generate a control program which can be executed directly or edited by an operator.

7. CONCLUSION

Solution to the problems of axle synchronization and exact positioning at the numerical control level ensures high competitive ability of technological equipment by enhancing its flexibility and utilization (including turn/mill machines). Moreover, such solution simplifies the kinematic diagram of working machines and allows to construct working machines with portal design of moving coordinates.

Static axle synchronization (e.g., for portal motion control) is rigorously defined during machine start-up. In the case of dynamic axle synchronization, a numerical control system provides a set of G-functions or high-level language functions. Modern numerical control systems implement synchronization modes such as synchronization with one leading axle, synchronization with several leading axles and cascade axle synchronization.

To implement synchronization, we have suggested the core architecture of a numerical control system with the motion synchronization block in an interpolator. To perform gear hobbing, an operator has been offered a set of G-functions with parameters calculated by “canonic” formulas. And finally, to realize different axle synchronization modes, an operator has been provided with a set of M commands for mode activation/deactivation.

The axle synchronization process in *AksiOMA Kontrol* system is controlled by an embedded tool, i.e., an oscilloscope used to monitor the relationship among hobbing cutter speed, workpiece speed and advance rate.

ACKNOWLEDGMENTS

This work was supported by the Federal Goal-oriented Program “Scientific and Educational Personnel of Innovative Russia” for 2009–2013 (state contracts nos. P901 and P717).

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