Hardware Implementation of the Mathematical Model Regulator for Controlling of Spindle Position

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Abstract – **In this paper, the realization of compensation system response for external displacements of the loaded spindle that control algorithm of proportional valves expenses of fluid is discussed.**

Keywords – **algorithm, bearing, control, hydrostatic, spindle.**

I. INTRODUCTION

In this paper the technical implementation of maintaining the value of a lubricating layer of hydrostatic bearing at constant level under the load from the cutting process on the basis of new designs of supports, where the initial gap can varies by fluid flow or by the geometry of the support channel of feedback the movement of the spindle, is proposed.

Control of size of the lubricant layer during of machining makes it possible to increase the stiffness of supports and its expand is used. Automating of the process of adjusting parameters of spindle of the hydrostatic bearing creates conditions for the development of new process technology of precision machining on machines with hydrostatic supporting nodes, providing reduced time for parts processing, increase productivity and reducing the cost of final products.

One of the main elements of the proposed method of control provisions of spindle are non-contact measuring transducers. The correct choice of meters provides adjustable hydrostatic bearing which sensitivity to small movements of the spindle within fractions of a micrometer and overall system performance and reliability of automatic compensation of vibrations. The decisive element in terms of precision spindle, along with transducers is fluid flow valves is analyzed.

II. RESULTS OF RESEARCH

Control algorithm of proportional flow valves for adjustable hydrostatic bearing (AHS) shown in fig.1.

Inputs are voltage regulators U_x, U_y, which working are proportional to the displacement of the spindle SP. The output of the microprocessor controller generates signals U_i, which coming to the proportional valves $PV_1 \ldots PV_4$ that, in turn, change their bandwidth Δq_i in accordance to regulation algorithm.

As a result, the corresponding values are formed for bearing capacity P_Σ in adjustable bearing of AHS to compensate for the external load P on the spindle. The pressure of fluid in the pockets p_{ki} of support was measured by dynamic fluid pressure sensors $PS_1 \ldots PS_4$, which generate analog signals U_{ti} after amplification and transform to digital type in block U_{pi} in block PM and submit to the regulator.

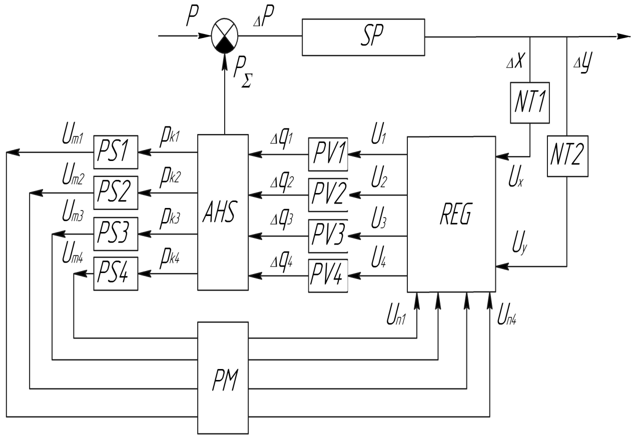


Fig.1 Block diagram of mechatronic system for adaptive control of position of front spindle for AHS

The main part of the algorithm of the regulator is dependence of corrective fluid expenses Δq_i on the values and directions of spindle displacements that were measured by noncontact sensors NT that can be used in manipulator [1]. To determine the position of the loaded spindle and can be used the high-frequency methods which have high sensitivity to deformation processes and loaded surface layers of friction [2].

In general, correction fluid flow which needed for the displacement of the spindle in the center position can be determined on the basis of equilibrium equations of forces, which applied to the spindle. The equation of forces equilibrium along the mutually perpendicular axes OX and OY can be written as:

$$\begin{cases} p_2 \cdot S_{eff2} - p_4 \cdot S_{eff4} = \sum P_x \\ p_1 \cdot S_{eff1} - p_3 \cdot S_{eff3} = \sum P_y \end{cases}$$

where p1 ... p4 – fluid pressure in the respective pockets; S_{eff1} ... S_{eff4} – the effective area of the respective pockets of support; $\sum P_x$, $\sum P_y$ – the total projection of external forces on the axis OX and OY respectively.

We assume that the effective area is the same for pockets of support (S_{eff}). Then, expressing the pressure and flow resistance of oil through leak fluid presented in form

$$p_{ki} = Q_i \cdot R_i \qquad (1)$$

and introducing notation $\Delta q_y = Q_1 - Q_3$ $\Delta q_x = Q_2 - Q_4$ after transformations we obtain

$$\Delta q_x = \frac{\dfrac{\sum P_x}{S_{еф}} + Q_4\left(R_4 - R_2\right)}{R_2} \quad (2)$$

$$\Delta q_y = \frac{\dfrac{\sum P_y}{S_{еф}} + Q_3\left(R_3 - R_1\right)}{R_1} \quad (3)$$

where Q_1 ... Q_4 - oil consumption through relevant AHS pockets at the time of measurement (at eccentric spindle position);

$R_1 \ldots R_4$ - oil leakage resistance from the relevant pockets at the time of measurement (at eccentric spindle position).

The total projection of external forces on the respective axes can be obtained as follows:

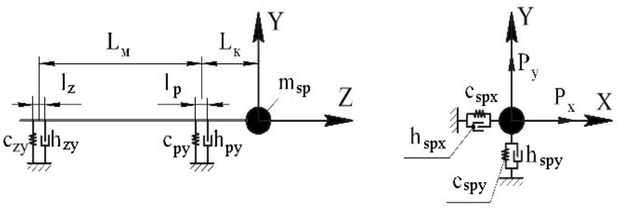
$$\sum P_x = m_{sp}\frac{d^2\Delta x}{dt^2} + h_{spx}\frac{d\Delta x}{dt} + c_{spx}\cdot\Delta x$$

$$\sum P_y = m_{sp}\frac{d^2\Delta y}{dt^2} + h_{spy}\frac{d\Delta y}{dt} + c_{spy}\cdot\Delta y$$

where m – mass of the spindle, reduced to the point of action of cutting forces;

h_{spx}, h_{spy}, c_{spx}, c_{spy} – equivalent damping coefficients (h_{sp}) and stiffness (c_{sp}) of spindle on the relevant direction.

To calculate the equivalent stiffness characteristics of the c_{sp} and consider elastic damping h_{sp} of the spindle system as equivalent single mass dynamic model (fig. 2), reduced to the point of force cutting.



a) b)

Fig. 2 Equivalent a) and resultant b) single mass spindle dynamic models of AHS

Design circuit of equivalent single mass system of spindle (Fig. 2, a) contains the reduced mass of the spindle m_{sp} and elastic system of the spindle in form of weightless beam which placed on the elastic-dissipative supports with distributed characteristics of rigidity and damping for the respective directions along the length l_p, l_z of bearing surfaces of the radial bearings. Mass of spindle m_{sp} reduced to the point of application of the projections P_x, P_y of cutting forces.

Reduced single mass of spindle system (Fig. 2, b) contains many m_{sp} which located on the elastic-dissipative support and characterized by the equivalent stiffness (c_{spx}, c_{spy}) and damping (h_{spx}, h_{spy}) for the relevant directions.

In view of the recommendations the equivalent characteristics of stiffness and damping was calculated as:

$$c_{spx\,(y)} = \left(\frac{L_к^2\left(L_к + L_м\right)}{3EJ} + \frac{\left(L_к + L_м\right)^2}{L_м^2 c_{px\,(y)}} + \frac{L_к^2}{L_м^2 c_{zx\,(y)}} \right)^{-1}$$

$$h_{spx\,(y)} = c_{ux}\left(\frac{L_к^2\left(L_к + L_м\right)}{3EJ} h_m + \frac{\left(L_к + L_м\right)^2}{L_м^2 c_{nx}} h_{px\,(y)} + \frac{L_к^2}{L_м^2 c_{zx\,(y)}} h_{zx\,(y)} \right)$$

Then, substituting expressions in (2) and (3), we get:

$$\Delta q_{x\,[y]} = \frac{\dfrac{1}{S_{eff}}\left(m_{sp}\dfrac{d^2\Delta x\,[\Delta y]}{dt^2} + h_{spx\,[y]}\dfrac{d\Delta x\,[\Delta y]}{dt} + c_{spx\,[y]}\cdot\Delta x\,[\Delta y] \right)}{R_{2\,[1]}} + \frac{Q_{4\,[3]}\left(R_{4\,[3]} - R_{2\,[1]}\right)}{R_{2\,[1]}}$$

Definition displacements ΔX, ΔY, velocities $\frac{d\Delta x}{dt}$, $\frac{d\Delta y}{dt}$, accelerations $\frac{d^2\Delta x}{dt^2}$, $\frac{d^2\Delta y}{dt^2}$, determined in real time in terms of meters installed along the axes OX and OY respectively.

The value of the expenses of liquid Qi bearing pockets, part of the formulas, approximately calculated by the formula:

$$Q_i = \frac{p_{ki}\cdot\delta_0^{\,3}\cdot D\cdot\phi_{k\tau}}{12\mu\cdot l_1}\cdot\left[\left(1 - \varepsilon K_\phi\right)^3 + C_L\left(1 - \varepsilon\cdot\cos\phi_{\tau i}\right)^3\right] \quad (4)$$

where $C_L = \dfrac{2\left(l_0 + l_1\right)}{D\cdot\phi_{k\tau}}$ $\quad K_\phi = \dfrac{2}{\phi_{k\tau}}\cdot\sin\dfrac{\phi_{k\tau}}{2}$

i – number of pocket; l_0 – width of the pocket; l_1 – axial width of jumper pocket; $\phi_{k\tau}$ – corner of pocket that covering half the length of tangential jumpers adjacent to the pocket; $\phi_{\tau i}$ – angle that determines the position of the middle of the bridge and tangential of i-th pocket in polar coordinates; φ_e - angle, which indicates the direction of displacement of the spindle in AHS (Fig. 3).

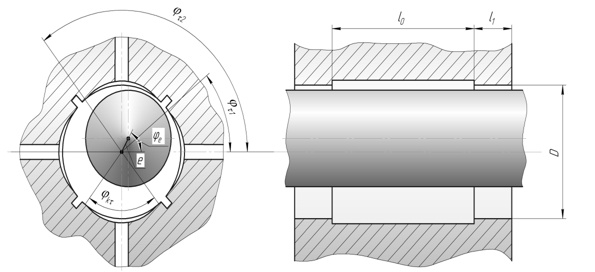


Fig. 3 Scheme to determine the Q_i in the radial AHS

Given the expression (1), the formula (4) determine the hydraulic resistance R_i:

$$R_i = \frac{12\mu\cdot l_1}{D\cdot\delta_0^3\cdot\phi_{k\tau}\left[\left(1 - \varepsilon K_\phi\right)^3 + C_L\left(1 - \varepsilon\cdot\cos\phi_{\tau i}\right)^3\right]}.$$

The pressure in the pockets of support p_{ki} defined by FPGA is based on analog-digital conversion (ADC) of continuous analog signal of dynamic fluid pressure in real time.

The relative eccentricity and direction of the displacement in hydrostatic spindle sleeve can be determined from the following trigonometric dependencies:

$$\varepsilon = \frac{\sqrt{\Delta x^2 + \Delta y^2}}{\delta_0}; \quad \phi_e = arctg\frac{\Delta y}{\Delta x}.$$

Thus, by correction fluid flow, such Δq_x, coming to the loaded pocket for OX axis, is defined the angle ϕ_e of location bearing of spindle neck. In general, for n-pocket bearing the values of corrective fluid expenses Δq_i come to the loaded pocket bearing the appropriate direction.

The proposed mechatronic system of adaptive control (SAC) refers to the digital type, in which the quantization signal in time and level is used. Quantization time making discrete digital system and level quantization is nonlinear. A characteristic feature of the SAC features is costly hydro mechanical inertia of the system in relation to digital. Thus, the maximum operation frequency is proportional valve costs less than 40 Hz, while the frequency of digital processing in embedded systems is of the order of tens of MHz. In this case, as noted in [3], the impact on the dynamics of quantum on SAC can be neglected. Therefore, to study the characteristics of digital consumable of SAC, should be used mathematical tools of analysis of linear continuous systems.

For hardware implementation of the mathematical model proposed controller chip programmable logic (FPGA) family company Altera MAX 10 [4].

The feature of this chip is built ADCs and hardware multipliers. Modern methods of design and embedded systems using FPGA chips can create on a single chip so-called system on a chip (System-On-Chip - SOC). This decision provides for the creation of all on-chip microprocessor, namely embedded microprocessor controller system bus, memory blocks and various peripherals [5].

As an embedded microprocessor, we will use the core processor NIOS II fast version, which is using software QSYS configured to accelerate computation control algorithm [6]. This core 32 bit processor with built-in commands and data caches, hardware multiplier and debugging embedded system applications.

In addition, all the control algorithm formulas are implemented as hardware peripheral modules that significantly increase the performance of the control algorithm and will offload the CPU from complex mathematical calculations.

Using the built-in ADC reduces the number of chips used to implement the control algorithm, simplify the implementation of the interface between the control system and the ADC and increase system reliability. Using the same system on a chip will shift the management of ADC embedded processor NIOS II.

Therefore, the overall configuration of internal control systems would look as follows (Fig. 3), and overall system management data transmission between modules is performed using NIOS II processor system bus and Avalon Interconnect Fabric (Address, Data and Control Bus),

ADC - module analog-to-digital conversion;

ROM - program memory, which stores all control algorithm program mechatronic systems;

RAM - memory for storing intermediate results of calculations;

Timer - the system timer to determine the time periods in embedded systems;

JTAG - interface for communication with built-in debugging stage of the program;

Sys ID - dongle for docking hardware and software of the system on a chip;

IRQ - interrupt controller from timer, ADC blocks and other peripheral modules;

PWM - power pulse width modulation to control valves;

P_1, P_2 ... P_n – hardware blocks to calculate different parts of the algorithm. Their block diagram for implementation is shown in Fig. 4.

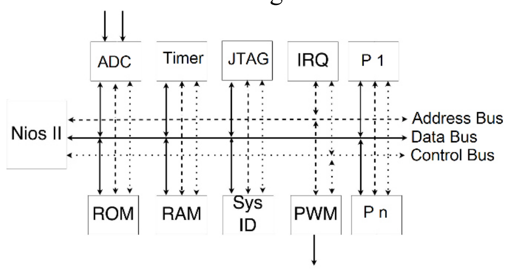


Fig. 4 Block diagram of a system on the chip

Fig. 5 shows a hardware multiplier block of architecture that can significantly accelerate the reduction process, reduce the scope of the scheme, which is necessary for the implementation of the algorithm, respectively, and reduce system cost of control.

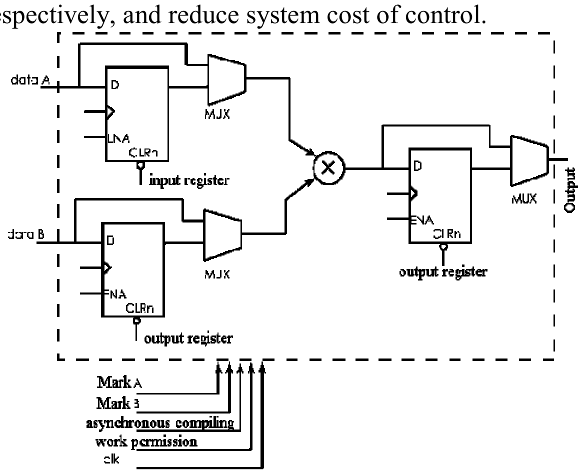


Fig. 5 Block diagram of FPGA multiplier

Each of calculation unit algorithm for microprocessor system is a peripheral module that is connected to the system bus using standard interface and its development includes only the development of the algorithm calculation. It is connected to the system, development address decoder controller system interrupt performed automatically by QSYS. The development of control system algorithm implemented in hardware description language VHDL, and programs for processor NIOS II - C language environment in software Eclipse.

Fig. 6 shows a block diagram of expenses calculation Δq_x.

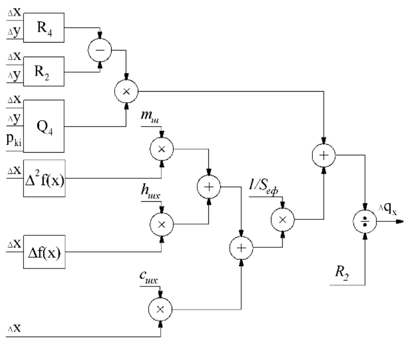


Fig. 6 Block diagram costing Δq_x for implementation on FPGAs

Correction expenses for the axis OY implemented by similarly to Δq_x.

In order to simplify the structure calculation Q_i, R_i introduced a number of constants and symbols used in the synthesis scheme for FPGAs:

$$const_1 = \frac{D \cdot \delta_0^3 \cdot \phi_{k\tau}}{12 \mu l_1};\ const_2 = 1 / const_1$$

$$G = \left(1 - \varepsilon K_\phi\right)^3 + C_L\left(1 - \varepsilon \cdot \cos\phi_{\tau i}\right)^3$$

Block diagrams that implement analytical dependence means by FPGAs are shown in Figure 7.

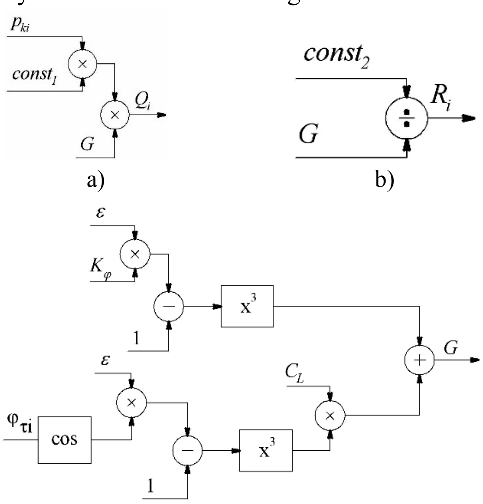
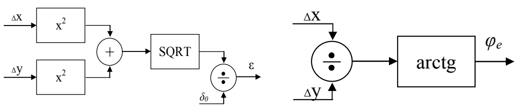


Fig. 7 Block diagrams to determine the liquid expenses Q_i (a), hydraulic resistance R_i (b), addition value of G (c) means by FPGAs

To calculate the trigonometric functions the rational is use of units of permanent storage devices that are embedded in the FPGA. Blocks, calculated the square and the cube of the input values, are multipliers of the input values to one or two times.

To calculate the position of the spindle in the resistance in polar coordinates (ε, φ_e) used the structure shown in Fig. 8.



a) b)

Fig. 8 Block diagrams for calculating the values of ε (a) and φ_e (b)

To calculate the expenses of corrective fluid is using first and second derivatives of the displacement of bearing spindle neck. Consider the second derivative computation in a discrete system based on finite difference method. The second derivative can be represented by the following relationship:

$$\Delta^2 f(n) = f(n) - 2f(n-1) + f(n-2), \qquad (4)$$

where f(n) - the current value of the argument in current tact;

f(n-1) - the value of the argument in the previous cycle; f(n-2) - the value argument two cycles ago.

For the realization of formula (4) will use the opportunities of embedded processor NIOS II, such as the execution of simple operations requires large computing costs. For similar reasons, the first derivative computation was realized.

Block of pulse width modulation to control valves also a peripheral unit for the processor NIOS II. It is the simple counter and digital comparator, the output of which is removed modulated signal. Number of units is equal to the number of proportional valves.

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III. CONCLUSION

The mathematical model regulator consumable characteristics of the hydrostatic bearing spindle on which is running the position of spindle of precision machining tools was developed.

The hardware implementation of the mathematical model of the regulator by FPGA, which provides coordination broadband analog and digital signals in the system and ensures high reliability of mechatronic control systems of spindle position, was proposed.

The technical solution which can be used to improve the accuracy and rapidity of wide range of spindle units of the technological machines was proposed.