IMPROVING MACHINING ACCURACY OF CNC MACHINES WITH INNOVATIVE DESIGN METHODS

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Abstract. The article considers achieving the machining accuracy of CNC machines by applying innovative methods in modelling and design of machining systems, drives and machine processes. The topological method of analysis involves visualizing the system as matrices of block graphs with a varying degree of detail between the upper and lower hierarchy levels. This approach combines the advantages of graph theory and the efficiency of decomposition methods, it also has visual clarity, which is inherent in both topological models and structural matrices, as well as the resiliency of linear algebra as part of the matrix-based research. The focus of the study is on the design of automated machine workstations, systems, machines and units, which can be broken into interrelated parts and presented as algebraic, topological and set-theoretical models. Every model can be transformed into a model of another type, and, as a result, can be interpreted as a system of linear and non-linear equations which solutions determine the system parameters. This paper analyses the dynamic parameters of the 1716PF4 machine at the stages of design and exploitation. Having researched the impact of the system dynamics on the component quality, the authors have developed a range of practical recommendations which have enabled one to reduce considerably the amplitude of relative motion, exclude some resonance zones within the spindle speed range of 0…6000 min

1. Introduction

In order to roughen the surface, it is necessary to relate roughness parameters with processing conditions. This topic was studied in a number of works, for instance, A.P. Sokolovsky, A.I. Isayev, A.G. Suslov, V.F. Bezyayzchny and others; where both theoretical and empirical estimated dependences were implemented to establish the above-mentioned relationship. It follows from the previous research that it is vital to take into account the dynamics of a technological system to achieve roughening of the surface.

Failing to consider this relationship, as a rule, quickly leads to the loss of machining accuracy, as well as worse productivity, reliability and processing quality.

The theoretical research includes the description of a mathematical model with both its making and solving, depending on time, frequency-domain and operator representation of processes and phenomena, occurring in the system.

Thus, for example, time domain representation of occurring processes is used to research the transient mode of the system, with the help of either differential or integral equations [1,3,4,7].
2. **Materials and methods**

Frequency-domain representation is implemented to study the steady mode which involves Fourier expansion of the time periodic function $g(t)$ with period $T$, and results in the description of the frequency spectrum and the amplitude of every harmonic.

The original representation of the system, based on the automated control theory, as a structure flowchart with a greater degree of detail between different hierarchy levels, requires either development of flowcharts or topological models; moreover, another alternative solution is the representation of a system via the matrix approach. One common disadvantage of these methods of describing the large-scale multivariable systems is the overwhelming complexity, awkwardness and poor readability, causing major problems in design.

Having searched for new more efficient methods of representation and the integrated study of complex machine systems, regarded as closed dynamic systems of various physical nature that takes into account the diversity of relations, external and internal forces and impacts on system elements has produced the following result [1, 2, 4].

The method is based on representing the system as a matrix of block graphs with a varying degree of detail between the upper and lower hierarchy levels.

This way allows combining the benefits of the graph theory and the efficiency of decomposition methods, it also serves well the illustrative purpose, which is characteristic for both topological models and structural matrices; in addition, it relies on the power of linear algebraic tools, so it enables algorithmization and computer calculations as any matrix-based research.

The primitive elements of a machine system are functional units: electric motors, transmitting mechanisms, framework parts – for the electromechanical system of a machine; transistors, diodes, resistors, integrated subsystems, etc. – for CNC and automated control systems and drives.

Certain sequences of elements in a system form kinematic, electric, hydraulic and other chains which transfer energy (the power part of a machine system) or transmit and transform signals (electric and electronics part of a machine – a control system).

These chains together with basic parts (a machine frame), completed by an assembly unit, can represent a unit (a module), drive, CNC machine, robot, robotic system, etc.

3. **Results and discussion**

Therefore, these automated machine workstations, systems, machines and units can be considered as complex physical systems the design of which can be analysed as containing the following interdependent parts: the design of chains and the design of structures, represented as algebraic, topological and set-theoretical models. Each model easily transforms into a model of another type, and, as a result, every model can be regarded as a system of linear and non-linear equations, the solutions of which define the system parameters.

Here is the system of inhomogeneous equations in a matrix representation:

$$[ A \{ x \} = [ H \{ f \},$$

or in the extended form:

$$a_{11}x_1 + a_{12}x_2 + \ldots + a_{1n}x_n = h_{11}f_1,$$

$$a_{21}x_1 + a_{22}x_2 + \ldots + a_{2n}x_n = h_{22}f_2,$$

$$\ldots$$

$$a_{n1}x_1 + a_{n2}x_2 + \ldots + a_{nn}x_n = h_{nn}f_n$$

When assuming that $a_{ij}(p)$, $h_{ik}(p)$, polynomial $p = d/dt$, while $a_{ij}(p)$ are not higher than the second order:
\[ a_{ij}(p) = m_{ij} p^2 + n_{ij} p + l_{ij} , \]

then it results in the system of differential equations in a symbolic form like this:

\[ a_{ii} x_i = \sum (-a_{ij}) x_j + h_{ii} f_i, \quad i = 1, 2, \ldots, n ; \quad i = j ; \]

or for a general case:

\[ a_{ii} x_i = \sum (-a_{ij}) x_j + \sum h_{ik} f_k, \quad i = 1, 2, \ldots, n ; \quad i = j ; \]

When every equation of the system is solved for the main variable, the resulting systems look as follows:

\[ x_i = \sum (-a_{ij} / a_{ii}) x_j + (h_{ii} / a_{ii}) f_i, \quad i = 1, 2, \ldots, n ; \quad i = j ; \]

Finally, the system is represented as a generalized signal graph – a topological structure which includes [2, 4, 6, 7]:

- a number of graph vertices \{ x_1, x_2, \ldots, x_n \}, where every vertex correlates with desired variable \( x_i \) and has weight \( a_{ii} \), determined by the coefficient of the given variable in the left side of the \( i \)-equation of the system;
- a number of source vertices \( f_i \);
- a number of edges \{ \( x_i, x_j \) \}, \( i, j = 1, 2, \ldots, n \), each of which is directed towards node \( x_i \) from node \( x_j \) and has weight \( (-a_{ij}) \), determined by the coefficient of the \( j \)-variable in the right side of the \( i \)-equation of the system.

This structure has the following advantages:
- simplicity of defining algebraic signs in the topological formula which depend on the parity of the number of nonintersecting loops;
- direct correlation with the general system of equations.

Here is the general model of a block matrix – a topological structure (Fig.1), which has both visual clarity, characteristic for flowcharts, and a detailed representation of signal transfer, information and energy flows.

![Figure 1. The ordered representation of the system topological structure](image-url)
It follows from the graph theory that every non-diagonal element - $a_{ij}$ describes the transfer of the impact from coordinate $-x_j$ to coordinate $-x_i$, while diagonal elements - $a_{ii}$ demonstrate the object characteristics with respect to every single coordinate $-x_i$. It is also assumed that the transfer line connects one diagonal element with another in an anticlockwise manner - "from top to bottom - on the right", bottom-up – on the left”.

The impacts of elements on the right hand side of the equations system are projected directly onto diagonal elements.

The physical significance of topological analysis involves the studies of the structural organization of the system and defines the importance of its component elements (units, links, subsystems) in the system.

Topological notions (path, loop, incidence, transfer, determinant, etc.) and model behaviours allow one:

- to make one of the most important conclusions, regarding the system stability (the system is stable only on condition that the loop part is stable as well as all edges outside the cycle);
- to establish the impact of component elements on the dynamic characteristics of a system via expressing the transfer functions and parameters of edges operators through such formulas as Mason’s gain;
- to research the system stability and performance, using the determinant of the topological model, presented as a product of determinants of independent loops and edges outside cycles.

It is important to note that the stability factor is defined for every single autonomous part which allows determining which loop part (subsystem, machine unit) has the greatest influence on system stability and performance. Consequently, this is the part that has to be modified first, and, if needed, it is combined with other system parts with the help of correction edges, expressed in practical terms as mechanical and non-mechanical linkage.

For a CNC lathe of a 1716PF4 model, the dynamic system, consisting of a frame, main motion and feed drives, can be presented as a generalized signal graph made of three nonlinear elements, described by functionals $k_1$, $k_2$, $k_3$ and connection matrix $[B]$. The graph determinant of this system looks as follows:

$$
\Delta = \begin{vmatrix}
1 - k_{11}a_{11} - k_{12}a_{12} - \cdots - k_{13}a_{13} \\
1 - k_{21}a_{21} - \cdots - k_{23}a_{23} \\
1 - k_{31}a_{31} - \cdots - k_{33}a_{33}
\end{vmatrix}
$$

$$
= k_1k_2k_3 \left( \frac{1 - k_{11}a_{11}}{k_1} \cdot \frac{1 - k_{22}a_{22}}{k_2} \cdot \frac{1 - k_{33}a_{33}}{k_3} - \frac{1 - k_{11}a_{11}}{k_1} \cdot \frac{1 - k_{22}a_{22}}{k_2} \cdot a_{31} - \frac{1 - k_{11}a_{11}}{k_1} \cdot a_{23} \cdot a_{31} - \frac{1 - k_{33}a_{33}}{k_3} \cdot a_{21}a_{12} - a_{12}a_{23}a_{33} \right)
$$

When $\Delta=0$, there is the boundary of stability of the given complex dynamic system which can have such dynamic characteristics that may not be observed in every individual subsystem.

Thus, for instance, according to some researchers, the dependence between the coefficient of sliding friction and sliding velocity $V$, mm/min, within the range of 0-100 mm/min, in the friction couple PTFE-cast iron basically represents an invariable and is equal to 0.05.

The authors have obtained the empirical data, defining the friction in the slide way of the longitudinal feed drive in the 1716PF3 model with different feed rates and a wide range of rotation frequency of the main motion drive; that prove that this dependence is only valid for low speeds of sliding.

The physical significance of this phenomenon can be explained by the effects of vibration level, generated by the main motion drive and transferred through the framework of the dynamic system of the feed drive; the direct relation and its feedback of the latter cause the emergence of new behaviours of the slide – the operating member of the machine.
The structure of the mechanical part of the drive, including a motor spindle, automated gear (reducer) and turning spindle unit, can be presented as a three-part mass model (Fig.2) with such parameters as the equivalent moment of inertia \( I_i \), drive and loading torques \( M_i \), the rotational angles of non-rigid mechanisms \( \phi_i \) (or rotary speed \( \omega_i \)), the compliance coefficient \( 1/ C_{ij} \) and damping \( -b_{ij} \).

**Figure 2.** The structural flowchart of the mechanical part of the drive

The frequency response analysis of the torsional behaviour of the main motion and feed drives has enabled one to establish two zones of intensive oscillations, one of which derives from the dynamics of the drive, while the other is conditioned by the natural frequency spectrum of the parts of the lathe head which causes mutual effects and reduces the quality of processing.

The methods of theoretical and empirical research include multivariate analysis, completed as numerous simulations of the system under study with different values of varying parameters [3]. This allows one to research the impact of the significant factors on the resulting estimations and give practical recommendations (bearing in mind the experimental study (Fig.3)) in order to obtain the optimal (rational) variant of the structure.

**Figure 3.** The graph of the relative motion of 1716PF3 model: 1 – amplitude-frequency response with the taper spindle carrier; 2 – amplitude-frequency response with the chuck spindle carrier.

The complex dynamic characteristic of the machine drive is the trajectory of the geometric axis of the transverse spindle.

The awareness (analytical and/or experimental) of the typical trajectory of spindle-axis rotation (the turning lathe of 1716PF3 and 1716PF4 model) as well as the spectrogram of the resulting surface of
the processed detail allow one to establish the correlation between system parameters and the quality of the finished detail (Fig.4).

Figure 4. The frequency spectrum of relative motion of the cutting machine.

4. Conclusion
The results of researching the impact of the dynamics of the system “tool-workpiece” on the quality of the processed detail have enabled to make a range of practical recommendations, such as, for example, increasing the joint rigidity of “frame-spindle slide”, engineering changes and further development of the reduction gear unit as well as updating the standard requirements for rotating units and parts of static and dynamic balancing.

This, in its turn, has considerably reduced the level of relative motion amplitude, enabled to get rid of some resonance zones within the spindle rotation range of 0-6000 min\(^{-1}\) and improved the quality of machining [4].

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