Parametric optimization of hybrid metalworking machinery quality

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Abstract. The research considers the problem of quality prognostics in the conceptual design of process equipment. We outline the fundamentals of the methodology for predicting the operational parameters distribution of hybrid metalworking machines. We demonstrate that only joint estimation of the spatial, temporal and energy characteristics of the process equipment facilitates achieving the maximum values of the machines integral quality indicators. The developed method of forming the structure of parameter series is recommended to use not only for creating new integrated equipment, but also for completing a base of metalworking machines using the existing enterprise stock.

1. Introduction
Quality is one of the absolute requirements of the market economy. Ensuring its optimal level is a priority in developing a general concept of process machines and equipment [1-6]. This problem should be solved as a complex task. In particular, the choice of the parameter (dimension-type) machine series structure should be carried out alongside the technical characteristics substantiation of its members. Given the current trends in the development of mechanical engineering, this task is an integral part of the automatic design of process equipment. Currently, there is no coherent theory of resolving this issue. Well-known research results do not form a single consolidated system.

Quality is a very capacious concept that displays a complex of multifaceted properties inherent in any object. In the most general case, it can be interpreted as a set of product properties that characterize its suitability to meet certain needs in accordance with the purpose. From an engineering point of view, quality is investigated by comparing the totality of the properties of any product with a similar product, taken as the base of comparison, or as a standard [7-11].

The quality, and consequently, a certain complex of consumer properties is planned during the design, therefore the problem of its optimization belongs in the field of prediction and should be solved at the initial stage of the process equipment concept development [12-17].

Predicting the quality of products primarily requires determining the minimum set of properties for its evaluation. They must be substantial and fit into the system of fundamental concepts and categories. These properties include space and time: the categories that reflect the forms of matter existence, such as the length and mutual order of material objects, the duration and sequence of events. The category of energy is employed as a general measure of movement and interaction for all types of matter.

However, these properties and the parameters or characteristics that describe them are usually not enough to describe artificial, i.e. man-made technical systems. A standard nomenclature of the main
indicators groups is used to implement a comprehensive assessment of a product quality. A fairly stable set of specific and complex indicators that are most relevant for the industry has traditionally been used in the practical machine tool building for identifying the technical level and competitiveness of process equipment, as well as for choosing it to perform a specific production task. The most important indicators are: efficiency, productivity, accuracy, reliability, processability, flexibility, ergonomics and aesthetics of machine tools.

Obviously, substantiation of the equipment basic parameters and technical characteristics most often requires dealing with their quantitative assessment: dimensions of the working area (space), speed capabilities (time) and drive power (energy). The additional parameters are most often given in the form of qualitative assessments, which determine the differences between specified objects. For example, hybrid metalworking machines are available in various classes of accuracy, architecture, with manual or programmed control, etc.

The intensified market production with limited costs of human, material and energy resources sets conditions for the choice of optimal technical characteristics as one of the main directions of equipment efficiency increase. An insufficient or excessive margin of process equipment leads to a decrease in its economic efficiency, an increase in capital expenditures and, consequently, a rise in the cost of products. The difference between the designed operational capabilities and the required task-specific capabilities of the equipment turns into losses (excessive or insufficient capabilities margin).

Losses can occur due to incomplete use of the workspace, spindle rotating frequency range, motor power, etc. For example, studies of the operating conditions of CNC milling machines showed that for performing 90% of operations the consumed main drive power does not exceed half of the nominal value; the factual working feeds are most often less than 1/6 of the maximum allowable ones; the table carrying capacity is used for less than 20%, etc. A similar situation is observed for machines of other groups [18]. The patterns obtained by foreign researchers do not differ from domestic ones. Notably, it was found that there is no significant difference between the CNC machines and the universal metal-cutting equipment with manual control in terms of using their technological capabilities. The purpose of this research is to propose a method of forming the structure of parameter series which provide an effective transition to the output of new process equipment.

2. Materials and methods

As shown in [19], the ability of the \(i\) technological system determined by its parameters (and characteristics) can be estimated using the so-called conditional average loss criterion \(R_i\), ensuring a minimum of decision making error:

\[
R_i = RC_i \left[ 1 - \prod_{j=1}^{r} p_{ij} \left( \frac{C_j - T_j}{\mu_j} \leq 1 \right) \right],
\]  

where \(RC_i\) is the reduced costs; \(p_{ij}\) is the probability of no losses in the technological system for the \(j\) parameter; \(C_j\) is the designed operational capabilities of the equipment for the \(j\) parameter; \(T_j\) is the used capabilities of the machine for the \(j\) parameter; \(\mu_j\) is the allowable value of the capability margin for the \(j\) parameter.

The minimum of this expression corresponds to the optimal variant of the technological system.

The choice of the structural type of the parameter series has a significant impact on the capabilities margin of its individual members. Ensuring maximum efficiency of the equipment during its design involves aiming at such a construction of the technological system in which its capabilities margin would have the lowest value. But this is possible only in conditions of mass production. For single and small-scale production, the increase the flexibility of the process equipment demands creating machines with an increased value of the allowable capabilities margin, even at the expense of a certain decrease in their efficiency.

The initial prerequisite for the most efficient use of the universal machines range is the equality of conditional average losses for all members of the parametric series:
\[ R_1 = R_2 = \ldots = R_k = \ldots = R_m = \text{const}, \]

where \( m \) is the number of members of the dimension-type series.

As stated previously, the development of machine tools parameter series implies standardization of their main parameter (swing over bed diameter, table width, etc.). Then the ratio between the main parameters of the neighboring members of the series will determine their regulatory margin of capabilities.

In this case, the dependence (1) can be transformed into a target function:

\[ R = \sum_{i=1}^{m} RC_i \left[ 1 - p \left( \frac{\varphi_i}{\varphi_i - 1} (1 - K_i) \leq 1 \right) \right] \rightarrow \text{min}, \]

where \( K = T_i / C_i \) is the utilization rate of the machine.

The reduced costs are known to grow as the main parameter of the equipment increases. Therefore, the analysis of the expression (3) demonstrates that the equality of conditional average losses for the machines range can be ensured if the parameter series is built with a variable denominator [20]:

\[ \varphi_1 > \varphi_2 > \ldots > \varphi_i > \ldots > \varphi_m. \]

Notably, the values of \( \varphi_i \) should be changed exponentially with the denominator \( \delta \).

Another way to ensure the condition \( R_i = \text{const} \) is to approximate the size of the workpiece or used cutting tools \( X \) to the maximum allowable ones. This in turn leads to a decrease in the ranges of variation \( D \) of the \( X \) parameter with the increase in equipment dimensions:

\[ D_1 > D_2 > \ldots > D_i > \ldots > D_m. \]

The synthesis of parameter series also necessitates ensuring the mobility of the machine tool population. This term refers to the ability of enterprises to quickly move to the release of new products based on existing equipment or, in extreme cases, with minimal equipment replacement.

This can be achieved by overlapping size ranges for individual members of the parameter series. However, repeated duplication significantly increases the cost of manufacturing and operating equipment though essentially does not improve its mobility. Given that the \( X \) parameter usually has a log-normal distribution for machines of a certain dimension-size, we recommend dividing the range of its variation into three approximately equal intervals (subranges). Then, the average (main) subrange \( a_m \) will account for more than 2/3 of the maximum performance processing. The remaining one-third of the work will be allocated to both of the other duplicate intervals \( a_{\min} \) and \( a_{\max} \). At the same time, the equipment can be used outside this dimensional range, but with some loss of performance as a result of non-compliance of the machine tools technical characteristics with optimal operating conditions.

Such a principle of forming a parameter series allows providing almost equal probability of the maximum performance processing of any size surface with a triple overlap of ranges.

3. Results and discussion

This is the methodology for constructing such parameter series: the source data for the synthesis procedure are the limit \( X_{\min} \) and \( X_{\max} \) of the \( X \) parameter varying. The data to be determined are the number of the series members \( m \) and the main equipment parameters \( X_{\maxi} \).

First, the minimum size of the interval is assigned and the value of its increment \( \delta \) is chosen. For practical reasons, the most preferred values are \( a_{\min} = 1.26 \) and \( \delta = 1.12 \). However, other options are possible.

All listed parameters are related by the correlation:

\[ D = a_{\min}^\delta (x^2 - \bar{x})^{1/2}. \]
where \( z \) is the number of a random variable \( X \) intervals; \( D = X_{\text{max}} / X_{\text{min}} \) is the range of random variable \( X \) variation.

The number of members of the parametric series is acquired by finding the logarithm of this expression and solving it with respect to \( z \):

\[
m = z - 2.
\]

(7)

After that, the denominators of the series are set:

\[
\varphi_i = a_{\text{min}} \delta^{k_i},
\]

(8)

where \( k_i = m - i \).

Thus, with an increase in the sequence number of the series member the value of \( \varphi \) decreases.

Defining the main parameters of the equipment is carried out according to the formula:

\[
X_{\text{max},i} = X_{\text{max}} \varphi^{k_i} \delta^{(k_i^2 - k_i)/2},
\]

(9)

where \( \varphi_m \) is the minimum value of the variable denominator of the series.

The value of the base (medium) \( \overline{a_i} \) and full \( D_i \) range of dimension variation \( X \) is set by the dependencies:

\[
\overline{a_i} = a_{\text{min}} \delta^{k_i + 1} \quad \text{and} \quad D_i = (\overline{a_i})^3.
\]

A graphic display of a parametric series with a variable denominator in logarithmic coordinates is presented in Figure 1.

Figure 1. Graphic display of a parameter series with a variable denominator in logarithmic coordinates (\( a_{\text{max}} \) is maximum subrange of the series; \( X_I \) and \( X_m \) are the average values of the \( X \) parameter for the first and \( m^{th} \) members of the series; for other symbols see the text)

As noted earlier, the main technical characteristics of the equipment are subject to concurrent optimization with the main parameter \( X_{\text{max},i} \). These characteristics include the limiting values of spindle rotating frequency, the allowable torque on it and the effective power limits. Any change in the structure of the parameter series automatically leads to a revision of these characteristics.

We proposed the methodology for the technical characteristics substantiation based on modeling the operational characteristics of machine equipment in [13, 15, 21]. By the operational characteristics we mean the variable values of the machine drives characteristics which depend on the processing modes, but do not exceed the technical characteristics. The essence of our approach to solving the problem is to
predict the distribution of these random variables system. The source data are the indicators of the speeds and cutting forces distribution when the machine performs specified functions. These parameters of processing operations are usually found by analyzing the relevant statistical information. The indicators of the diametrical dimensions distributions of the processed workpieces and the used cutting tools can be calculated by the dependencies:

\[
\sigma_i = \frac{\ln \bar{a}_i}{2};
\]

\[
\ln X_i = \ln X_{\text{max}} + (\ln \delta - 3\sigma_i);
\]

\[
\overline{X_i} = \exp \left( \ln X_i + \frac{\sigma_i^2}{2} \right),
\]

where \( \sigma_i \) is the standard deviation of the random variable \( X \); \( \ln \overline{X_i} \) is the average value of the logarithm of the random variable \( X \); \( \overline{X_i} \) is the average value of \( X \).

**Figure 2.** The distribution pattern of the machine operational characteristics

For the sake of clarity, the simulated system is represented as a distribution pattern (Figure 2), in which the values of characteristics are plotted in logarithmic coordinates: horizontal is the spindle rotation frequency \( n \), vertical is the torque \( M \), and diagonal is the effective power \( N \). The pattern shows the lines of equal probabilities of the performed work and the optimal scope of the simulated operational characteristics limiting values. They correspond to the extreme maximum values of the differential functions \( f(y) \) second derivative of the machine characteristics \( y \) resulting distributions:

\[
f(y) = \sum_{q=1}^{\omega} p_q f_q(y),
\]

where \( p_q \) is the probability of the processing conditions implementation \( q \); \( f_q(y) \) is the differential function of the elementary (specific) characteristic distribution for the processing condition \( q \) (\( y \) is the natural logarithm of \( n, M \) or \( N \)); \( \omega \) is the total number of the machine processing conditions.
In contrast to the generally accepted approach, the methodology additionally provides for limiting the minimum used power values. This significantly increases the average power factor (cos φ) of the engine and reduces energy consumption.

If necessary, all the characteristics thus obtained are subjected to subsequent adjustments taking into account the series of preferred numbers, standard values of motor power, etc. For the convenient choice of the optimal variant of the technical characteristics values alongside the simulation we propose to simultaneously calculate the percentage of work performed on the machine with the maximum performance under the established limitations of operating characteristics.

4. Conclusion
The procedure for optimizing the spatial, temporal and energy characteristics of machine tools is plausible only if these issues are solved concurrently. It facilitates achieving maximum integral indicators values of the process equipment quality.

The suggested approach to forming the structure of parameter series may be used not only for creating a new hybrid equipment, but also for completing a base of metalworking machines using the existing enterprise stock.

From a practical point of view, this will ensure a rapid transition to the release of new products with minimal economic costs, which is currently of particular relevance.

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