Reliability of quality forecast for hybrid metal-working machinery

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Reliability of quality forecast for hybrid metal-working machinery

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Abstract. The research considers the problem of quality prognostics in the conceptual design of process equipment. We propose the basic methodology of forecasting the operational parameters distributions for general-purpose cutting machines. Extreme local maxima of the basic functions second derivatives are suggested for selecting the optimum values of the machines' basic technical characteristics. We used the reliability of the quality forecast to evaluate its accuracy. The reliability is determined by the implementation of the corresponding estimates with the lowest uncertainty range at the selected probability value. The influence of initial operating parameters uncertainty on the forecast reliability was investigated by statistical modeling methods. We established the efficient application area of the proposed method depending on the degree of process equipment versatility. We suggest practical recommendations on providing forecast reliability of the basic specifications of integrated cutting machines.

1. Introduction
The problems of increasing labor productivity and reducing production costs are always relevant in modern production conditions as they determine the strategy of industrial development all over the world. The solution to these problems is possible only by providing high quality of technological machines [1-5], primarily, hybrid metalworking machines and integrated complexes, which are the basis of modern engineering [6 - 10].

The assessment of the quality increase feasibility requires approaching the task considering both the process machines performance standard and specific conditions of their use by consumers. The major difficulty is that for the general-purpose integrated metalworking machines, these conditions are not determined, as they depend on the type of production, variable nomenclature of the processed parts and applied cutting instruments, as well as frequently changing operating costs.

The main indicators of the quality of hybrid metal-working machines are the efficiency and flexibility (mobility). They are usually set at the initial stage of the integrated equipment conceptual design. And the accepted level of quality should be kept within the whole life cycle of the product. Taking into account the design period and the duration of the created process equipment operation, the task of choosing the optimal quality refers to the area of long-term forecast [11], the uncertainty of which increases with the increase the investigated period.

From the economic point of view, the excess quality is as unprofitable as insufficient one [12], which conditions the need to ensure the reliability of forecast estimates. The purpose of this research is...
to determine the degree of the forecast uncertainty influence of the general purpose-machines operating conditions on the reliability of their optimum quality choice.

2. Theory and methods
The quality is determined by the manufacturing capabilities of the equipment, which, in turn, depend on the size, speed, power and output characteristics of the machines. The former are dependent on the equipment parametric series structure [13], and the rest are the functions of the applied cutting modes and are linked by correlation dependence:

\[ N = \frac{M \cdot n}{9554}, \]

where \( N \) is the effective cutting power, kW; \( n \) is the spindle rotation speed, min\(^{-1} \); \( M \) is the spindle torque, N·m.

All these parameters are of random character and their distribution (Figure 1) is well described by the function:

\[ f(x) = \sum_{i=1}^{m} P_i f_i(x), \]

where \( P_i \) is the probability of the \( i \)th combination of processing kind, workpieces materials and applied cutting tools; \( f(x) \) is the differential function of the marginal \( i \)th distribution; \( m \) is the number of processing conditions combinations; \( i \) is the multi-index of the processing conditions combinations.

Since the information is not complete at the conceptual design stage, the optimum values of equipment specifications are expedient to define by the second derivative local maxima (Figure 1) of the basic function \( f''(x) \rightarrow \text{Max.} \)

The \( P_i \) probability forecast is achievable with sufficient statistical data for the retrospective period. However, the immediate forecast of \( f(x) \) distributions is difficult due to the inability of considering the diversity of the equipment application conditions in the long run. Therefore, the research [14] proposed to replace the immediate forecast of the specifications with a simpler forecast of the operational processing parameters \( a \). These include diameters of workpieces or the applied cutting tools: \( a \), \( V \) velocities and cutting forces \( P \). All these parameters are established to have lognormal distribution under certain processing conditions \( m \) [14]. The lognormal distribution can be constructed with the known average values of the specified parameters \( E_{\ln a} \) and their average square deviations of \( \sigma_{\ln a} \). These parameters are defined by the dependencies:

\[ \sigma_{\ln a} = 3 - \sqrt{9 - 2\left(\ln a_{\text{max}} - \ln a\right)}, \]

\[ E_{\ln a} = \ln a = \ln a_{\text{max}} - 3 \cdot \sigma_{\ln a}. \]
Applying the property of distributions stability and the theorem of mathematical expectations and dispersions [15] for the composition of similar distributions of random values $a$, it is possible to easily calculate the distributions parameters of the basic machine specifications [14]. But this requires additional consideration of the correlation between the initial operating parameters $R_n$, $R_M$ and $R_N$ [16].

In general, the validity of a variable forecast can be evaluated by such concepts as accuracy and reliability. However, accuracy can be applied only when the event has already taken place. Accuracy is evaluated as the difference between the expected and actual values. Therefore, at the designing stage only reliability is applicable for the evaluation of the forecast validity.

The reliability of specifications forecast is expedient to determine applying a certain range of $D_x$ uncertainty which determines the possible variation interval of specifications values in corresponding quantiles distributions. The forecast reliability depends on the implementation of the corresponding estimate with the lowest uncertainty range and the given probability value.

The previous task was accomplished using the Monte Carlo method [17], which assumes the existence of information about the distribution laws of the initial data. Four possible distribution variants were analyzed to assess their impact on the uncertainty of the various specifications of the machine. The indices of initial distributions were set according to the character of the analyzed parameters trend and the magnitude of the possible $\delta$ deviation within $\pm 40\%$.

Two hundred operational situations were randomly modeled in each experiment to reduce labor intensity. It allowed reaching the conclusions with the probability of $p = 0.995$ with a permissible error $\varepsilon \leq 0.1$ [16]. The adequacy verification of the received specifications distributions was theoretically executed according to the Pearson’s criterion $\chi^2$ [15].

The results of the conducted preliminary experiments prove that the specifications uncertainty is well approximated by logarithmically normal function at normal and uniform distributions of initial factors, because for all the investigated characteristics $P(\chi^2) > 0.05$. If this hypothesis is taken as basis, it is possible to establish certain correlation between the half-decile range of uncertainty $D_x(90)$ and average quadratic deviation of $\sigma$. This ratio is expressed by the dependence of $D_x(90) = \exp 3.29 \sigma$ [15].

This range covers 90% of all possible specifications variants, which allows applying it as a target function in the future. It should be noted that the maximum values of $D_x(90)$ are fixed at the normal distribution of the initial factors, and the minimum values are fixed at a uniform one. Therefore, all further studies were limited to consideration of the normal distribution of the initial parameters error. Normal distribution is characterized by the greatest range of specifications uncertainty.

3. Results and discussion

A group of lathe-based hybrid process equipment was subjected to the study of specifications uncertainty forecast. For this equipment we singled out 20 combinations of processing conditions which cover more than 95% of potentially performed types of treatment [14]. The results of the experiments are presented in Figure 2.

![Figure 2. The forecast uncertainty of machines specifications](image-url)
If $D_x(90) \leq 2$ is adopted for practical reasons, it is possible to limit the deviation of the initial data from the trend $\delta$ by the values $\pm 37\%$ at the forecasting.

Determining the influence degree of each of the initial parameters on the reliability of the equipment specifications forecast is of considerable practical interest. A special study was conducted to determine the significance of the individual parameters. The analyzed initial parameter was varied within the specified boundaries with fixed values of all other factors. The results of the simulation are reflected in Figure 3.

Studies have shown that attention should primarily be paid to the forecast of the processed surfaces mean diameters and applied cutting tools as well as average cutting modes, since the greatest contribution to the specifications uncertainty is made by them.

The maximum values of operational parameters and all correlation coefficients do not have such a noticeable impact on the result of the simulation. The probability of specific processing conditions reproduction on the machine manifests itself only with minimum values of $\delta$ and $m$.

Since the method of quality substantiation [14] is mainly focused on general-purpose machines, the identification of specifications forecast reliability dependence on the degree of equipment versatility is of particular interest. The equipment versatility is usually characterized by the number of technological operations $m$ performed on the machine. Mathematical modeling demonstrated that with the increase of the machines versatility the uncertainty of the specifications forecast with $m > 10$ is steadily reduced (Figure 4).

Figure 3. The influence of the initial parameters on the forecast reliability of the hybrid metalworking machines

Figure 4. The dependence of the forecast uncertainty on the versatility of the hybrid machine
This result is consistent with the arguments of other authors [11] that the forecast uncertainty of a large number of microobjects sum decreases with the increase in their number approximately in the ratio \( (\sqrt{n})^{-1} \).

The results of these experiments facilitate choosing the optimal strategy for the preparation of the initial data, which allows implementing the forecasting procedure with minimal costs and without significantly reducing its reliability. For example, the simpler method of expert estimation is expedient to use for the forecast of non-essential initial factors, and the method of extrapolation requiring gathering of statistical information should be used for significant initial data. In this case, the logistics curve is appropriate as a mathematical model adequately reflecting the evolutionary process of changing these factors. The parameters of the curve are determined by selective research of the workpiece machining conditions in retrospective period. The forecast of the processed workpieces geometry distributions and the applied cutting tools is not obligatory as these factors are set according to the optimization of process equipment parametric series [13] and therefore do not require any special studies.

4. Conclusion
The research showed the possibility of ensuring reliability of quality forecast at the stage of conceptual design of general-purpose metalworking machines.

We demonstrate the feasibility of substituting a deterministic quality forecast for the interval one, expanding the area of optimal solutions search. We present the data on the quantitative estimation of forecast reliability of machines specifications dependency on the level of initial information uncertainty. We determined the factors having the greatest influence on the quality of the equipment and suggested practical recommendations on the quality maintenance.

We also established the efficient application area of the developed quality optimization method depending on the degree of the equipment versatility.

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