Determining the operational loads of the hybrid metalworking machines drive

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Abstract. Numerous studies are devoted to determining the operational loads of metalworking machines. They employ various approaches including those based on analytical methods of calculation. However, their use is not always appropriate, since they do not take into account many features characteristic of the actual operating conditions of hybrid metalworking machines. The article proposes a universal method of substantiating the performance specification of the integrated machine-tool equipment based on mathematical modeling of its operating conditions. This technique allows generating objective data on the design loads of machine tools, which enables providing the necessary level of reliability of newly designed machines that have no analogues. The proposed approach provides the possibility of using automated design systems at the initial stage of creating the general concept of new process equipment.

1. Introduction

Most parts of the machine drive (gear and belt drives, shafts, bearings) work in conditions of prolonged loading under cyclic exposure. The main reason for the failure of the parts operated in this mode is the destruction of the material. Notably, the stresses at cyclic loading are significantly lower than the ultimate strength under static loading. Therefore, the rational choice of operating loads when estimating the fatigue strength of these parts is the key to improving the drive reliability [1-4].

The traditional approach to this task is based on calculating the distribution patterns of the drive operation time at various combinations of rotation frequencies and effective torques. This information is usually obtained on the basis of operating conditions data of analogous machine tools. However, calculating the machine drive parts at the initial design stage requires operating not with equivalent stresses, but with equivalent loads, since the specific design of components and their parts, as a rule, is not yet known [5-11].

The task becomes much more complicated at developing a fundamentally new machine design without any analogue. This is due to the fact that the operational loads of machines represent a system of correlated random variables depending on numerous and various factors, whose combinations are multivariant and probabilistic. In addition, the operating conditions of the designed machine are to be predicted long before they are tested in practice [9, 10, 12-17].

The reliable information is most often absent at the stage of a draft proposal development. Therefore, the issue of the reasonable designation of optimal operating loads has not been resolved so far. Using the standard techniques and recommendations leads to increased metal intensity of machine tools.
2. Materials and methods

The machine’s operating characteristics [effective power $P$ (kW), rotation speed $n$ (r/min) and torque $T$ (N m) on the spindle] form a system of interconnected random variables depending on a large number of additive and multiplicative factors (parameters of technological operations). Therefore, the principle of superposition should be taken as the basis of a mathematical model that adequately reflects the specific conditions of metal-cutting equipment operation [10, 14, 17]. In accordance with it, the differential distribution function for the system of operational characteristics is:

$$f(x, y) = \sum_{q=1}^{\omega} p_q f_q(x, y), \quad (1)$$

where $f_q(x, y)$ is the differential function of operational characteristics elementary (specific) distributions $x$ and $y$ (respectively $T$ and $n$) for certain $(q)$ processing conditions (the power $P$ is not included in the arguments of this function, since it is derived from $n$ and $T$); $p_q$ is the probability of machine operation in these conditions; $\omega$ is the number of different processing conditions implemented on the machine.

Numerous statistical studies have established that the considered operational characteristics can be described by a log-normal distribution law under certain combinations of technological factors for some processing conditions. Consequently, we change the variables in the formula (1): $x = \ln T$; $y = \ln n$ after which the function $f(x, y)$ can be represented as a probability surface. All the initial information necessary for its construction can be obtained at the stage of predicting the machine performance specification [10, 14, 17] or taken from the design reference.

The analysis of expression (1) leads to the conclusion that the final pattern of the operational characteristic differential distribution function is formed by adding together the particular functions taking into account their weighting coefficient. Moreover, constructing the distribution patterns of all operational characteristics allows determining the most efficient values of each characteristic separately, which essentially solves the problem of the initial optimization stage. Since “reduced costs” cannot be taken as an optimization criterion at an early design stage, it is necessary to resort to analyzing the nature of the change in the modeled dependence (1); its second derivative being best suited for the purpose:

$$f''(x, y) = \sum_{q=1}^{\omega} p_q f_q''(x, y), \quad (2)$$

wherein

$$f_q''(x, y) = \frac{1 - t_q^2}{\sigma_q^3 \sqrt{2\pi}} e^{-\frac{t_q^2}{2}} \quad \text{at} \quad t_q = \frac{x - E_q}{\sigma_q}, \quad (3)$$

where $t_q$ is the normalized deviation, $\sigma_q$ is the standard quadratic deviation of a random variable logarithms, $E_q$ is the mathematical expectation.

In this case, the optimization task essentially results in establishing the extrema of the objective function $f''(x, y) \rightarrow \max$. At the final optimization stage we proceed to a comprehensive analysis of the obtained system of operational characteristics distribution and determine the performance specification values based on the analysis results. The frequency of rotation $n$, the torque $T$ on the spindle, the cutting power $P$, related by a commonly accepted expression in mechanical engineering $P = T \cdot n / 9554$, form a system of random variables described by the function:

$$f(T, n) = \sum_{q=1}^{\omega} p_q f_q(T, n), \quad (4)$$
The density of elementary log-normal distributions \( f_q(\ln T, \ln n) \) of an interdependent random variables system is expressed by the formula:

\[
f_q(\ln T, \ln n) = \frac{1}{2\pi \sigma_{\ln T} \sigma_{\ln n} \sqrt{1-R_q^2}} e^{-\alpha},
\]

at

\[
\alpha = \frac{1}{2(1-R_q^2)} \left[ \frac{(\ln T - E_{\ln T_q})^2}{\sigma_{\ln T}^2} - \frac{2R_q(\ln T - E_{\ln T_q})(\ln n - E_{\ln n_q})}{\sigma_{\ln T} \cdot \sigma_{\ln n}} + \frac{(\ln n - E_{\ln n_q})^2}{\sigma_{\ln n_q}^2} \right],
\]

where \( R_q \) is the correlation coefficient of random variables \( \ln T \) and \( \ln n \).

However, studying the loads acting on individual elements rather than the entire surface of the drive is best performed with the use of the performance distribution pattern, which is a family of equal density curves (lines of equal probability). It is formed by cutting a surface with a \( f(x, y) \) series of planes parallel to a horizontal plane and projecting the obtained curves onto this plane [10, 14, 17].

Consistently integrating the function \( f(x, y) \) within a certain region \( S \) bounded by the \( ABCDE \) framework of characteristic values (Figure 1), one can find the probabilities \( p_q \) of the machine operating conditions for all combinations of \( n_i \) and \( T_j \), as well as the corresponding power \( P_q \). The probability of hitting a point with coordinates \( x_i \) and \( y_j \) in the elementary region \( \Delta S \):

\[
p_q[(x, y) \in \Delta S] = \int \int_{\Delta S} f(x, y) dx \, dy
\]

**Figure 1.** The distribution pattern of the machine operational characteristics

The work volume performed on a machine with a maximum performance is determined by summing these probabilities for the entire region of \( S \). If necessary, the position of the boundaries and, consequently, the values of operational characteristics are also adjusted (changing the position of the boundaries is also conditioned by the need to correlate the values of \( n \) with a series of preferred numbers and rounding the values of \( T \)).
The obtained probability values for the realization of the characteristics $n_i$ and $T_j$ can later be used to calculate the equivalent load acting on any designed drive element.

3. Results and discussion

The implementation of the proposed method is considered on the example of the CNC machine main motion drive. The simulation algorithm is quite simple. For convenience of analysis, the region $S$ selected on the diagram is divided into a number of subregions (zones) $S_k$. The number of subregions in the general case should be one higher than the number of the drive rotation frequency stages (in this example, $k = 5$; see Figure 1).

Within each of the zones, all the possible combinations of the values of $n_i$ and $T_j$ are scanned sequentially within the limits specified:

$$n_i \in \{n_{\min}, n_{\max}\}; \quad T_j \in \{T_{\min}, T_{\max}\}.$$  

The required power $P_{ij}$ is calculated for any combination of these conditions and then the possibility of its implementation is checked on the designed machine. If the value of $P_{ij}$ is within the range from $P_{\min}$ to $P_{\max}$ (see figure 1), then the probability of a given conditions combination for some elementary site $\Delta S$ is determined by formula (2). Simultaneously the desired torque values $T_i$ are calculated, as well as the expected number of $N_l$ loading cycles for each $l$ drive element:

$$T_i = T_j/(u_l \cdot \eta_l); \quad N_l = 60 \cdot n_i \cdot u_l \cdot p_{ij} \cdot \tau,$$

where $u_l$ and $\eta_l$ are, respectively, the gear ratio and the kinematic chain efficiency of the $l$ element to the spindle; $\tau$ is the technological lifespan of the drive, hours.

The efficiency of the machine main motion drive is determined according to the methodology [18], which provides for the differentiation between constant and variable components of energy losses. The technological lifespan of the drive is established, as a rule, by the customer in the design task of the machine.

The procedures described are repeated in a cycle sequentially as the zone number increases until all zones that are functionally provided with a specific drive element are examined. The resulting calculations of the values of $T_i$, and $N_l$ are used to determine the desired equivalent load $T_{\text{equivalent}}$ according to the methodology [19]:

$$T_{\text{equivalent}} = m \sqrt{\frac{1}{N_0} \sum_{i=1}^{K} T_{ij}^m \cdot N_l},$$

where $N_0$ and $m$ are respectively the base number of loading cycles and the slope of the fatigue curve descending arm [20]. They depend on the design features of the projected drive element and the physical and mechanical properties of its material; $K$ is the number of the considered drive elements.

4. Conclusion

The proposed approach to solving the problem is consistent with the approved methods for calculating various machine drive elements for fatigue strength (endurance); the mathematical model of equivalent loads does not require additional initial information besides the obtained at previous design stages data. Furthermore, this technique allows generating objective data on the design loads of machine tools, which enables providing the necessary level of reliability of newly designed machines that have no analogues.

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