Determination of parametric reliability of machining technological systems by simulation technique

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Abstract. The article deals with the problem of determining parametric reliability of technological systems for machining parts. The paper describes the methodology of defining the probability of task implementation by quality factors for technological systems by means of simulation technique.

1. Introduction

Current technological systems, aimed at technological processes and operations for machining components, represent a set of interconnected technological equipment, production tools and executives. The fact that technological systems have various interconnections and handling factors which are of probabilistic nature makes it difficult to provide product quality regulated by many factors. Thus, provision of required quality factors and service properties of components mainly depends on reliability of metal working technological systems [1, 2].

The reliability of the technological process (operation) is its property to provide production work-order quantity retaining its quality and permanent parameters of this process.

It is typical of technological systems as any other systems to have different kinds of failures. According to State Standard 27.004-85 technological systems can have parametric failures when they keep their functioning, but run one or more perfection factors of working surfaces away from the limits of the normative document.

So, the product quality depends on the parametric reliability of a technological system, which is characterised by the probability of this system no-failure operation, according to the parameter of the component quality.

Randomness of technological system processes stresses the reasons for applying a simulation technique to determine reliability factors. This paper contains the results of using this technique to estimate the parametric reliability of the technological system for antifrictional treatment of shaft journals.

2. Results and Discussion

In general case, the probability of task implementation according to a product quality factor provided by the technological process (operation) is:

$$P_i(t) = P\{x_{li} \leq x_i(t) \leq x_{ui}\}, \quad (1)$$

where $x_i(t)$, x_{ui}, x_{li} – are respectively actual, upper and low acceptable values of *i*-controlled parameter.

The methodology of defining the probability of task implementation for technological systems by means of simulation technique is based on determination of polynomial (2) and multiplicative (3) models of processes for forming component quality factors:

$$Y_i = \beta_0 + \beta_1 X_1 + \ldots + \beta_i X_i + \ldots + \beta_k X_k, \quad (2)$$

$$Y_i = b_0 \cdot X_1^{b_1} \cdot X_2^{b_2} \cdot \ldots \cdot X_k^{b_k}, \quad (3)$$

where Y_i – i-quality factor of the surface after working; X_k – k-working environment factor; b_0, b_1, …, b_k – regression coefficient values which are allocated in accordance with the normal law of expectation $M\{b_k\}$ and average quadratic deviation $S(b_k)$.

Probability P of task implementation by quality factor Y in a specified interval is taken as a parametric reliability factor:

$$P\left\{Y \in \left(\overline{Y} - \delta\overline{Y}; \overline{Y} + \delta\overline{Y}\right)\right\},$$

where $\overline{Y}$ – an average value of the specified quality factor; δ – a relative acceptable value of its changing ($0 \le \delta \le 1$). Values $\left(\overline{Y} - \delta\overline{Y}\right)$ and $\left(\overline{Y} + \delta\overline{Y}\right)$ correspond to values x_{li}, x_{ui} (1).

To calculate this factor it is necessary to know expectation Y_{i0} and average quadratic deviation σ_{i0} of the component quality factor under study. Simulation techniques of forming parameters Y_i represent so-called "black box models" and are of a statistical nature. It is advisable to use Monte-Carlo method to predict quality factors Y_i and their attributes $M\{Y_i\}$ and $S\{Y_i\}$, which are value estimations Y_{i0} and σ_{i0}.

The use of Monte-Carlo method is reasonable for systems whose models are described by complicated stochastic equations. In such cases when it is impossible to make a model because of the lack of data or the complexity of analytical model, Monte-Carlo method is often the only way to obtain related data.

If the only random variables in simulation models (2) and (3) are coefficients β_0 and β_i, and taking into account the properties of expectation and a random variable we can obtain the following expressions for estimations $M\{Y_{i0}\}$ and $S^2\{Y_{i0}\}$:

– for additive models:

$$M\{Y_{i0}\} = M\{\beta_0\} + \sum_{i=1}^{k} X_i M\{\beta_i\} = b_0 + \sum_{i=1}^{k} X_i b_i, \qquad S^2\{Y_{i0}\} = S^2\{\beta_0\} + \sum_{i=1}^{k} X_i^2 S^2\{\beta_i\};$$

– for multiplicative models:

$$M\{Y_{i0}\} = exp(ln\, M\{\beta_0\} + \sum_{i=1}^{k} ln\, X_i M\{\beta_i\}) = exp(ln\, b_0 + \sum_{i=1}^{k} b_i\, ln\, X_i),$$

$$S^2\{Y_{i0}\} = exp(ln(S^2\{\beta_0\} + \sum_{i=1}^{k} (ln\, X_i)^2 S^2\{\beta_i\}).$$

If models (2) and (3) have one or two working factors X_i as random ones, then it is not possible to find analytical expression for estimations $M\{Y_{i0}\}$ and $S^2\{Y_{i0}\}$. Their determination is connected with data array processing Y_{iN}, obtained as a result of the computer experiment by N executions of simulation models in Monte-Carlo method.

The results of simulation models show that some engineering and technological constraints are used as input data.

There are determined rated values of technological factors X_i, which allow obtaining the desired value of parameter Y_0. At the same time some simulation models use coefficients $b_i = M\{\beta_i\}$. When calculating the machining conditions which provide obtaining value Y in the specified interval $[Y_{min}, Y_{max}]$ we make an obligatory analysis of implementing the requirements for dimensional accuracy and form defects of the working component.

One of the main problems is to choose the number of model executions N during the computer experiment. The number of executions N should satisfy the specified accuracy of value estimates $M\{Y_i\}$ and $S^2\{Y_i\}$ according to the results of computer experiments.

Let the requirements to the expectation estimate be the following:

$$P\{Y_{i0} - d \le M\{Y_i\} \le Y_{i0} + d\} = 1 - \alpha, \tag{4}$$

where $(1 - \alpha)$ is the probability that interval $(Y_{i0} \pm d)$ contains estimate $M\{Y_i\}$.

Assuming the normal allocation of value Y_i obtained as a result of the computer experiment, we assume that the number of executions, which provides dependence (4), can be expressed as follows:

$$N_1 = \frac{(\sigma_{i0} z_{\alpha/2})^2}{d^2}, \tag{5}$$

where $z_{\alpha/2}$ – is two-way standard normal statistics; σ_{i0} – is an average quadratic deviation of quality factor Y_i; d – is allowable difference between the estimate and the true value of the expectation for parameter Y_i.

Thus, the use of correlation (5) is difficult, as it includes unknown value σ_{i0}. Let us express value d as a fraction of σ_{i0}: $d = \sigma_{i0} / a$. Now let us put it into (5) and we obtain:

$$N_1 = \frac{(\sigma_{i0}\, z_{\alpha/2})^2}{\left(\sigma_{i0}/a\right)^2} = a^2 \cdot z_{\alpha/2}^2 .$$

Here for estimate N_1 we have known values and we can use it successfully.

The problem of defining the number of model executions N_2 with the specified accuracy for dispersion estimate can be solved in the following way:

$$P\{(1 - d)\,\sigma_{i0}^2 \le S^2\{Y_i\} \le (1 + d)\,\sigma_{i0}^2\} = 1 - \alpha.$$

Here α is the number defining the degree of estimate proximity $S^2\{Y_i\}$ to true dispersion σ_{i0}^2 $(0 \le d \le 1)$.

A transducer of pseudorandom variables is used during the computer experiment to generate random variables X_i, β_{0j}, β_{ij}, ξ_{0i}, ξ_{ij}. At first, there are generated and uniformly distributed values in interval (0, 1), then a normally distributed random variable with parameters $M\{\beta_i\} = b_i$ and $S\{\beta_i\}$ is formed.

For parameter Y_i a simulation model like (3) has the following problem definition for the computer program: "Calculate N values of the function

$$Y_i = f(X_1, \ldots, X_j, \ldots, X_k; b_0, b_1, \ldots, b_j, \ldots, b_k; S\{\beta_0\}, S\{\beta_1\}, \ldots, S\{\beta_j\}, \ldots, S\{\beta_k\})$$

so that

$$Y_i = b_0 \cdot \prod_{j=1}^{k} X_j^{RNDN_i(b_i, S\{\beta_i\})},$$

where X_1, X_2, …, X_k – are values of input parameters of the technological process;

– b_0, b_1, …, b_k – are expectations for model coefficients;

– $S\{\beta_0\}$, $S\{\beta_1\}$, …, $S\{\beta_k\}$ – are their standard deviations;

– $RNDN_i\,(b_i, S\{\beta_i\})$ – is a normally distributed random variable with distribution parameters b_i and $S\{\beta_i\}$.

After calculating N values of parameter Y_i there is a check of statistical hypotheses and estimation of distribution parameters. For this purpose it is necessary to calculate $M\{\tilde{Y}_i\}$ and $S^2\{\tilde{Y}_i\}$:

$$M\{\tilde{Y}_i\} = \frac{\sum_{i=1}^{N} Y_{ij}}{N}, \qquad S^2\{\tilde{Y}_i\} = \frac{1}{N-1}\sum_{j-1}^{N}\left(Y_{ij} - \tilde{Y}_i\right)^2,$$

where Y_{ij} – values of i-parameter obtained in j-execution; $\tilde{Y}_i$ – average value of the quality factor of component Y_i, obtained in calculations during the computer experiment.

According to obtained data $\tilde{Y}_i$ distribution bar charts are made, and there are checked hypotheses on the distribution law by means of criterion χ^2 (Weibull distribution, normal distribution and log-normal distribution are considered). Value χ^2_{calc} is determined by the following expression

$$\chi^2_{calc} = \sum^{\ell} \frac{(\phi_0 - \phi_\ell)^2}{\phi_\ell},$$

where ϕ_0 – is observed frequency for each bar chart interval; ϕ_ℓ – is theoretical frequency for each interval.

If $\chi^2_{calc} \le \chi^2_{table}$ for this level of importance α and a number of freedoms, then there are no reasons to reject null hypothesis, and the distribution law corresponding to this hypothesis is accepted.

After these calculations there is a determined probability of task implementation according to dependences:

$$P\{Y_{i\,min} < Y_i < Y_{i\,max}\} = \Phi\left(\frac{Y_{i\,max} - M\{\tilde{Y}_i\}}{S\{\tilde{Y}_i\}}\right) - \Phi\left(\frac{Y_{i\,min} - M\{\tilde{Y}_i\}}{S\{\tilde{Y}_i\}}\right), \quad (6)$$

$$P\{Y_i < Y_{i\,max}\} = 0{,}5 + \Phi\left(\frac{Y_{i\,max} - M\{\tilde{Y}_i\}}{S\{\tilde{Y}_i\}}\right). \quad (7)$$

Dependence (6) is applied in case of two-way limitation of parameter Y_i, and (7) – in case of one-way limitation.

Taking into account that state parameters of a surface layer are often specified with a symmetrical tolerance variability interval as

$$Y_i = M\{Y_i\} \pm \delta M\{Y_i\},$$

where δ is a relative variability interval width (specified in design documentation), then the estimation of probability of task implementation by the technological system for quality factor Y_i is carried out depending on value δ.

When studying reliability factors of the technological system by means of the simulation technique on statistical models, one should take into account that it is possible to simulate only “past”, i.e. data obtained experimentally at the stage of getting simulation models. Thus, to confirm the prediction of the simulation model it is necessary to assume that the basic form of distribution of technological process parameters remains unchanged and its features relevant to a certain time interval will repeat. These assumptions should be made for a normally operating technological process.

Let us take an example of using this method for determination of reliability of tribotechnical characteristics and roughness parameters in the technological system of antifrictional treatment of shaft journals for plain bearings.

The technological process includes finish-turning operations by polycrystalline cbn (cubic boron nitride) cutting tool, layering soft copper-bearing break-in film and diamond burnishing.

Finish turning was made by standard cartridge toolholders of geksanit at cutting speed V_t = 65 – 200 m/min; at feed S_t = 0.05 – 0.15 mm/rotation; at cutting depth t = 0.1 – 0.25 mm; at rigidity j = 2.6 – 16.2 кN/mm.

The soft break-in film was layered by means of the frictional brass coating or chemical copper plating.

Diamond burnishing was carried out by the diamond indenter with tip radius r = 3.5 mm; burnishing power Q_{DB} = 100 – 300 N; processing speed V_{DB} = 65 – 100 m/min; feed S_{DB} = 0.075 – 0.15 mm/rotation.

Tribotechnical characteristics of samples were tested at a special test bench with friction slide bearings working with lubricant at dynamic loads – relative interfacial slip speed V_{run} = 10 – 50 m/min; average linear joint load P_{run} = 30 – 50 N/mm; relative change of the average load at dynamic aging $\Delta p = \pm$ (15 – 25) %.

We studied the following tribotechnical joint characteristics under the conditions of sliding friction: friction coefficient at the beginning f_1 and at the end f_0 of aging; initial wear values h_{01}, h_{02}, aging ways L_{01}, L_{02} and wear rates I_1, I_2 for shafts and bushes, respectively.

For the tested system the corresponding simulation models were made:

$$Y_i = b_0 K_1 K_2 V_t^{b_1} S_t^{b_2} t^{b_3} j^{b_4} Q_{DB}^{b_6} S_{DB}^{b_7} V_{DB}^{b_8} V_{run}^{b_{10}} P_{run}^{b_{11}} \Delta_p^{b_{12}},$$

where Y_i – i-tribotechnical characteristics; K_1, K_2 – coefficients in view of break-in film type M_b and bush material respectively M_{bush}; b_k – regression coefficient.

The reliability of formation of operational parameters was determined by simulation modelling according to the suggested plan.

The results of computer experiments of models showed that tribotechnical characteristics under study can be controlled by changing the factors of the tribotechnological system within wide limits with a great level of reliability (Figure 1).

A statistical data manipulation also showed the possibility to control tribotechnical characteristics (f_1, f_0, (h_{01}+ h_{02}), I_1, I_2) in the following sequence beginning with the most effective factor: $\Delta p \rightarrow V_{run} \rightarrow M_b \rightarrow S_{DB} \rightarrow S_t \rightarrow Q_{DB} \rightarrow j \rightarrow V_t \rightarrow M_{bush} \rightarrow t \rightarrow P_{run} \rightarrow V_{DB}$.

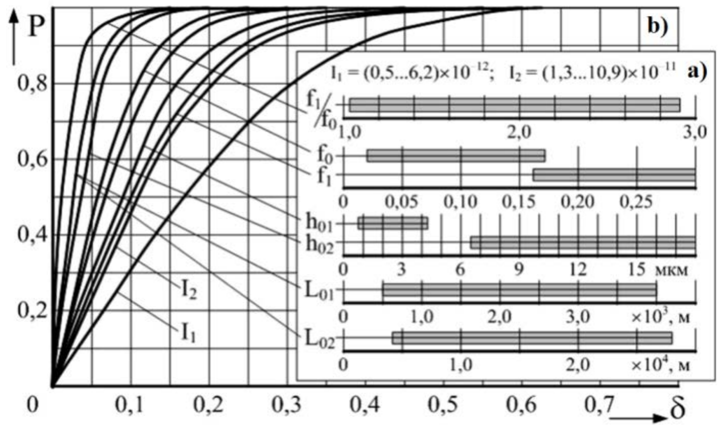

Figure 1. Diagram of changing (a) tribotechnical characteristics and reliability (b) of their providing $P\left(Y_i \in \left(\overline{Y_i} \pm \delta \overline{Y_i}\right)\right)$ depending on value δ in the technological system under study

3. Conclusion

The developed methodology of defining parametric reliability of technological systems by quality factors for working components helps to choose the best optimal technological process of working which has the maximum value of reliability as an optimality criterion that in consequence provides a high quality of working components.

References

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