Regression analysis of the results of planned computer experiments in machine mechanics

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Abstract. The possibility is considered on the basis of the planned computational experiment at the stage of mathematical modeling to efficiently construct convolutions of the received information. This allows us to build a direct functional relationship between the parameters and the quality criteria of the dynamic system. Formulas for calculating the coefficients for some types of regression dependencies are obtained, pre-calculated estimates of the variances from below and from above are given both for the coefficients and for the values of the regression function (i.e., the error forecast of the quality criterion). The results of research on the mathematical model of acoustic emission of loom elements are presented; a mathematical model for the propagation of acoustic energy by the design of the machine is constructed; Such assessments made it possible to develop recommendations for reducing machine noise.

1. Introduction
Conducting mathematical experiments should be purposeful and optimal. The specific nature of the various fields of scientific research led to the development of a variety of methods and their modifications to the planning of extreme experiments [1].
In the study of machines and mechanisms, the specificity of this field of scientific knowledge is associated with the construction on the basis of classical mechanics of mathematical models in the form of a set of differential equations (ordinary, linear and nonlinear, in partial derivatives), and analysis of the solutions of these equations, depending on the parameters of the system and the specified quality criteria cars [2,3,4]. Taking into account the specific nature of the investigation of the problems of machine mechanics, the authors proposed the PLP search method (planned LP search) [5], which, on the one hand, makes it possible, on the basis of computational experiments, to perform a quasi-uniform survey of the region of the investigated parameters $G(\bar{\alpha})$, on the other hand, as a result of special planning of these experiments, quantitative estimates of the influence of the variable parameters $\alpha_i$ on the analyzed properties of the machine (estimates developed in mathematical statistics) are applied.
With the use of simulation in the problems of analysis and synthesis of dynamic systems, they face the problem of obtaining a large amount of information, and hence the problems of processing and interpreting the results obtained. One possible way to solve these problems is to reduce the...
information obtained on the basis of statistical processing of the results of simulation modeling. In particular, widely used dependencies in the form of generalized of the power Kolmogorov-Gabor polynomial

$$\Phi_k(\alpha) = \beta_0 + \sum_{j=1}^{r} \beta_j \alpha_j + \sum_{j=1}^{r} c_j \alpha_j' + \sum_{j=1}^{r} d_{ij} \alpha_j' \alpha_j'^{i},$$

where $$\Phi_k(\alpha)$$ is the value of the k-th criterion of system quality ($$k = 1, m$$); $$\alpha$$ - a vector of design parameters of the system ($$\alpha = \alpha_1, \ldots, \alpha_n$$); $$s$$ and $$r$$ are the numbers of the natural series, greater than or equal to two; $$j = 1, r$$; $$\beta_0$$, $$\beta_j$$, $$c_j$$ and $$d_{ij}$$ are the coefficients to be estimated from the results of the experiments. We introduce the vector of coefficients $$\vec{b} = (b_1, \ldots, b_p)$$, estimated in expression (1), where $$p = 1, n - 1$$, and $$n$$ in the general case is defined by the formula

$$n = (r^2 + 3r + 2) / 2.$$  

It follows from (2) that even at $$r >> 3$$ $$n >> 10$$. Obviously, such a power-law dependence, useful in some cases, is most often inefficient due to the cumbersomeness of expression (1) and, therefore, does not lend itself to operational interpretation. There is a problem of reducing the number of terms in expression (1), which is directly related to the decrease in the dimension $$r$$ of the space of variable parameters $$\alpha_j$$. In the PLP-search method, this problem is solved on the basis of the constructed procedure for carrying out the experiments and using the variance analysis. So we assume that the real number of parameters $$r' < r$$.

2. Estimation of regression model parameters

The standard method for determining the unknown coefficients of expression (1) is the method of least squares (LSM). Using the LSM procedure (1), we obtain a $$b_p$$ system of linear equations of the form

$$dQ/db_p = 0,$$

where $$Q = \sum_{j=1}^{N} [\Phi_{k,j}(\alpha) - \Phi_{k,j}^2(\alpha)]^2$$; $$N$$ is the number of experiments on a computer, $$\Phi_{k,j}^2(\alpha)$$ the value of the quality criterion obtained on a computer as a result of calculations on the mathematical model. To represent the form of the system of equations (3), we write the first equation of this system:

$$N b_0 + b_1 \sum_{j=1}^{N} \alpha_{1,j} + ... + b_r \sum_{j=1}^{N} \alpha_{r,j} + \sum_{j=1}^{N} \alpha_{r+1,j} + ... + b_{pr} \sum_{j=1}^{N} \alpha_{pr,j} +$$

$$+ b_{pr+1} \sum_{j=1}^{N} \alpha_{pr+1,j} + ... + b_{pr+1} \sum_{j=1}^{N} \alpha_{pr+1,j} + ... = \sum_{j=1}^{N} \Phi_{k,j}^2.$$  

Already from equation (4) it is clear that to find the coefficients $$b_p$$ it is necessary to calculate various functions of the parameters $$\varphi(\alpha_j)$$, for example, $$\sum_{j=1}^{N} \alpha_{r,j}$$, $$\sum_{j=1}^{N} \alpha_{pr+1,j}$$. In addition, it is necessary to calculate the right-hand sides of equations (3). For an arbitrary arrangement of vectors $$\alpha$$ in the space of variable parameters, all the indicated functions $$\varphi(\alpha_j)$$ and right-hand sides are usually counted by a computer and then use some standard procedure for solving a system of linear equations.

In the case of a study of a dynamical system on a computer with the help of a PLP-search, it is possible to calculate every function of $$\varphi(\alpha_j)$$ in advance using the formulas proposed below. This is possible, since in PLP-search all the number of $$N$$ experiments is carried out on a computer in series by $$M$$ experiments in each, i.e. $$N = M T$$, where $$T$$ is the number of series of experiments, and pseudo-random numbers $$d_{ij}$$ of the $$L_{pr}$$-sequence are used.

Let's consider in detail the derivation of the formula $$\varphi(\alpha_j) = \sum_{i=1}^{M} \alpha_{j,i}$$. Let us write down the expression for calculating $$\alpha_{0,j}$$:
where \( 0 < q_{j,l} < 1 \), \( \alpha_{j,l} \in (\alpha_{j,1}, \alpha_{j,w}) \) and \( \Delta \alpha_j = \alpha_{j,w} - \alpha_{j,1} \). In the PLP-search \( M_j = 2^{2^v} \) \( (v=2,3,\ldots) \), and the index \( j \) ranges from \( 2^v \) to \( 2^{v+1}-1 \). In view of the above, the expression for \( \varphi(\alpha_j) \) takes the form

\[
\varphi(\alpha_j) = \sum_{i=2}^{2^{v+1}-1} \alpha_{j,i} = \sum_{i=2}^{2^{v+1}-1} \left( \alpha_{j,0} + q_{j,i} \Delta \alpha_j \right) = 2^v \alpha_j + \Delta \alpha_j \sum_{i=2}^{2^{v+1}-1} q_{j,i}.
\]

(6)

On the interval \([2^v; 2^{v+1}]\), the number \( q_{j,l} \) is represented as a fraction

\[
q_{j,l} = (2(l-2^v) + 1)/2^{v+1}
\]

(7)

Taking into account (7), expression (6) takes the form

\[
\varphi(\alpha_j) = 2^v \alpha_j + \Delta \alpha_j \sum_{l=2}^{2^{v+1}-1} \frac{2(l-2^v) + 1}{2^{v+1}} = 2^v \alpha_j + \frac{\Delta \alpha_j}{2^{v+1}} [1 + 3 + \ldots + (2^{v+1} - 1)] = \frac{M_j}{2} (\alpha_j + \alpha_{j,w}).
\]

(8)

Analogously to (8), using the formulas (5) and (7), we can find expressions for the sum \( \sum_{j=1}^{N} \alpha_{j,l}^s \) for any \( s \geq 1 \). In [6] the formulas for these sums are given for the most commonly used values of \( s \). In order to obtain the values of \( \varphi(\alpha) \) for all \( N \) experiments on a computer, we need to multiply the values calculated by tabular formulas by the number of series \( T \). Otherwise it is the sums of the form \( \sum_{j=1}^{N} \alpha_{j,l}^s \). Exact expressions for calculating such sums can not be found. However, in the implementation of the matrix of planned experiments in series with a large number of experiments in each \( (M_j = 16, 32,\ldots) \), it turned out that these sums can be calculated from approximate formulas with a sufficient degree of accuracy:

\[
\sum_{j \in M_j}^{2M_j-1} \alpha_{j,l}^s \approx M_j E(\alpha_{j,l}^s),
\]

(9)

where \( E(\alpha_{j,l}^s) \) is the mathematical expectation of the quantity \( y_j = \alpha_{j,l}^s \). Taking into account that \( \alpha_{j,l} \) and \( \alpha_{j,l} \) are independent pseudo-random uniformly distributed numbers computed by formula (5), we obtain \( E(\alpha_{j,l}^s) \) the following expression:

\[
E(\alpha_{j,l}^s) = E(\alpha_{j,l}^s) E(\alpha_{j,l}^s) = \frac{(\alpha_{j,1}^{s+1} - \alpha_{j,w}^{s+1})(\alpha_{j,1}^{s+1} - \alpha_{j,w}^{s+1})}{(s+1)(t+1)\Delta \alpha_j \Delta \alpha_j}.
\]

(10)

When calculating the sums \( \Sigma y_s \), for all \( N \) experiments formula (9) takes the following form:

\[
\sum_{j=1}^{M_j} \left( \sum_{l=1}^{2M_j-1} \alpha_{j,l}^s \right) \approx M_j T E(\alpha_{j,l}^s).
\]

(11)

The error in the computation by formula (11) can be estimated as follows:

\[
\delta = \left| 1 - \left( \sum_{j=1}^{M_j} \left( \sum_{l=1}^{2M_j-1} \alpha_{j,l}^s \right) \right) / M_j T E(\alpha_{j,l}^s) \right|.
\]

(12)

Obviously, \( E(\delta) = 0 \). Let us calculate the variance \( \sigma^2(\delta) \):

\[
\sigma^2(\delta) = \sigma^2 \left( \sum_{j=1}^{M_j} \left( \sum_{l=1}^{2M_j-1} \alpha_{j,l}^s \right) \right) / \left[ M_j T E^2(\alpha_{j,l}^s) \right].
\]

(13)

For the internal sum of the numerator in formula (13), we can write

\[
\sigma^2 \left( \sum_{j=1}^{M_j} \alpha_{j,l}^s, \alpha_{j,l}^2 \right) = \frac{(\alpha_{j,1}^{s+1} - \alpha_{j,w}^{s+1})(\alpha_{j,1}^{s+1} - \alpha_{j,w}^{s+1})}{(2s+1)(2t+1)\Delta \alpha_j \Delta \alpha_j} - \frac{(\alpha_{j,1}^{s+1} - \alpha_{j,w}^{s+1})^2}{(s+1)^2(t+1)^2(\Delta \alpha_j \Delta \alpha_j)^2}.
\]

(14)

The substitution of (14) in (13) gives an expression for the variance \( \sigma^2(\delta) \):
\[
\sigma^2(\delta) = \left[ \frac{(s+1)^2(t+1)^2(\alpha_{7+1}^2 - \alpha_{r+1}^2)(\alpha_{2+1}^2 - \alpha_{r+1}^2)\Delta \alpha_j \Delta \alpha_k}{(2s+1)(2t+1)(\alpha_{r+1}^2 - \alpha_{r+1}^2)^2(\alpha_{r+1}^2 - \alpha_{r+1}^2)^2} \right] \frac{1}{M/T}.
\]

As can be seen from formula (15), the quantity \( \sigma^2(\delta) \) does not depend on the dimension \( r \) of the space of variable parameters \( \alpha_i \), is symmetric with respect to the exponents \( s \) and \( t \). It also follows from (15) that the variance of the error \( \delta \) depends on the values of \( \Delta \alpha_j \) and \( \Delta \alpha_k \) and tends \( M/T \to \infty \) to zero as \( t \) increases. However, it is clear from (10) and (12) that if \( \alpha_{r+1} = |\alpha_{r+1}| \) or \( \alpha_{r+1} = |\alpha_{r+1}| \) and at least one of the exponents \( s \) or \( t \) is an odd number, then we can not use formula (11), since in accordance with formula (15) \( \sigma^2(\delta) \to \infty \). Analysis of the functional dependences of \( \sigma(\delta) \) on \( T \) for various \( M_j \), carried out for the cases \( s = t = 1 \) and \( s = 2 \) and \( t = 1 \), shows that \( \sigma(\delta) \) decreases significantly after 5-7 series, does not change significantly. To significantly reduce the variance of the error \( \delta \), it is necessary to increase the number of experiments \( M_j \) in the series.

3. Solution of the two-criteria problem of optimal design of the weaving system of the loom

Let us consider a concrete example of the application of the above procedure for investigating the sensitivity of criteria to changes in parameters in the problem of multicriteria design of a loom according to acoustic criteria. Any task of designing a modern technical device is multicriteria, even if a hierarchy of criteria is established. However, I would like to emphasize that when using the decision-making methodology in design problems of technical devices, two groups of quality criteria should be distinguished. The first group includes all those criteria that characterize (assess) directly the quality of the required work and the corresponding technical characteristics (accuracy, speed, vibration, size, etc.). The second group includes all those criteria that characterize the technical and economic properties of the projected device (cost, labor, reliability, environmental adaptability to the environment, etc.). At the same time, analysis of the first group of criteria provides quite a lot of opportunities in formalizing the very process of selecting a set of permissible variants, and hence complete automation of the entire process with the help of a computer. Vulnerable in this process is in many cases the lack of functional dependence of the criteria of the first group on the parameters of the device being designed. However, on the basis of simulation experiments on computers, this gap can be eliminated in each specific case by constructing approximation models of criteria.

In [7], based on the use of the method of the planned PLP search experiment in the space of variable parameters \( \eta_j \) (1,...,6), the region \( G(\bar{\eta}) \), where a probability of \( P \geq 95\% \) can find variants of the vibration proof coating of the weaving loom system, good from a natural point of view, was identified numerically. And this point of view consists in the fact that a variant with standardized qualities of \( \lambda_k \) (\( \kappa = 1,2 \)), estimating the noise level \( (0 \leq \lambda_1 \leq 1) \) and the consumption of the vibration-isolating material \( (0 \leq \lambda_2 \leq 1) \), would be close to the ideal, albeit unrealistic, version of the coverage. As the criteria for identifying the region in the space of variable parameters, the utility function

\[
\Phi_j(\bar{\eta}) = \sum_{i=1}^{2} c_i \lambda_i
\]

and function

\[
\Phi_i(\bar{\eta}) = \left| c_1 \lambda_i - c_2 \lambda_i \right| / \sqrt{c_1^2 + c_2^2}, \quad \text{criteria } \lambda_1 \text{ and } \lambda_2,
\]

satisfying the condition. In the future, to simplify the analysis and calculations, it is assumed that \( c_1 = c_2 = 0,5 \).

The fact that the region \( G(\bar{\eta}) \) does contain variants that satisfy the definition of a good variant is indicated by the results of a numerical experiment carried out in this area. 190 variants were calculated on the computer, in which the maximum and minimum values of \( \lambda_1 \) and \( \lambda_2 \) determined the following intervals of change:

\[
0,690 \leq \lambda_1 \leq 0,952 \text{ and } 0,539 \leq \lambda_2 \leq 0,835.
\]

Such a final result in [7] has the disadvantage that knowing a region’s \( G(\bar{\eta}) \) boundaries by solving a particular design problem of a vibration protection device is of little use in itself. After all, for every new option in this area, all the calculations must be carried out again, and the question of the sensitivity of \( \lambda_1 \) and \( \lambda_2 \) to variations of the damping coefficients \( \eta_i \) remains unresolved.
Therefore, the problem of restoring the immediate functional connection between the criteria \( \lambda_1 \) and \( \lambda_2 \) and the parameters \( \eta_i \) is solved below; in the selected area \( G(\vec{f}) \). The success in constructing such a dependence is related to the depth of the physical representations about the modeled phenomenon and the successful choice of its form, the completeness of the experimental data. Before proceeding to a description of the construction of such dependences, we classify the parameters \( \eta_i \) whose boundaries of variation form the region \( G(\vec{f}) \):

\[
0,010 \leq \eta_i \leq 0,055; \quad 0,010 \leq \eta_2 \leq 0,060; \quad 0,010 \leq \eta_1 \leq 0,156; \\
0,010 \leq \eta_6 \leq 0,105; \quad 0,15 \leq \eta_7 \leq 0,156; \quad 0,024 \leq \eta_8 \leq 0,156.
\]

(17)

The normalized values of the parameters \( \eta_{ij} \) are calculated from formula \( \eta_{ij} = (\eta_i - \eta^*_i) / (\eta_{ij}^* - \eta^*_i) \), and the region \( G(\vec{f}) \) is transformed into a single six-dimensional hypercube \( \mathcal{K}^6 \) with an edge \([0; 1]\).

The construction of polynomial dependencies \( \lambda_i(\vec{\eta}_j) \) and \( \lambda_2(\vec{\eta}_j) \) is associated with the use of multiple regression methods. However, such dependences are often of little value at least because of the large number of parameters and their combinations that are included in these dependences. In this case, a different path was used. It is known that the product \( V = \Pi \eta_{ij} \) indirectly characterizes the consumption of a vibration-insulating material. It is also known that an increase in \( V \) leads to an increase in \( \lambda_1 \) and a decrease in \( \lambda_2 \). Therefore, the following dependences were chosen for the construction:

\[
\tilde{\lambda}_1 = a \log(V + b) + c, \quad \tilde{\lambda}_2 = d \log(V) + f.
\]

(18)

By minimizing the expressions \((\lambda_{ei,2} - \tilde{\lambda}_2)^2\) and \((\lambda_{ei,1} - \tilde{\lambda}_1)^2\) with a given accuracy \( \delta \), for each one they \( i = 1,80 \), find their own set of parameters \((a; b; c)\) and \((d; e; f)\), and then the values \( a; b; c; d; e; f \) are averaged over 80 realizations. Here \( \lambda_{ei,1} \) and \( \lambda_{ei,2} \) - the values of the criteria \( \lambda_1 \) and \( \lambda_2 \), obtained in experiments on a computer. As a result, the following expressions are obtained:

\[
\tilde{\lambda}_1 = 0,0525 \log(V + 2 \times 10^{-6}) + 0,9852, \quad \tilde{\lambda}_2 = 0,4555 - 0,0955 \log(V + 2 \times 10^{-6}).
\]

(19)

The approximate dependences (19) obtained are checked for the significance of predictive properties (adequacy) in the region of \( \mathcal{K}^6 \). Calculating the mean values \( \bar{\lambda}_1, \bar{\lambda}_2, \) and variances \( \sigma^2_{1i}, \sigma^2_{2i} \) using numerical experiments, we obtain: \( \bar{\lambda}_1 = 0,8514, \bar{\lambda}_2 = 0,7106, \sigma_{1i} = 0,0521, \sigma_{2i} = 0,0796 \). Using these same data, determining the confidence intervals in \( 2 \sigma \) for \( \lambda_1 \) and \( \lambda_2 \), we obtain:

\[
0,695 \leq \lambda_1 \leq 1 \quad \text{and} \quad 0,472 \leq \lambda_2 \leq 0,762.
\]

(20)

Inequalities (16) and (20) are in good agreement with each other. Values of the variances of the predicted values \( \tilde{\lambda}_1 \) and \( \tilde{\lambda}_2 \) are calculated by the formulas

\[
\sigma^2_{1T} = \frac{\sum_{i=1}^{80} (\lambda_{1i} - \bar{\lambda}_1)^2}{N - n - 1}, \quad \sigma^2_{2T} = \frac{\sum_{i=1}^{80} (\lambda_{2i} - \bar{\lambda}_2)^2}{N - n - 1},
\]

where \( n \) is the number of coefficients defined in each of formulas (18). By calculations, we obtained \( \sigma_{1T} = 0,0262 \) and \( \sigma_{2T} = 0,0675 \). Using the Fisher criterion, we check the significance of equations (19) \( F_1 = \sigma^2_{1i} / \sigma^2_{1T} = 3,95 \) and \( F_2 = \sigma^2_{2i} / \sigma^2_{2T} = 1,39 \). These values of the Fisher test for degrees of freedom \( f_1 = N - 1 = 79 \) and \( f_2 = N - n - 1 = 76 \) and significance level \( p = 0,05 \) are larger than the corresponding theoretical value \( F_T = 1,34 \). This result \( (F_1 > F_T \) and \( F_2 > F_T) \) indicates that with a probability of \( P \geq 95\% \), the predictive properties of the equations for \( \tilde{\lambda}_1 \) and \( \tilde{\lambda}_2 \) are sufficiently reliable. What useful information does the dependency (19) give directly to the designer? First of all, if the coverage option is estimated using some utility function, for example \( \Phi_1(\vec{\eta}_i) \), an analogous function \( \Phi_2(\vec{\eta}_i) \), it is possible to predict the value \( \Phi_3(\vec{\eta}_i) \) at specific values \( \eta_{ij} \), knowing in advance about the absolute value of the discrepancy in the values of \( \tilde{\lambda}_1 \) and \( \tilde{\lambda}_2 \). If \( \Phi_4(\vec{\eta}_i) = \varepsilon \), then \( \Phi_4(\vec{\eta}_i) \) depends on \( \varepsilon \) as follows:

5
\[ \Phi_j(\bar{\eta}) = 0.7204 + 0.2054\varepsilon, \]  

(21)

where \(|\varepsilon| \leq m\). It follows from the dependence (21) that for \(\varepsilon = \pm 20\%\) the difference between the maximum and minimum values \(\Phi_j(\bar{\eta})\) is only 0.08. In this case, to each pair of values of \(\Phi_1(\bar{\eta})\) and \(\Phi_2(\bar{\eta})\) there corresponds a specific value of \(V\). It is important that this value of \(V\) can be achieved by any combination of values \(\eta_{ij}\), and hence also \(\eta_j\). It is also important that the values \(\lambda_1\) and \(\lambda_2\) are insensitive to the variations of \(V\). Indeed, on the basis of (19), the sensitivity functions \(S_1\) and \(S_2\) with respect to \(V\), are equal to \(S_1 = \frac{d\tilde{\lambda}_1}{dV} = 0.0525V + 2 \times 10^{-6}\); \(S_2 = \frac{d\tilde{\lambda}_2}{dV} = -0.0955V + 2 \times 10^{-6}\).

Analysis of the functions \(S_1\) and \(S_2\) shows that, starting from a certain value \(V \geq 0.0001\), both criteria become insensitive to changes in the values of this parameter \(\eta_j\) up to its maximum value \(V_{\max} = 1\) from the region (17), and there will be a tendency to decrease \(\tilde{\lambda}_1\) and increase \(\tilde{\lambda}_2\).

4. Conclusion

Based on the results of this paper we draw the following conclusions. First, on the basis of the application of the PLP-search method, when simulations were carried out on computers, it was possible to isolate the region \(G(\bar{\eta})\), that is the generator of such variants of the vibration protection coating of the loom, in which the standardized quality criteria \(\lambda_1\) and \(\lambda_2\), with a high degree of probability exceed 0.5. Secondly, on the basis of identifying this area and understanding the physical processes, it was possible to construct mathematical models that reliably relate the values of the criteria to the values of the variable parameters. Third, on the basis of the constructed mathematical models of criteria \(\lambda_1\) and \(\lambda_2\), the functions of the sensitivity of the criteria with respect to variable parameters are constructed; thereby creating objective opportunities for the preliminary selection of a compromise cover option according to the criteria of the first \(\lambda_1\) and second \(\lambda_2\) groups. It should be noted that the approximated dependences obtained were sufficiently well coordinated with the approximated mathematical models of the systems. At the same time, these dependencies turned out to be compact, easily interpreted and informative.

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