# Methods of Machine Improvement & Contemporary Problems of Machine Science

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(Metody Sovershenstvovaniya Mashin
i Sovremennye Problemy Mashinovedeniya)



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# Contents

## *INTRODUCTION*

Machine science covers a complex of scientific disciplines relating to machinery construction without regard to the branch of industry concerned or the end purpose of the machine. Like architecture in construction, contemporary machine science in machine design determines the direction and theory of development of improved highly reliable energy-efficient machines and mechanisms at minimal cost in materials and energy. Advances in contemporary machine science, which has been greatly enriched in recent decades by fundamental achievements in physics, mechanics, chemistry, electronics, computers, automatic control, etc., have supported progress in Soviet machinery manufacture.

Steady improvement in machinery manufacture demands further elaboration of scientific fundamentals and extensive use of advances in machine science. We have now perfected automatic assembly lines and automatic machines; robotics are being developed, and flexible automated production (FAP) systems are being introduced, including "unmanned" factories. The attention of scientists, engineers, and designers is concentrated on drastic improvement of the quality of the machines produced to meet current reliability and safety requirements and on the development of fundamentally new future-generation machines. Unfortunately, advances in the design and perfection of machines, instruments, and mechanisms and methods for their design and operation are not yet used consistently as "working tools" in the hands of the creative designer of new technology. Important scientific research results obtained in the field of modern machine science are often dispersed among numerous papers published in topical collections, in scientific academic journals, the proceedings of various conferences and symposia, candidate and doctorate dissertations, and narrowly specialized monographs.

The main purpose of this first publication in the series *Fundamentals of Machine Design* is to formulate new priority problems for modern machine science and map out ways to their solution. Accordingly, it considers problems in the dynamics of machines and methods for optimum design in designer-computer dialogue, problems of machine reliability and machine-science advances in the area of wear resistance of machines and mechanisms. The book includes material on promising research toward the creation of robots and automated complexes and presents the basic properties of certain new materials. It contains generalized scientific results in the area of machine science and is of independent value. It is the author's opinion that it will facilitate the use of all subsequent publications in the series that give example calculations and reference data in support of the design of highly reliable, economical, and energy-efficient new-generation machines.

The book is based on the results of the work done at the A. A. Blagonravov Institute of Machine Science, AS USSR. A. P. Gusenkov, A. V. Chichinadze, R. F. Ganiev, R. B. Statnikov, and A. I. Korendyasev participated in its preparation, and the author takes this occasion to thank them.

CHAPTER 1

# CONTEMPORARY METHODS FOR OPTIMUM DESIGN OF MACHINES AND STRUCTURES

## *STATEMENT OF PROBLEM; INITIAL DATA*

The complexity and difficulty of problems that require solution during the design process have increased enormously. The creation of machines on a qualitatively new level presupposes application of the most important advances in the fundamental sciences, design and technology, protection of operating personnel from vibration and noise, and consideration of contemporary economic, social, and ecological problems. Machine quality improvement problems must be solved at the design stage, when it is necessary and possible to examine all aspects of the design, i.e., to take account of a large number of often contradictory requirements. Thus, it is necessary to satisfy in each machine such requirements as minimum weight and adequate reliability, high speed and minimum dynamic loading, low cost and longevity, and others, i.e., it is necessary in the design of machines and mechanisms to specify optimum parameters for them (structural, kinematic, dynamic, operational), the parameters most consistent with the numerous requirements that they must meet. In existing design practice, this problem is solved by working through several alternatives with completion of the corresponding calculations. The elaboration of even a very large number of alternative variants by the traditional approaches is incapable in principle of giving the designer an idea of the capabilities of the machine, since, for example, if 10 different values are assigned to each of 10 parameters, it would be necessary to examine $10^{10}$ variants – a problem beyond the capability of even modern computers.

It is becoming increasingly expensive to solve the problems by traditional methods, and the negative consequences of adopting other than optimal solutions are becoming more and more serious. The situation is further complicated by the fact that these are multicriterion problems with contradictory object functions, so that it is difficult for the designer to choose a valid compromise solution: the classical methods being used to find extreme values, and most of the new optimization search methods were designed only for solution of single-criterion problems. Successful solution of a multicriterion problem requires a valid determination of an admissible solution set (regions of variation of the parameter vector of the system being designed).

The development of a rough plan for a machine or structure can proceed by any traditional method. After sketching out the design, the designer can determine and specify on the basis of design considerations the limits of variations of each of the parameters of the machine, on which all of its characteristics depend. Criteria and characteristics, on the basis of which the designer can judge the quality of the machine in the course of design, must be formulated. Characteristics of this kind that apply to various machines are mass, power, speed, the strengths of various assemblies and components, vibration levels at various points on the machine, cost, economy of operation, etc. The number of quality criteria that can be analyzed during the design process by specifying optimum parameters is unlimited, and this is very important for the creation of a high-quality machine or structure.

To choose optimum parameters for a machine in the design stage, it is necessary to have working formulas or a ready-made program that describe the behavior of the object of study and can be used to calculate the projected system and all quality criteria for any given set of parameters.

Most examples of modern technology, both specialized (aircraft, gyroscopic instruments, vibration machines) and traditional (mining machinery, metalworking machine tools, rolling mills, turbines, internal-combustion engines, etc.) operate in dynamic and often quite severe regimes. This is a result of the higher speeds and lighter weights of modern machines, random variation of the resistance forces with process loads, and other factors. Accordingly, modern machines should be regarded in solving optimum-design problems as vibrating systems that interact with the energy source and process load and work under patterned or random excitation conditions. This lends special importance to investigation of the dynamic properties (vibrations and motion stability) of the systems being designed, with allowance for the properties of the energy sources that supports the work of the machine.

For examples of modern technology that operate in dynamic regimes, methods have been developed in recent years on the basis of further development of the theory of nonlinear mechanics for study of the spatial stability and nonlinear resonant vibration of solids, and for the interaction of nonlinear, parametric, and autoparametric systems with energy sources of limited power [12,15,16,18,36,105]. It is these dynamic phenomena that must be taken into account in the design of machines.

Quality criteria are calculated using methods and programs for specified parameters of the object [3,95,96,114]. Each of these calculations is conventionally known as a test. Trial points are chosen in the multidimensional parameter space with the aid of uniformly distributed $LP_\tau$ sequences that differ in their optimum uniformity properties and can be used in a minimal number of tests to obtain a rather complete picture of the resource capabilities of models with respect to each quality criterion [95,96]. In this case, the trial points possess the following property: their projections onto any coordinate axis in the parameter space are different and distributed quasiuniformly. Using N trial points, each of the parameters is assigned N different values uniformly distributed over the entire range of the parameter variation. Thus, the number of trial values for each parameter is equal to the number of tests. A method developed for selection of trial points ensures a uniform scan of the entire parameter space in a comparatively small number of tests, and, consequently, makes the method efficient [3,95].

The values of each criterion are used to compile test tables in which the quality criteria are arranged in decreasing order, i.e., the model that is best with respect to the given criterion comes first. Since a certain parameter "set" coded into the test number corresponds to each model, the table of tests shows what must be done to obtain the machine that is best with respect to a given quality criterion.

As a rule, there is no machine or structure optimum in all criteria simultaneously; therefore, the results of the test-table analysis are used to validate the choice of a compromise solution.

Since the tables of tests show the capabilities of a design with respect to each quality criterion, the designer, consulting with the customer, can specify sensible limitation on each criterion that will be practically attainable on the one hand and satisfy the customer on the other. He can then test by calculation whether there exists a design that satisfies all of these constraints simultaneously. It is these designs that compose the admissible set of solutions from which the designer and customer choose the optimum model. If no such designs have been found, the constraints can be relaxed. It is also possible to increase the number of tests or broaden the ranges of the parameter variation.

Thus, the designer obtained a real opportunity to validate a statement of the multicriterion optimization problem – that of considering a set of contradictory criteria simultaneously – and this led to creation of a qualitatively new method for the design of machines and structures. Another advantage of the method that makes it convenient for application in the real world is the practical possibility of designing large systems that require intervention of the designer in the calculation process, that is the so-called designer-computer dialogue regime can be used effectively. The techniques that have been elaborated make it possible to increase the density of the points in the parameter space, thus obtaining more complete information on the models under investigation if it is needed. A practically useful aspect is the possibility of repeating an experiment, even with different initial data for one of the points of the multidimensional space.

The generalized procedure for the statement and solution of optimum-design problems using man-machine dialogue opens the following possibilities:

– considering as many quality criteria as are necessary for complete analysis of the functioning of machines and structures (from the standpoint of various contradictory criteria, such as stability, vibroactivity, strength, reliability, metal used, efficiency, dynamic loading, technological efficiency, economy, vibration and noise suppression, etc.);

– determining the admissible set of solutions;

– identifying nonessential criteria whose values do not vary appreciably;

– demonstrating dependent or, conversely, contradictory criteria;

– determining the effects of parametric constraints of an integral criterion;

– identifying parameters that are immaterial with respect to a given criterion;

– formulating integral criteria and determining optimum parameters of projected machines and structures on the admissible solution set.

Fundamentally important problems of the mechanics of machines have been solved on the basis of this method: parametric and dynamic synthesis from design-engineering, production-engineering, economy, and other quality criteria, machine acoustics, the design of heavy-duty machines with limited energy source power, optimization of process conditions for the operation of vibration machinery, and investigation of ecological aspects of the design of "breakthrough" machines.

The system being designed depends on r variable parameters $\alpha_1, \ldots, \alpha_r$ – rigidity, inertia, dissipative, etc., which are the coordinates of a point $\alpha = (\alpha_1, \ldots, \alpha_r)$ in r-dimensional parameter space. The coordinates of this point usually enter into the differential or finite equations that describe the functioning of the system, and specifically the dynamics (kinematics) of its mechanisms, machines, and structures.

Generally, constraints apply parametric

$$\alpha_j^* \leqslant \alpha_j \leqslant \alpha_j^{**}, \quad j = \overline{1, r}; \qquad (1)$$

and functional

$$C_l^* \leqslant f_l(\alpha) \leqslant C_l^{**}, \quad l = \overline{1, t}, \qquad (2)$$

where $\alpha_j^*$ and $\alpha_j^{**}$ are the a priori specified limits of variation of the parameter $\alpha_j$; $f_l(\alpha$ are the functional constraints that depend on $\alpha$; and $C_l^*$ and $C_l^{**}$ are the a priori specified limits of variation of the $l$-th functional constraint. The limits $\alpha_j^*, \alpha_j^*, C_l^*, C_l^{**}$ are not varied in the solution of the optimization problem.

In addition to the constraints, there are local criteria $\Phi_1(\alpha), \ldots, \Phi_k(\alpha)$, which depend on integral curves, as, for example, in machine-dynamics problems.

Let us define the local criterion as a numerical characteristic that is monotonically related to the system quality. Let us assume for the sake of argument that all $\Phi_\nu(\alpha) > 0$, and that the smaller the value of each of the functions $\Phi_\nu(\alpha)$ the better the system (other conditions the same).

In the r-dimensional space of the variable parameters, the parametric constraints (1) define a parallelepiped $\pi$ whose volume $V_\pi = \prod_{j=1}^{r} (\alpha_j^{**} - \alpha_j^*)$, where $\alpha_j \in [\alpha_j^*, \alpha_j^{**}]$. The functional constraints (2) define a certain admissible subset G in $\pi$ (Fig. 1a), which, generally speaking, can be unconnected, whereas $f_l\nu(\alpha)$ and $\Phi_\nu(\alpha)$ are piecewise-continuous. Let us assume that the volume of subset G is

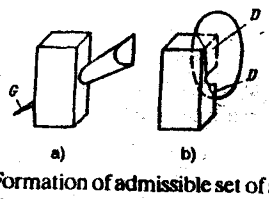


**Fig. 1.** Formation of admissible set of solutions: a) solution subset G; b) admissible solution set D.

positive and the ratio $\gamma = V_G/V_\pi$ is not too small.

One of the local criteria or some combination of these criteria is usually chosen as the deciding criterion $\Phi(\alpha)$. It is then easy to state the problem of finding the optimum parameters of the point $\alpha = \hat{\alpha}$, such that $\Phi(\hat{\alpha}) = \min \Phi(\alpha)$; $\alpha \in G$. However, this statement does not usually lead to the final solution of the problem, or some of the criteria do not satisfy the requirements made of them. To avoid this situation it is necessary to introduce criteria constraints:

$$\Phi_\nu(\alpha) < \Phi_\nu^{**}, \quad \nu = \overline{1, k}, \qquad (3)$$

where $\Phi_\nu^{**}$ is the poorest acceptable value of the criterion $\Phi_\nu(\alpha)$.

We denote by D (Fig. 1b) the set of points $\alpha$ that satisfy constraints (1)–(3) so that $D \subseteq G \subseteq \pi$. If the functions $f_j(\alpha)$ and $\Phi_\nu(\alpha)$ are piecewise-continuous in $\pi$, then subsets G and D are closed.

Calling the parameter D the admissible point set, we can state the optimization problem: find a point $\alpha = \alpha^\circ$, such that

$$\Phi(\alpha^\circ) = \min \Phi(\alpha), \quad \alpha \in D. \qquad (4)$$

If set D is nonempty, a solution of problem (4) exists and all $\Phi_\nu(\alpha^\circ) \leq \Phi_\nu^{**}$, which suits the designer.

Thus, to get from the initial data to the optimization problem (4) it is necessary to specify reasonable constraints $\Phi_\nu^{**}$ and ensure that set D is nonempty. The above method of investigating the parameter space makes it possible to resolve the two questions and gives the designer additional information that aids him in selection of the decision criterion (decision rule) $\Phi(\alpha)$.

Investigation of the parameter space consists of three steps.

**I) Preparation of test tables** – a computer function. N trial points $\alpha_1, \ldots, \alpha_N$ uniformly distributed in subset G are chosen. All local criteria $\Phi_\nu(\alpha_i)$ are calculated at each of the points $\alpha_i$. A table of tests is set up for each criterion with the values $\Phi_\nu(\alpha_1), \ldots, \Phi_\nu(\alpha_N)$ arranged in increasing order:

$$\Phi_\nu(\alpha_{i_1}) \leqslant \Phi_{i_\nu}(\alpha_{i_2}) \leqslant \cdots \leqslant \Phi_\nu(\alpha_{i_N}), \quad (5)$$

where $i_1, i_2, \ldots, i_N$ are the numbers of the corresponding trial points (numbers of the tests for each value of $\nu$) [95].

**II) Selection of criterial constraints** – a step that assumes intervention by the designer (or customer). Examining in succession each of the tables prepared in accordance with relation (5), the designer must specify the constraints $\Phi_\nu^{**}$. He is interested in reducing these values, but if all $\Phi_\nu^{**}$ are made too small, the set of admissible points D may prove empty. The test tables are analyzed for a sound choice of decision criteria $\Phi(\alpha)$, since this makes it possible to consider not only preliminary indications as to the importance of the various criteria $\Phi_\nu(a)$ but also their actual possibilities.

**III) Testing problem (4) for solvability**, another computer function. Some one of the criteria, for example $\Phi_{\nu_1}(\alpha)$, is fixed and the table corresponding to it is inspected.

Suppose $s = s(\nu_i)$ is the number of values in this table that satisfy the chosen criteria constraint:

$$\Phi_{\nu_1}(\alpha_{i_1}) \leqslant \cdots \leqslant \Phi_{\nu_1}(\alpha_{i_s}) \leqslant \Phi_{\nu_1}^{**}. \qquad (6)$$

By trying the existing values $\Phi_\nu(\alpha_i)$, ..., $\Phi_\nu(\alpha_{i_s})$ for all values of $\nu$ it is easy to verify whether there is among the points $\alpha_{i_1}, \ldots, \alpha_{i_s}$ at least one such that all inequalities (3) are valid at once. If there is such a point, set D is nonempty, and problem (4) is solvable. Otherwise it is necessary to return to the second step and require that the designer (or customer) make "concessions" in specifying the $\Phi_\nu^{**}$. If these "concessions" are extremely undesirable, it is possible to return to the first step and increase the number of trial points so that the second step can be repeated with larger-volume test tables.

**Remark.** The computer inspects, one at a time, all k rows of the k $\times$N matrix $||\Phi_\nu(\alpha_i)||$ in the first step and s columns of this matrix in the third step.

To select trial points, let us use points of the $LP_\tau$ sequence $Q_1, \ldots, Q_i, \ldots$

The points $\alpha$ are chosen as follows. The Cartesian coordinates of the present point $Q = (q_{i1}, \ldots, q_{i,r})$ are used to find the Cartesian coordinates of a point $\alpha^{(i)} = (\alpha_1^{(i)}, \ldots, \alpha_r^{(i)})$, which belongs to $\pi$:

$$\alpha_j^{(i)} = \alpha_j^* + q_{ij}\left(\alpha_j^{**} - \alpha_j^*\right). \qquad (7)$$

The system to be designed is calculated for $\alpha = \alpha^{(i)}$ and conditions (2) are tested. If they are satisfied, the point $\alpha = \alpha^{(i)}$ is chosen as a trial point and all $\Phi_\nu(\alpha)$ are calculated; if not, point $\alpha = \alpha^{(i)}$ is rejected.

Expressions of the form of (7) can be used to select criterial constraints with orientation to the relative values of local criteria.

In the third step we generally find not one, but $N_0$ trial points belonging to D that can serve as initial points for various local-search procedures. The procedure used to plot and select these points is based on their uniform distribution in D.

Analysis of test tables makes it possible to detect unimportant criteria whose values do not vary appreciably, to identify dependent or, on the other hand, contradictory criteria, to determine the effects of parametric constraints on the integral criterion, to identify parameters that are immaterial with respect to some criterion, to specify a Pareto solution, set, and to determine optimum parameters. The most important results of test-table analysis include acquisition of an admissible set of models and determination of reserve model capabilities with respect to all local quality criteria. In most practical problems, optimum machine and structure parameters are chosen only on the basis of the test-table analysis, and later attempts to improve the parameters are generally found to be ineffective.

Figure 2 presents one variant of the structural diagram of a dialogue system for selecting optimum machine and structure parameters.

The procedure discussed above enabled designers and customers for the first time to analyze as many local criteria as are necessary. This approach should be regarded as the most correct and promising for analysis of complex multiparameter, multicriterion problems of coordinated machine and structure design.

## *DETERMINATION OF OPTIMUM PARAMETERS FOR A RESONANCE MACHINE*

Referring to the series-produced VRA-8 resonant vibration machine, which was designed for use in shaping reinforcedconcrete products, let us solve problems that are general and traditional to the designer: can it be improved, where is there room for improvement, and at what cost can this be accomplished?

Modern industrial-type resonant vibration machines are based on elastic systems with nonlinear characteristics, which make it possible to guarantee stable operation of the machine in the process

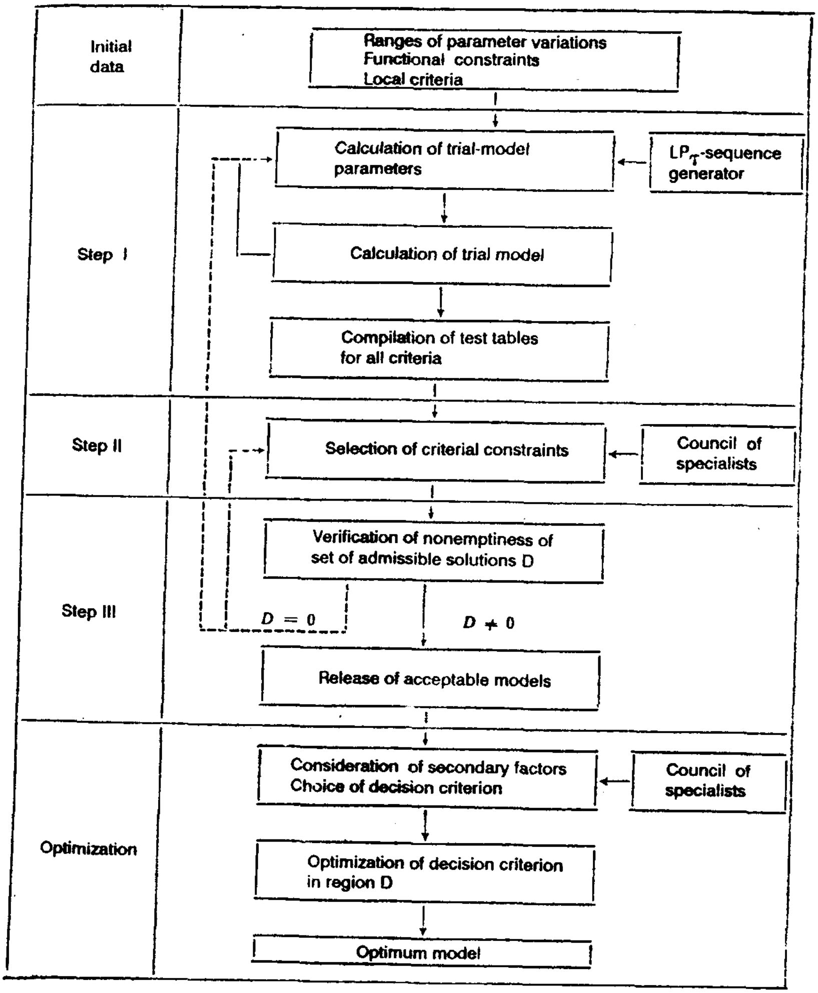


Fig. 2. Structural diagram of dialogue system for statement and solution of optimum-design problems for machines and structures.

and to adjust the vibration laws and vibrating parts with the object of optimizing them. Problems in the analytic design of resonant vibration machines reduce to selection of parameters for the nonlinear system and the drive with which the periodic motions of the vibrating component will come closest to meeting process requirements (maximum productivity) and design constraints while ensuring stability of operating regimes as the process load varies.

Figure 3 shows a schematic design for a resonant antisymmetric vibration platform. The platform is a two-mass vibrating system in which the masses are the vibrating element 1 and the equalizing frame 2. The main elastic couplings are between them and include the supporting elements 3 and buffers 13, which clear one another as adjusted and impact only when the masses move to close the gap. This gives rise to unequal accelerations of the working element as it moves up and down, i.e., an asymmetric vibration cycle. To reduce dynamic loads on the baseplate, the working element and the equalizing frame are mounted via snubbers 4 and 5 on rigid stands 6, with the snubbers on the

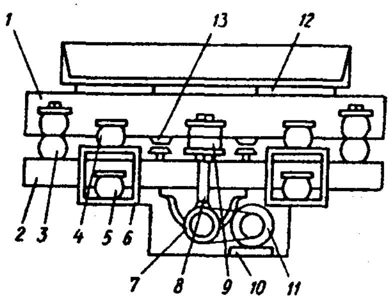

Fig. 3. Diagram of resonant asymmetric platform.

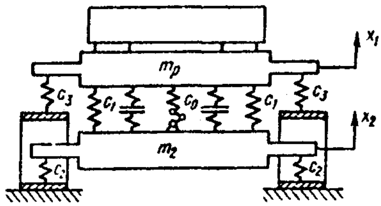

Fig. 4. Model for synthesis of parameters of nonlinear system and resonant vibroplatform drive.

working element and equalizing frame on the same vertical axis on each stand. Vibrations are excited by the eccentric-link drive 7, which is secured to the frame and connected to the working element by links 8 and elastic couplings 9. The drive shaft is turned by electric motor 10 working through v-belt drive 11. The molds with the concrete are secured to the working element by electromagnets 12.

In their general formation, problems in the dynamics of resonant vibration machines reduce to analysis of the system formed by the drive, the machine, and the medium being processed. But to synthesize the parameters of the nonlinear system and drive of a resonant vibration platform it is possible to use a simplified computing scheme based on assumptions commonly made for applied vibration-theory problems (Fig. 4). The principal moving masses are assumed to be absolutely rigid and conditions that ensure single-coordinate motion of these masses must be satisfied. The masses of the elastic couplings are ignored in the calculations, and the restoring-force characteristic of the main elastic couplings is assumed to be bilinear (Fig. 5). Allowance for energy dissipation in the elastic couplings is based on a viscous-friction hypothesis in