ON DESIGN OPTIMIZATION BY THRESHOLD PASSING METHOD

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ABSTRACT

The philosophy of design optimization is described after reviewing the currently used design methods, and the design optimization by the threshold passing method is presented.

The object function for the apparatus is assumed to have two valued penalty, zero or infinite, that is, the penalty for the function is infinite when one of the object quantities does not pass the threshold and zero when all the object quantities pass the threshold. The designer adjusts the condition of threshold passing through "learning" from the comupter outputs. The "design parameter space is obtained automatically using the automatic digital computer by mechanizing the above process, and the optimization is left to the judgement of the designer.

Results of experimentation of this method on a negative feedback control system are presented, and the problems experienced in this experimentation are discussed.

1. INTRODUCTION (1)(2)(3)

The design processes for most apparatus or machine systems are the following:

(a) Trial & Error Method
(b) Pure Synthesis Method
(c) Automatic Convergence Method

Method (a) is the time-honored design process, in which the designer estimates initial values for key design variables, calculates the physical dimensions with respect to the apparatus, and then calculates the performances under certain specified conditions. These are compared with the specifications and desired performances, and if the calculated values differ from those desired, the designer adjusts the initial values and repeats the calculation. This process is continued until the calculated values are within acceptable limits. As the design "home in", more detailed description of components and more comprehensive and accurate performance calculations are necessary. This may involve thousands of small steps such as selecting particular pieces of design information, integrating these with other pieces of information, calculating physical size, checking all design informations to ensure that it is still adequate, and then, calculating performances. When the designer is certain the design is acceptable, he will write out design output documents which contain all of the relevant information.

Pure synthesis method is one which most designers are tempted at some time in their careers to force to apply. Multivariable charts, nomograms, and other short-cut techniques have been tried by the hundreds. Though some of these are excellent approximations to a design and give good initial values for key variables in the Trial and Error and Automatic Convergence Method, very few of these are accurate or detailed enough to yield a complete design, because of the limits to the number of variables which can be handled by two-dimensional graph papers.

Automatic convergence method involves initial estimation of the key design variables and then a step-by-step improvement by the convergence technique such as the method of steepest ascent.[(4),(5)] To describe this process for any complicated apparatus is very difficult, because the designer's judgement should be built into the process. Once it has been described in an intelligible fashion, however, the design process which is generally a sort of data processing can be delegated to the clerk. The designer becomes an evaluator rather than a slide-rule pusher.

Design optimization is the ultimate goal of the designer. However, it may take days or weeks for a designer to accomplish only one acceptable design. He is generally compelled to give up with the better or alternate design, and it may be a mere dream to attain the optimum design. Time and cost have been the unsurmountable barrier for the design optimization until the designer harnesses the tremendous capability of modern high power automatic digital computers for his design work. It is a generally accepted opinion that "true" design optimization will be possible only through the modern high-speed digital computer.

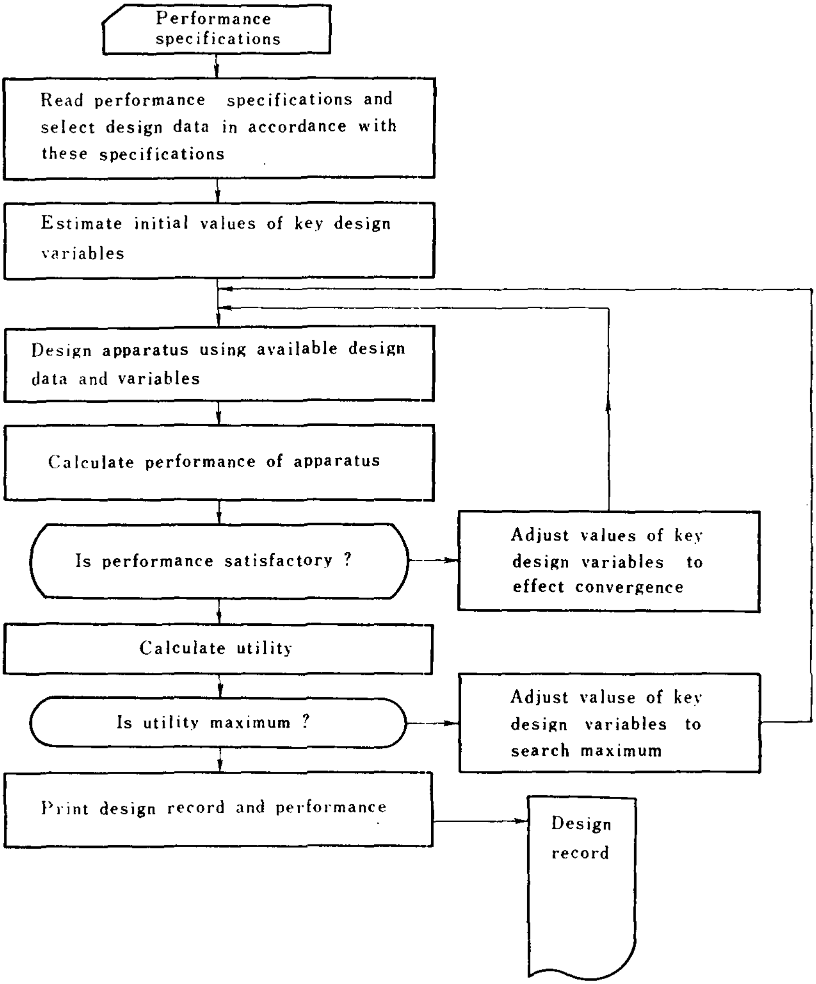

Fig. 1. Flow Diagram for Design Optimization by Automatic Convergence Method

If the object functicn is defined objectively and determined mathematically for the apparatus to be designed, the automatic design optimization by automatic convergence method is possible through the application of modern high-speed digital computer (cf. Fig. 1). The utility of object function is compared with one already stored, and if the former is lager than the latter, store the former with the design data, and try the next improvement until the summit is reached with respect to the utility. There is, however, no guarantee that it is the highest summit, or even a second one. The "true" optimization is, therefore, left to the judgement and experience of the designer.

2. THRESHOLD PASSING METHOD

In the foregoing it has been tacitly assumed that the design variables could be continuously changed by the designer, and the object function is defined objectively and determined mathematically. Obviously these are not always the case in practice, and some discussions on these may be justified.

The first problem that the design variables are not always continuous quantities is inherent in the design process because of manufacturing requirements, available tools and dies, industry and company standards, etc., and to ignore the discreteness would be an inadmissible simplification of the problem. In fact, with the present trend of industry towards standardization, mass production and automation, discreteness is becoming more and more important. The method of steepest ascent or similar method, therefore, losts the power to effect automatic convergence, since the climber is faced at every step with vertical walls.

The second problem of objective and quantitative formulation of the object function is one of the most difficult problems to solve in the theory of Operations Research. The utility may be weight, dimensions, cost, quality, customer's satisfaction; the balanced best interest of the manufacturer, customer, and the public; or a combination of these quantities with other intangible factors, which is impossible to define objectively and determine mathematically. The over-all decision with respect to the design optimization, therefore, is best left to the judgement and experience of the designer who is responsible, by providing him the pertinent data.

In aiming the practical realization of design optimization in such a situation, the author chosed a realistic and down-to-earth approach towards optimization and devise the method of "threshold passing" in

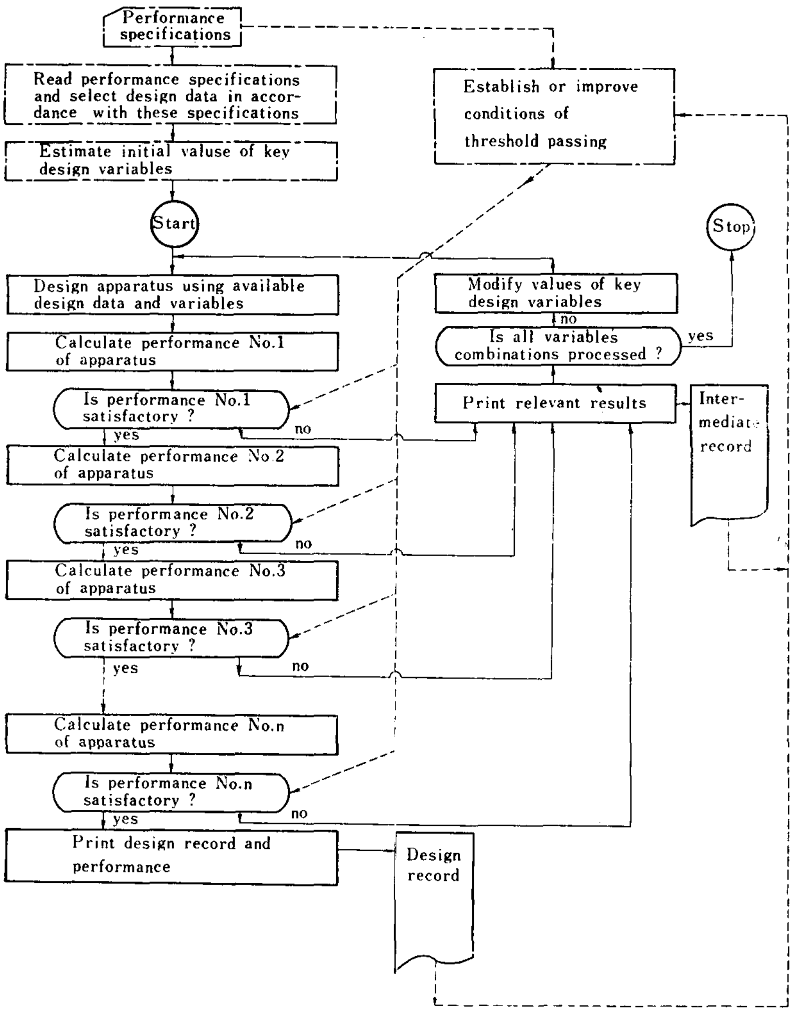

Fig. 2. Flow Diagram of Threshold Passing Method
⟶: Information Flow in Machine
--→: Information Flow in Man
[dashed box]: Engineering Judgement

order to assist the designer to make the final decision (cf. Fig. 2). For the convenience of applying automatic digital computers, the object function which is the function of object quantities is assumed to have two-valued penalty, zero or infinite; that is, the penalty for the function is infinite when one of the object quantities does not pass the threshold and zero when all the object quantities pass the threshold. Because of the industry's trend towards more discreteness, all the key design variables are assumed to be discrete quantities. The threshold and decision rule associated with it may be developed from the specifications, desired performances or some rules of thumb. All the combinations among discrete quantities of key design variables are processed in the computer and the "pass parameter space" are obtained. The designer selects as the optimum design one point in the space, taking into account of the intangible factors. The total number of cases for one optimum design may be very large. If there are six independent design variables in all and each variable has ten discrete values, the total number of cases is one million. Modern high-speed automtic digital computers alone can perform such a herculean task.

The mechanization of the Threshold Passing Method involves a large amount of selection and processing of data and logical decision operations. Nevertheless, the programming of the computer for the method is rather an easy task since all the rules for making decisions, for selecting components, for modifying the value of design variable, etc., are simple, clear-cut and uniquely defined after the thresholds are established. The designer can override the computer program by modifying the decision rule associated with the threshold without special input programs. Hence, this method is an evolutionary process. The designer may first establish the thresholds by guess, but he can improve them always in the course of designing process by utilizing the new knowledge which may be developed through "learning" from the computer outputs.

3. EXPERIMENTATION

The system to be experimented is a negative feedback control system in which controlled object $G(s)$ is not manageable. The problem is to attain the optimum dynamic performance of the system through managing the independent design variables of the compensating network $H(s)$ (cf. Fig. 3). Where $G(s)$ and $H(s)$ are

$$G(s) = -A(s-\alpha)/(s+1)(s+2),$$

$$H(s) = \frac{K}{k} \cdot \frac{s+kc}{s+c} \cdot \frac{s+d}{s+md}.$$

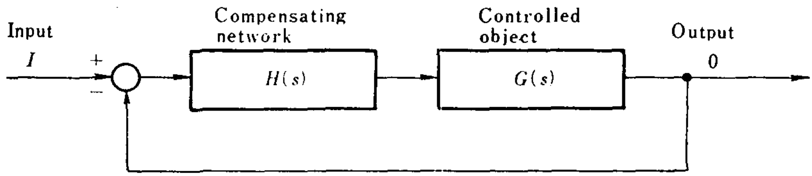

Fig. 3. Negative Feedback Control System

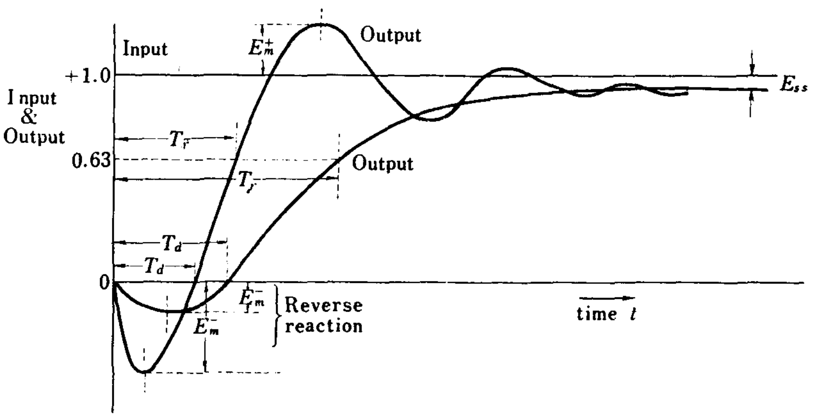

Fig. 4. Object Quantities Associated with Indicial Response

The author has chosen as the object quantities, the stationary offset (E_{ss}), undershoot (E_m^-), overshoot (E_m^+), and response time (T_r), which are all associated with the indicial response of the system (cf. Fig. 4). The criteria of threshold passing associated with the object quantities are that the magnitute of every object quantity E_{ss}, E_m^-, E_m^+, and T_r should be smaller than the prescribed value. There are conflicting relations among these objective quantities, and how to find the best compromise among them is the object of the experimentation.

The design optimization is tried for three design where α, the parameter of the controlled object $G(s)$, is 0.5, 1.0 and 2.0, respectively (cf. Fig. 5). The numerical values assigned to the design variables are as follows:

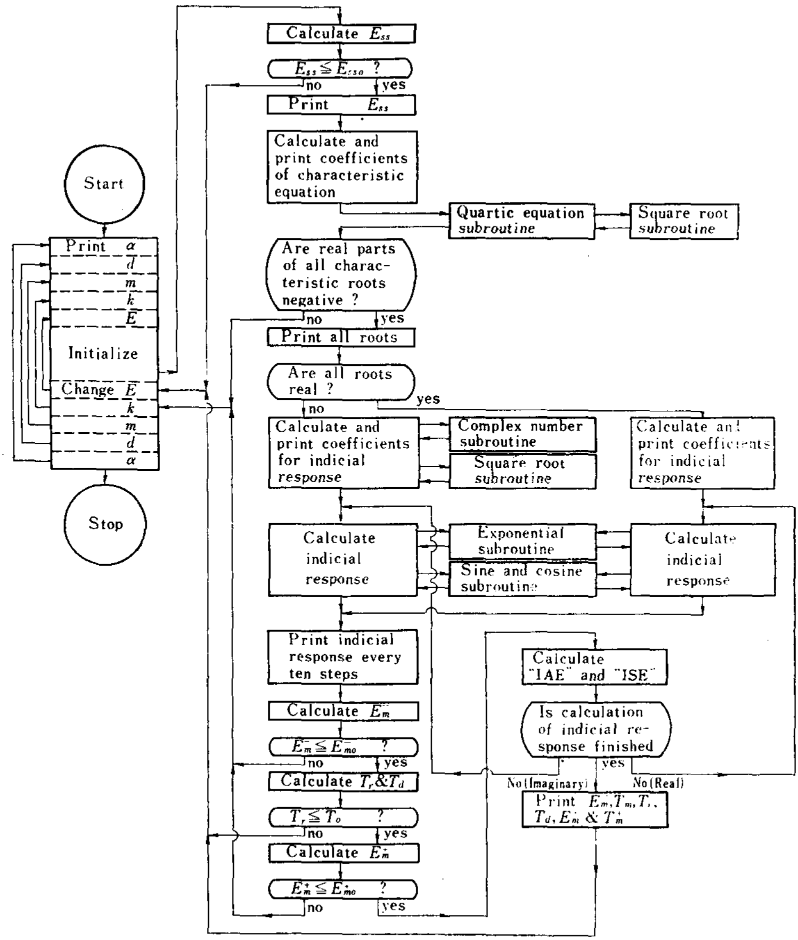

Fig. 5. Simplified Flow Diagram for Experimentation

$$A=1, \quad c=0.01, \quad d=\begin{cases}1\\2\\3\end{cases}, \quad m=\begin{cases}3\\6\\10\end{cases}, \quad k=\begin{cases}50\\100\\200\\300\end{cases}$$

and $E(=K/k)$=zero to the value in 0.3 step when the system becomes unstables.

To accomodate with the last statement, it is necessary to insert the threshold that the system should be stable, in addition to the ones already described. The thresholds are arranged in the order so as to minimize the machine time. The "Integral of Squared Error" (ISE) and "Integral of Absolute Error" (IAE) are also computed in this experimentation which are the popular measures of goodness of the system's dynamic performance. Some intermediate results of calculations have been typed

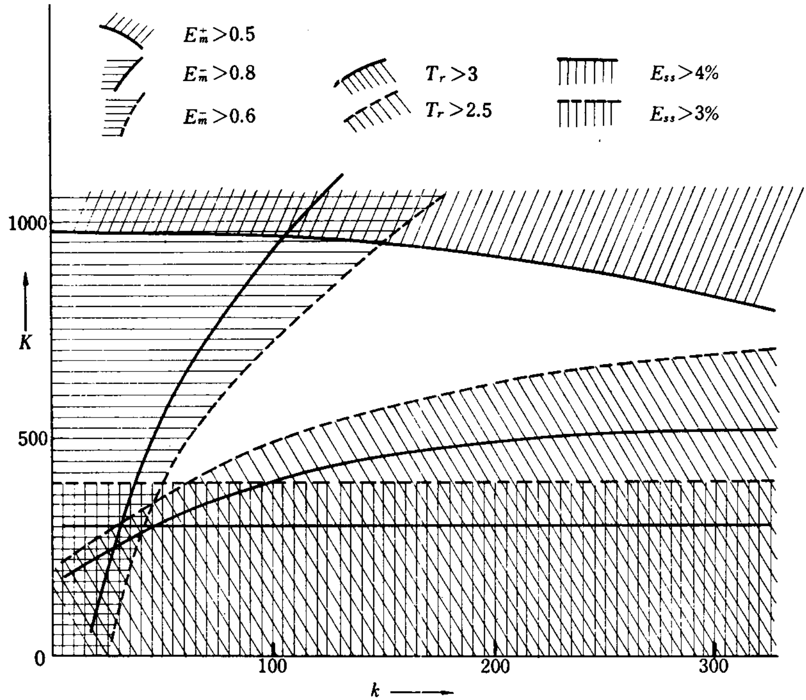

Fig. 6. Example of "Pass Parameter Plane" ($\alpha=1$, $d=3$, and $m=6$)

out in appropriate step of the computer program in order to assist the "learning" of the designer.

Some results of experimentation are shown in Figs. 6 and 7. Fig. 6 shows the conflicting relations among the four object quantities E_{ss}, E_m^-, E_m^+, and T_r taking K and k as coordinates, when $\alpha=1$, $d=3$, and $m=6$. In the figure, the plane without hatching is the "pass parameter plane" —— a cross-section of the "pass parameter space" which is shown in Fig. 7.

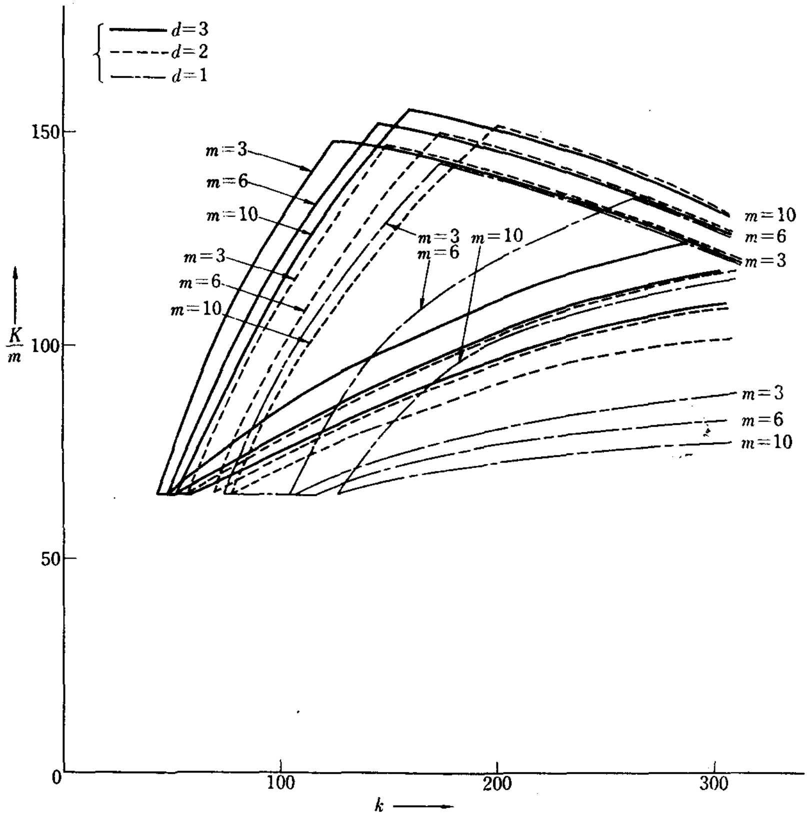

Fig. 7. Example of "Pass Parameter Space" for One Design ($\alpha=1$)

The computer mainly used was NEAC 2203, a commercial stored program machine of Japanese made, which has a magnetic drum memory of ten digit decimal two thousand words. The average execution time for one step of instruction is roughly 7 ms. The total number of words in this computer program is about 1700. The total number of parameter combination for the optimization of three design was about 1,100, and the machine time for a parameter combination was about 8 minutes when it passed all the thresholds. The net production machine-time for this experimentation was about 90 hours, and the machine cost may be over ¥1,800,000 ($5,000).

However, the production time may be reduced drastically (to the order of one-tenth) by improving the scheme of computation, by discarding the computation of ISE and IAE which have been proved not to be the proper measures of goodness of the system's dynamic performance, and through efficient control of the condition of threshold passing by the designer. Nevertheless, the cost of design by such a simple method may be unduly expensive even for such a simple example. Hence, the more elaborate method such as one presented by Klahr may not be realistic since this is hardly expected to yield additional information that will pay for the extra cost incurred in the elaboration.[6] When the number of key variables increases the machine time will increase "exponentially", and it is imperative, therefore, to use a very high-speed computer, since the production cost is said to be roughly inversely proportional to the square root of computer speed. The mental labor of the designer associated with in-process adjustment and balancing of the conditions of threshold passing may also increase remarkably. Automating of the threshold adjustment through "learning" by the computer itself will, therefore, become necessary in order to relieve the designer from this heavy mental burden.

4. CONCLUSIONS

(1) The method is a down-to-earth approach to the design optimization for which the application of a very high-speed digital computer is essential.

(2) The design optimization by this method is an evolutional process in which the designer can override the computer program and improve

the thresholds by utilizing the new knowledge which may be developed through "learning" from the computer outputs.
(3) The method guarantees the designer to obtain the "highest summit" if he chooses the range of value of key design variable sufficiently wide and properly.
(4) The method may ideally be suited to study new ideas, proposed new developments or special customer requirement because of the flexibility inherent in this method.
(5) The method may also be applied to obtain the optimal facto combination for the operation of man-machine system.

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