Product Development by Design Navigation Method*

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Manufacturers must be able to develop new products within a specified time period. This paper discusses a method for developing high performance products from a limited number of experiments, utilizing the concept of "function error". Unlike conventional methods where the sequence of design, prototyping and experiment must be repeated several times, the proposed method can determine optimal design values directly from experimental data obtained from the first prototype. The theoretical basis of the method is presented, then its effectiveness proven by applying it to design an extrusion machine and a CNC lathe.

Key Words : Design, Machine Tool, Design Engineering, Design Navigation Method, Axiom, Function Error, Product Development, Experimental Design, Injection Machine, CNC Lathe

1. Introduction

To develop a new product, it is usually necessary to repeat the process sequence of design (or redesign), prototyping, and evaluation, finalizing the product's design parameters only when its functional requirements have been met. If the redesigned product is found by evaluation to be unsatisfactory, the cycle must be repeated. By taking up further development time/expenses, this sets back the delivery schedule and reduces the company's competitive strength, which could lead to huge losses. It is therefore important to employ a method by which a product satisfying the functional requirements can be quickly developed, from as few prototypes as possible. In this paper, the author proposes a product development method where a new concept is employed to evaluate prototypes based on orthogonal tables, as used in experimental design. It is called the Design Navigation Method (DNM).

The Taguchi method⁽¹⁾ is a well-known product development method which is also based on experi-

mental design, used for developing products possessing robustness (i.e., affected little by the operating environment). Meanwhile the purpose of DNM is to develop products in which several specifications (or requirements) must be balanced with each other.

Design methods for satisfying multiple functional requirements, based on multi purpose optimization techniques⁽²⁾, are also actively studied in the field of optimal design. Yet, optimal design requires that the relation between the product's functions and its design parameters be clearly delineated, and so is not applicable to the early prototype stage, where this relation is still unclear. DNM, however, can be applied to the entire development process, including prototyping, to design products that meet multiple, clearly set forth functional requirements.

This paper first discusses the concept of "function error" and the axiom used for design evaluation. The function error corresponds to the "information value" of the Information Integration Method⁽³⁾⁻⁽⁵⁾, which is an evaluative method previously proposed by the author. A description follows on how this concept is used to evaluate data obtained from experiments, which were designed by means of an orthogonal table. Finally, the validity of DNM is demonstrated by two case studies, where it was applied to develop actual products.

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Fig. 1 Practical value of functional requirement E

2. Design Navigation Method

2.1 Definition of function error

When a new product is to be designed, it must generally satisfy multiple functions (including cost), among which there exist trade-offs. To achieve a proper balance among the requirements, some index is needed to evaluate them. For this index, we use the concept of function error, which is defined below.

A product's performance will generally vary according to its design parameters. Performance is also affected by environmental factors such as temperature and humidity, so that it will vary even with fixed design parameters. Suppose now that, for a given functional requirement E , the various performance values shown in Fig. 1 were obtained. Here, requirement E is represented by the abscissa, where the circles indicate measured results.

Denoting the mean value and the standard deviation (square root of unbiased variance) by m and σ , respectively, we define $m \pm k\sigma$ as the performance range of this product (or system), and call it the system range. k is the safety factor. Meanwhile, the desirable performance range (or specification), which should be determined in a rational and rigorous manner, is called the design range. When the desirable performance is determined as a range of more than or less than a value, only a unique value Ed is given as a boundary point. The common range is the overlap between these two ranges.

The function error D is then defined as follows:

$$D = \ln(SR/CR) \quad (1)$$

This corresponds to the "information value" used in the Information Integration Method^{(4),(5)}. The function error is a measure of how much the data (performance) range strays from the design range, that is, under the given conditions, the "error" of the function relative to its target range. When the system range falls entirely within the design range, SR and CR coincide and the function error D is zero. Conversely, if the system range falls entirely outside of the design

Fig. 2 System range of design parameter A for functional requirement E

range, D diverges to infinity. The function error D is determined in this manner for each evaluation item, then they are summed up. The sum is called the total function error D_t . For example, given three evaluation items, E , F , and G , for which the respective function errors are D_e , D_f , and D_g , we obtain D_t as:

$$D_t = D_e + D_f + D_g \quad (2)$$

We now propose the following axiom regarding the function error:

Axiom: The smaller the total function error is, the better is the system.

The "system" here can be a product or technology under development, or it can refer to the operating condition of some product.

2.2 Determination of design parameters

We now describe the steps for analyzing experimental data using the above evaluation method in order to determine the design parameter values. Design parameter A is varied so as to take on the values, $A_1, A_2, \dots, A_p$, each of which yields multiple (n) experimental data on a given evaluation item, say E . These data will exhibit a scattered distribution depending on the other design parameters and experimental conditions. For the n data points gathered for A_1 , the mean m and standard deviation σ (square root of unbiased variance) are obtained. The two points representing $m \pm k\sigma$ are then plotted above A_1 , as shown in Fig. 2, corresponding to the upper and lower limits of the system range. The upper and lower limits are similarly plotted for the remaining parameter values, $A_2, \dots, A_p$. The points representing the upper limits are now fitted with a line or a quadratic (or other) curve, while those for the lower limits are fitted with another curve. On the same graph, the design range is now entered. In the example of Fig. 2, this is given by Ed and lower values. We

Fig. 3 Total function error curve and optimum parameter A_{op}

can now obtain the common range for any design parameter value between $A1$ and A_p , and also, from Eq. (1), the function error curve with regard to evaluation item E . This procedure is repeated for the other evaluation items to obtain similar function error curves, which are then added together to obtain the total function error curve (see Fig. 3).

The total function error curve can either be 1) zero for some parameter range (or value), or 2) positive for all parameter values. When the total function error is zero, the system range is entirely contained in the design range, so that all evaluation items will be satisfactory at this parameter value regardless of any external disturbance. If, however, the total function error remains positive throughout the parameter range, the parameter value, A_{op} , which minimizes the total function error is assumed to be the optimal value when all evaluation items are taken into consideration.

The question may arise as to whether the parameter range or value that produces zero or minimum total function error would not be affected by other design parameters. In experimental design, the effect of one design parameter on the evaluation of another is called interaction. When interaction is strong, the number of experiments needed to accurately determine the parameter value rises. When the concept of function error is used, however, no additional experiments are needed once a total function error of zero is achieved. This difference arises from the fact that, in most parameter design methods based on experimental design, the evaluated item is either maximized, minimized, or made to approach a target value, whereas an evaluation based on function error requires only that the function satisfy the target range. This is illustrated below.

Let A and B be two design parameters, each of which is varied so as to take two values, $A1$ and $A2$, and $B1$ and $B2$, respectively. Four experiments were then conducted, representing the possible combina-

Fig. 4 Experimental result for E with interaction factors

Fig. 5 Function error for E with interaction factors

tions of the two parameters. Suppose that when the results of evaluation item E are plotted against design parameter A , we obtain Fig. 4. In this case, the plotted points are fitted with a line. The relation of parameter A and evaluation item E is affected by interaction with parameter B , so B must be known beforehand to determine the optimal value (minimum for instance) of A with respect to evaluation item E .

Meanwhile, an evaluation employing function error would proceed as follows. Suppose that the design range for evaluation item E is set at E_d or less, as in Fig. 5(a). From this, the function error curve (assuming a safety factor of $k=1$) of Fig. 5(b) is obtained. The function error vanishes in the range $A3$ to $A4$, where the functional requirement for item E is satisfied for any value of parameter B . Thus, any

value between A_3 and A_4 can be chosen independently of B . Under the condition that the function error is zero, the functional requirement is always satisfied even if the other design parameters and environmental conditions are the worst. In practice, there is no problem even in cases where the minimum total function error (corresponding to A_{op}) is non-zero but sufficiently small because the other design parameters are also determined to reduce the function error. When there are several items that must be evaluated, the function error for each item with respect to parameter A is determined, then added together to obtain the total function error. The parameter value at which the total function error is zero (or sufficiently close to zero) is chosen.

Another possible question is whether interaction should not be distinguished from the experiment environment, as factors contributing to the scattered distribution of an evaluation item. Clearly, one should be able to come up with a more accurate optimal parameter value if interaction is delineated sufficiently. Yet, a large number of experiments would be needed to determine the complex interaction existing between design parameters and evaluation items. Even then, the final solution will always involve some degree of approximation. This would seem to justify in many cases looking at the problem as a whole and seeking a solution that would satisfy the requirement range under any condition. Indeed, the proposed method was conceived from this standpoint, i.e., that of developing products while keeping the number of experiments at a reasonable level.

If the function error corresponding to A_{op} is still found to be relatively large, the product likely contains a fundamental flaw in its design. In such cases, a basic re-examination of the design is in order. The question then is "what is the highest total function error (at A_{op}) that can be tolerated?" This remains as a subject for future study, although our experience points to unity (one) as the upper limit.

2.3 Development procedure

Using the product development method based on the concept of function error, one can determine such parameters as needed to design/develop a product in a rational manner while keeping the number of experiments under control. While there are many orthogonal tables, here we give an example using an L_9 orthogonal table (see Table 1). The orthogonal table is first set up.

1) Parameters that must be specified in the design are selected (in our case, A, B, C and D). The number of parameters depends on the type of orthogonal table used.

2) Three levels are set for each parameter. For

Table 1 L_9 orthogonal table

No.	Design parameters				Experimental results for evaluation items		
	A	B	C	D	E	F	G
1	A1	B1	C1	D1	E1	F1	G1
2	A1	B2	C2	D2	E2	F2	G2
3	A1	B3	C3	D3	E3	F3	G3
4	A2	B1	C2	D3	E4	F4	G4
5	A2	B2	C3	D1	E5	F5	G5
6	A2	B3	C1	D2	E6	F6	G6
7	A3	B1	C3	D2	E7	F7	G7
8	A3	B2	C1	D3	E8	F8	G8
9	A3	B3	C2	D1	E9	F9	G9

instance, values of A_1 , A_2 and A_3 are set for A . The number of levels differ with the orthogonal table.

3) There is no upper limit on the number of evaluation items. Our example has three: E, F and G.

4) The design range (required value) for each item is determined.

5) Preparations are made for the tests following the orthogonal table.

6) A series of nine tests are conducted according to the orthogonal table, and evaluation items (E, F, G) are measured (E_1 , F_1 , G_1 , etc., in the example). The function error curve is then determined from the test results.

7) For a particular evaluation item (say, E), collect all data obtained with one parameter level (E_1 , E_2 , and E_3 corresponding to A_1) to form a group. Each E_i can consist of several data points.

8) Calculate the mean m and standard deviation σ of that data group, and starting with a safety factor of $k=1.5$, assign $m \pm k\sigma$ as the upper and lower limits of the system range at A_1 .

9) Determine the system ranges for the other levels of the same parameter (A_2 and A_3) in a similar manner. The three upper limits for A_1 , A_2 , and A_3 are then fitted by a quadratic (or other) curve, as are the lower limits. If the curve has too large curvature, where the system range for a parameter level is extremely different with the others, redesign the parameter levels and execute the experiment again.

10) From the system ranges and design range (Ed) for this evaluation item (E), calculate the function error for a suitable parameter range.

11) In the same way, determine the function error for that parameter (A) with regard to the remaining evaluation items (F and G), and add them together to obtain the total function error.

12) Plot the total function error as the ordinate against parameter A as the abscissa, then locate the curve's minimum and find the corresponding parameter value A_{op} . From the axiom, this is the optimal parameter value for A when all evaluation items are considered together. If the function error assumes

zero over a wide parameter range, or if it is not sufficiently close to zero at A_{op} , so that the optimal value cannot be determined, change the safety factor k and repeat steps 8)–12).

3. Case studies

To illustrate the application of DNM to actual product design, the design improvement of a horizontal extrusion machine and the development of a CNC lathe feed mechanism are now described. The former followed the procedure described in the previous section, showing an example of straight forward DNM design. The latter involved many design parameters, which were determined in stages, each involving a DNM evaluation. In spite of the many design parameters, the resulting design was excellent and little affected by interaction.

3.1 Application in horizontal extrusion machine

The above method was applied to improve a horizontal extrusion machine (Fig. 6). While an existing design was improved in this instance, the process applies equally when newly designing a product, where the basic design has already been set out and the design parameters identified. Thus, parameters that cannot be established from theory and experience are determined by a series of experiments employing various parameter levels.

The main objective in redesigning this machine was to reduce the wear of the ring valve and screw head. Thus, as evaluation items, the ring valve's wear at its inner diameter and lengthwise direction, the screw head's wear, power consumption, and the plastic material's flow rate (a measure of productivity) were selected.

Various parameters affect the plastic extrusion process. For the present study, we chose as parameters four items—the ring valve's inner diameter and length, the screw's rotary speed, and the barrel's temperature setting—which greatly affect the above evaluation items and the machine's overall performance. We thus used an L_9 orthogonal table.

Three levels were then set for each parameter, and the extrusion machine was operated at these parameter settings. Since testing wear under normal operating conditions would take excessive time, for

Fig. 6 Horizontal extrusion machine

the present study we employed an accelerated test by mixing WA #1000 abrasive grain into the plastic molding material (polypropylene); the mass ratio of polymer and abrasive grain was 3:1.

Ideally, the design range should be determined from the product's target specifications or from theoretical considerations. If, for instance, we know that the ring valve will cease to function properly when the wear exceeds 0.05 mm, that value should be used as the design limit. For the present case, however, such figures were not available and so, as the next best step, we calculated the mean values of the nine tests and used them as the acceptable design range limits; in other words, a value that was better (for example, less wear) than the mean was taken as satisfactory. The specific design ranges thus determined were 0.005 mm or less for the ring valve's wear at its inner diameter; 0.316 mm or less wear in the ring valve's lengthwise direction; 0.448 mm or less screw head wear; 27.3 kW or lower watt consumption; and 96 g/min or higher material flow rate.

Meanwhile, the systems ranges for the evaluation items were determined from the tests. Test data on the evaluation items are shown in Table 2. The data were then used to determine the optimal parameter settings following the procedure described in section 2.

In the present example, we employed a safety factor of $k=1.5$, which produced negative values for some of the system range's lower limits. Since this is not possible in reality, the "zero" line (or abscissa) was set as the lower limit. The total function error curves for the four design parameters were then obtained. The curve for the screw's rotary speed is presented in Fig. 7. Although the function error remains relatively large here, the optimal setting was determined from this curve since there were many evaluation items and the influence of interaction was thought to be small.

From the total function error curves, the parameter values that minimized the total function error

Table 2 Result of experiments

No.	Wear amount mm			Power consumption kWh	Material flow rate g/min
	Ring valve		Screw head		
	Inside diameter	Length	Length		
1	0.004	0.268	0.330	36.0	93
2	0.004	0.552	0.124	19.3	119
3	0.001	0.453	0.624	12.6	114
4	0.005	0.187	0.275	25.9	97
5	0.007	0.602	1.184	16.4	64
6	0.003	0.268	0.549	33.6	77
7	0.005	0.207	0.488	19.5	108
8	0.001	0.043	0.187	25.0	92
9	0.005	0.261	0.274	43.1	99

Table 3 Experimental results of the improved system

Experiments	Wear amount mm			Power Consump- tion kWh	Material flow rate g/min
	Ring valve		Screw head Length		
	Inside diameter	Length			
Improved	0.001	0.148	0.247	15.3	130
Present	0.005	0.234	0.533	32.3	54

Fig. 7 Total function error for revolution speed of screw

were found to be as follows: the ring valve's inner diameter: 26 mm; ring valve length: 11 mm; screw rotary speed: 115 rpm; and barrel temperature setting: 242°C.

Following this, a comparison test was carried out to check the validity of the method. In our case, we compared the newly designed model, which incorporates the optimal conditions determined above, with the previous product, in which all four design parameters are at level 2 (A_2 , B_2 , C_2 , D_2). The results are shown in Table 3.

From the results, we see that a machine which has parameter values determined by this method meets all of its design range settings, with all evaluation items showing considerable improvement over previous values.

A product which has been designed to improve a single evaluation item will likely perform better in that aspect than one based on the present method. But this does not guarantee that other evaluation items will also be satisfactory as there is usually a trade-off among them. For example, if reducing wear had been our only objective, then we could have just lowered the machine's productivity. Slowing down the operation will naturally create less wear, while reducing the power consumption as well. Thus, there is a trade-off between productivity on the one hand, and wear and power consumption on the other. Because the present method takes into consideration the effect that changes in different design parameters have on each evaluation item, its final solution is satisfactory from an overall standpoint.

In the present example, we determined the optimal values for four parameters against three evalua-

Fig. 8 Photograph of the developed CNC lathe

Fig. 9 Positioning mechanism of the CNC lathe

tion items. Although 81 tests are in general needed when four parameters must each be checked at three levels, we were able to obtain sufficient information in our case from nine tests. If we also include the final test for confirmation, only ten tests sufficed. Incidentally, this product development project was completed in four months.

3.2 Application to design of ball-screw nut feed mechanism for CNC lathe

One project undertaken at our research lab was to develop a human-oriented CNC lathe (see Fig. 8). DNM was applied to the optimal design of the ball-screw nut feed mechanism (see Fig. 9) for this CNC lathe.

Heat generated during operation of the ball-screw nut is known to cause it to deform from thermal expansion, adversely affecting the machining accuracy (i.e., positioning precision). Thus, the x -axis positioning precision, its settling time (i.e., number of motion cycles), and the lubrication oil consumption at the sliding surface were chosen as evaluation items.

Fig. 10 Cascade application of DNM to positioning mechanism design

The design parameters, which must satisfy these items, were then identified. Yet, each item was affected by a different set of design parameters, with some overlapping among them. Thus, positioning precision depended on the ball-screw nut preload, type of support bearing, and ball-screw nut pretension; the settling time for positioning precision depended on the ball-screw nut pretension, bearing retainer gap, and the lubricating oil's supply interval; while lubricating oil consumption depended on the lubricating oil's supply interval and discharge. Simultaneously satisfying the three evaluation items would have excessively raised the number of required tests. For this reason, we decided to apply DNM in stages and establish the set of design parameter values relevant to each evaluation item in turn. The procedure is outlined in Fig. 10. The design parameters, $P1$ through $P6$, respectively denote the ball-screw nut preload, type of support bearing, ball-screw nut pretension, bearing retainer gap, the lubricating oil's supply interval, and lubricating oil discharge. The evaluation items, $E1$ to $E3$, respectively denote the positioning precision, its settling time, and lubrication oil consumption.

First, a series of tests were conducted to establish design parameters affecting the positioning precision. Three levels were set for each parameter as follows: ball-screw nut preload: 50, 100, and 150 kg; bearing type: those manufactured by companies A, B, and C; and ball-screw nut pretension: 0.02, 0.03, and 0.04 mm. The optimal settings were found to be preload 98 kg, bearing by company A, and a pretension of 0.0312 mm. The total function errors at optimal settings were

$Dt=2.21$ for ball-screw nut preload, and $Dt=3.51$ for support bearing type.

Next, tests were conducted to establish the design parameters affecting settling time, with positioning precision and settling time as evaluation items. The levels for the parameters were ball-screw nut pretension: 0.02, 0.03, and 0.04 mm; bearing retainer gap: 0.02, 0.03 and 0.04 mm; and the lubricating oil's supply interval: 5, 15, and 25 minutes. Meanwhile, ball-screw nut preload and bearing type were set at the optimal settings found above, that is, 98 kg and bearing A.

The optimal settings were found to be ball-screw nut pretension: 0.035 mm; bearing retainer gap: 0.02 mm; and the lubricating oil's supply interval: 5 minutes. Note that the ball-screw nut pretension of 0.035 mm differs from the setting of 0.0312 mm obtained above. Since the ball-screw nut preload and bearing employed for this stage were the optimal ones found in the previous stage, the newly obtained value (0.035 mm) was assumed to be more reliable and so was used henceforth. The total function errors at optimal settings were $Dt=0$ for ball-screw nut pretension, and $Dt=0$ for bearing retainer gap.

Finally, tests were conducted to establish the design parameters affecting lubricating oil consumption, with positioning precision, settling time, and lubricating oil consumption as the evaluation items. The tested levels were lubricating oil's supply interval: 5, 15, and 25 minutes, and lubricating oil discharge: 0.1, 0.05 and 0.03 cc. Meanwhile, ball-screw nut preload, bearing type, ball-screw nut pretension, and bearing retainer gap were set at the optimal settings found at the previous stage. The optimal settings were found to be lubricating oil's supply interval: 25 minutes, and lubricating oil discharge: 0.05 cc. The total function errors at optimal settings were $Dt=0.571$ for discharge, and $Dt=0.06$ for the lubricating oil's supply interval.

A test was then conducted using a CNC lathe which had a ball-screw nut feed mechanism with the optimal parameter settings obtained above. The positioning error caused by deformation of the ball-screw nut is as shown in Fig. 11: the settling time was found to be 30 motion cycles (450 sec.), after which the positioning precision, when compensated for backlash, remains within $2\ \mu\text{m}$. The consumption of lubricating oil was found to be 0.12 cc/hr. When compared against typical values found in a conventional CNC lathe of a similar type, with a positioning precision of $5\ \mu\text{m}$, settling time 50 motion cycles, and lubricating oil consumption of 1.2 cc/hr, the results obtained here are much superior. At the outset of this project, there were some concerns about the high number of design

Fig. 11 Experimental results based on optimal design parameters

parameters and on whether our method of establishing sets of design parameters in progressive stages would yield converging solutions. However, it was found that the parameter settings resulted in evaluation items (i.e., performance) that fully met their respective design ranges (i.e., specs), as long the first round of tests produced total function errors no greater than about $Dt=3$.

4. Conclusions

1) Based on the concept of function error, the author proposed the design navigation method (DNM). This method is used to develop a product in which several evaluation (or performance) items, among which there are trade-offs, must be satisfied; this end is achieved by establishing multiple design parameters based on a limited number of tests.

2) The relation between function error and interaction, which is of relevance in experimental design, was clarified.

3) DNM was applied to design an extrusion machine, which confirmed the validity of the method.

4) DNM was applied to design the ball-screw nut feed mechanism of a CNC lathe. Here, DNM was applied in progressive stages so that the number of tests could be kept low and still allow the determination of a large number of design parameters that

would satisfy multiple evaluation items.

As of this date, over ten firms have employed the product development method presented here and with good results. For example, it was used to establish the machining process of acupuncture needles, develop the chuck for a dental handpiece, develop an optical circulator element, improve an electronic parts connector, and so on.

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References

- (1) Taguchi, G. and Yokoyama, Y., Experimental Design Methods for Product Design, (in Japanese), (1988), Japanese Standards Association.
- (2) Eschenauer, H., Koski, J. and Osyczka, A., Multi-criteria Design Optimization, (1990), Berlin, Springer-Verlag.
- (3) Nakazawa, H., Process Design Using the Concept of Amount of Information, J. Japan Society of Precision Engineering, (in Japanese), Vol. 49 (1983), pp. 1246-1250.
- (4) Nakazawa, H., Information Integration Method, (in Japanese), (1987), Corona-sha.
- (5) Nakazawa, H. and Ohtsubo, T., Study on a System to Determine Optimal Search Conditions Based on the Information Integration Method, J. Japan Society for Precision Engineering, (in Japanese), Vol. 57, No. 5 (1991), p. 863.
- (6) Imai, H., Information Theory, (in Japanese), (1997), Shokodo.