UNCERTAIN DESIGN BASED ON ROBUST DESIGN METHOD WITH AN APPLICATION TO T-PEEL TEST APPARATUS

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ABSTRACT: Measurement apparatus can accurately measure against errors to ensure high robustness, which is conventionally achieved through parameter design. This study proposes a robust design method, which is adaptive to any environment and can handle any uncertainty in the environment, by incorporating the set-based design concept into the conventional parameter design to ensure robustness. The proposed method represents design parameters as ranged values, obtains optimum conditions from both conventional and outside level values, and employs an evaluation index to reflect the designer's intention. The algorithm is represented in five steps: (a) determination of design variables, (b) planning and conduct of an experiment, (c) calculation of signal-to-noise (SN) ratio for each experiment, (d) conduct of a supporting experiment, and (e) application of the set-based design method. The proposed method is applied to a T-peel test apparatus' design. Owing to the proposed design method's application, the SN ratio of the proposed method exhibited the feasibility of attaining higher values compared to the SN ratio of the conventional parameter design's optimum condition. Furthermore, the designer could use the proposed evaluation index to select a range solution reflecting a subjective intention. The proposed method is more robust than the conventional parameter design and can design a measurement apparatus considering the designer's intention.

KEYWORDS: *Robust Design; Parameter Design; Set-Based Design; SN Ratio; T-Peel Test Apparatus*

1.0 INTRODUCTION

In general, measurement apparatuses are required to be able to accurately measure against errors, such as systematic errors and accidental errors, mainly occurring at the time of measurement. Thus, measurement apparatuses are required to be highly robust. Design of most measurement apparatuses adopt the conventional parameter design [1, 10]. Parameter design employs an alternative index called signal-to-noise (SN) ratio using an experiment through an orthogonal array and maximizes SN ratio to derive optimum condition, or rather, a highly robust condition against error factors. Nevertheless, parameter design's optimum condition is selected from the level value of the control factor represented by a point-based value; estimating the optimum condition outside such level value is challenging and needs additional experimenting. For such estimation, incorporating uncertain information on the part of the designer, such as subjective experience and intuition, to set the control factor level may be feasible.

Accordingly, this study integrates the set-based design method into the conventional parameter design [2]. This study proposes an uncertain design based on robust design that derives various range solutions considering the values outside the level value by setting uncertain information and design solutions as ranged values. Moreover, this study evaluates the range solution with an evaluation index that reflects the designer's intention. To validate the effectiveness of the proposed method, the method is applied to the design problem of a T-peel test apparatus. The obtained results are compared with those of the conventional parameter design method.

2.0 PROPOSED METHOD

2.1 Determination of Design Variables

In principle, the proposed robust design method is an extended parameter design with the incorporation of set-based design concepts [3]. Figure 1 shows a procedure of the proposed method. Before the design process is started, the designer confirms the objective function of the measurement apparatus. Further, the designer considers the relation between the input (measuring characteristics) and output (signal factor) of the system. Next, the designer defines design variables related to both the experimental condition and test apparatus structure. Finally, the design variables are classified into three categories: control, signal and noise factors. A control factor is a design variable that can be controlled and its value can be arbitrarily changed. Signal and noise factors refer to presumed sources of error or rather some uncontrollable design variables, such as environmental and experimental factors. After the three factors have been determined, the designer assigns the defined control, noise, and signal factors to an orthogonal array.

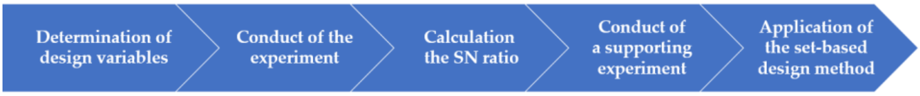


Figure 1: Procedure of the proposed method

2.2 Conduct of the Experiment

The designer conducts a measurement experiment according to the planned orthogonal array in Section 2.1 and measures the resulting values under each experimental condition. The designer calculates the SN ratio of each experimental condition from the obtained result. SN ratio η is defined as in [4] such as

$$\eta = \frac{\frac{1}{4r}(S_\beta - v_e)}{v_n} \tag{1}$$

where r is effective divisor, S_β is variation of proportional term, V_e is error variance and V_n is total error variance.

2.3 Conduct of a Supporting Experiment

From the derived range of design solutions in Section 2.2, the designer selects the design parameters that can attain the highest SN ratio and conducts a supporting experiment to evaluate the reproducibility of the main experiment. In addition, the designer compares the SN ratio gain in the supporting experiment with that in Section 2.2 (the main experiment). In general, it is assumed that an experiment is reproducible when the SN ratio gain difference is within 3 db [5].

2.4 Application of the Set-based Design Method

The designer applies the calculated SN ratio in Section 2.2 to the set-based design method. The set-based design method defines design variables as ranged values, rather than point values, and is a design method that derives various range solutions by removing impractical solutions as the design phase progresses. As such, even if the designer changes the requirement of the system during the design process, the derived range solution will still contain a solution that meets the requirement. Thus, a flexible design method is possible with this method, with no backtrack.

Accordingly, the derived design solutions are evaluated herein based on previously proposed evaluation indices, which represent the designer's preference [3], as described in Section 2.4.3. In the proposed design method, the design variables defined as range values are divided equally and the required performance for each range is derived. Moreover, these evaluation indices are applied to quantitatively assess the derived range solutions. Thus, the designer can select the feasible range solutions. The setting of the necessary information for applying the set-based design method is described as below.

2.4.1 Determination of the Designer's Preference

The designer defines a preference value, normally in the scale of [0, 1]. Where preference value of 0 or 1 for a design variable means that the variable is not preferred or preferred for the design solution, respectively.

2.4.2 Derivation of a Range Solution

The designer divides the design variables set into an arbitrary number of sets. Based on the relation between such design variables and the required performance of the measurement apparatus, the designer derives the ranged value of performance that can realize each divided range of design variable using the particle swarm optimization algorithm as well as the various range solutions that completely meet the required performance.

In this study, the equation that indicates the relation between the design variables and the required performance is derived as an approximation formula employing the radial basis function interpolation method based on the level values of control factors and the SN ratio of each experimental condition.

2.4.3 Evaluation of the Range Solution

To select the range solution that reflects the designer's intention, the range solution derived in Section 2.4.2 is evaluated using evaluation indices. Details of the evaluation indices are shown below. Moreover, evaluation indices (i)-(v) can be used by the designer to select a solution satisfying its own requirements.

i. Design Variable Preference (*DVP*) is an index indicating the designer's preference for design variables. An example of the calculation is shown in Figure 2 (a). Where DV_{MAX} is the maximum value of the design variable and DV_{MIN} is the minimum value of the design variable.

$$DVP = \frac{\int_{DV_{MIN}}^{DV_{MAX}} F(x)\,dx}{DV_{MAX} - DV_{MIN}} \tag{2}$$

ii. Preference of Performance (*PP*) is an index of the designer's preference for performance. An example of the calculation is shown in Figure 2 (b). Where P_{MAX} is the maximum value of the preference and P_{MIN} is the minimum value of the preference.

$$PP = \frac{\int_{P_{MIN}}^{P_{MAX}} G(x)\,dx}{P_{MAX} - P_{MIN}} \tag{3}$$

iii. Robustness of Performance (*R*) is an index of performance variation. An example of the calculation is shown in Figure 2 (c). Where $PMAX_j$ is the maximum value of a design solution, $PMIN_j$ is the minimum value of a design solution, $PMAX_{all}$ *is* the maximum value of all design solutions, and $PMIN_{all}$ is the minimum value of all design solutions.

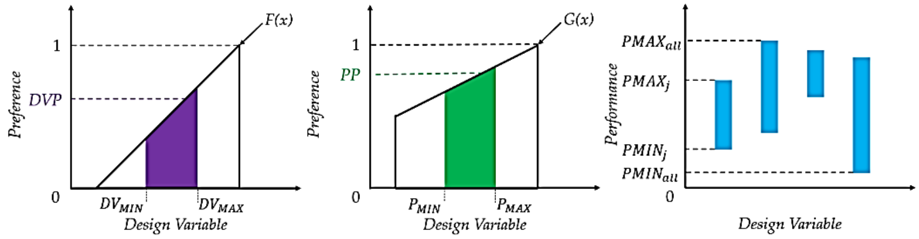
$$R = \frac{PMAX_j - PMIN_j}{PMAX_{all} - PMIN_{all}} \tag{4}$$

iv. Performance Rating (*value* and *Rp*) where *value* is an index of performance evaluation while *Rp* is its normalized value.

$$value = \frac{PP}{R} : Rp = \frac{value}{valuemax} \tag{5}$$

v. *Rall* is an overall score integrated design variable and performance evaluation value.

$$Rall = \sqrt{DVP \times Rp} \tag{6}$$



(a) (b) (c)

Figure 2: Calculation example of evaluation indices: (a) calculation example of DVP, (b) calculation example of PP and (c) calculation example of R

3.0 CASE STUDY: T-PEEL TEST APPARATUS

3.1 Outline of the T-Peel Test Apparatus

The proposed method is applied to a T-peel test apparatus to validate its effectiveness and robustness. The primary objective here is to minimize the variation in the measured peeling force of the apparatus and subsequently search for an optimum condition where the obtained SN ratio is higher than that obtained when using the conventional parameter design. Figure 3 shows an outline of the T-peel test apparatus.

Figure 4 shows the specimen. The measurement object is a film used in general confectionery packaging bags, which comprises clear deposition polyethylene terephthalate (PET) and vacuum metallized PET (VMPET). The force used to peel off the bonding plane is the peeling force in this case.

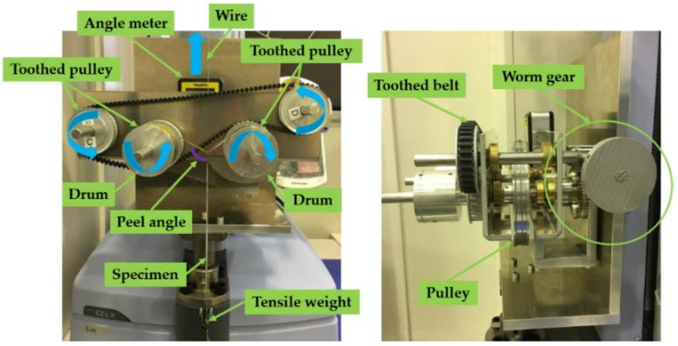


Figure 3: Outline of T-peel test apparatus

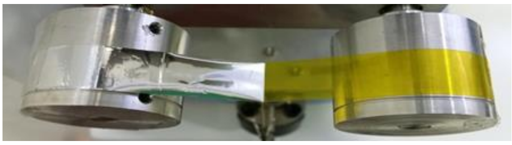


Figure 4: Measurement specimen

3.2 Experimental Design

A summary of all the factors and their corresponding level values is provided in Table 1.

Table 1: Definition of control, signal and noise factors

Control factor	Unit	Level 1	Level 2	Level 3
A: Tensile weight	g	15	30	
B: Drum diameter	mm	30	40	50
C: Peel angle	°	90	105	120
D: Peel speed	mm/s	2	5	8
E: Data region	%	30	50	70
Signal factor				
M: Specimen width	mm	10	15	20
Noise factor				
N: Peel angle division	°	2	−2	
O: Sampling		minimum	maximum	

3.2.1 Control Factor

Following the definition of control factor provided by the studies as shown in [6-7], five factors namely, tensile weight (*A*), diameter of drum (*B*), peel angle (*C*), peel speed (*D*) and data region (*E*) are all classified as control factors. Tensile weight (*A*) is the tension load attached to the end of the unpeeled part of the specimen film, as shown in Figure 3. Diameter of drum (*B*) is the diameter of the two drums, as illustrated in Figure 3. Peel angle (*C*) is the angle between the back surface of the end of the peeled part (VMPET part) and the unpeeled part, as shown in Figure 3. Peel speed (*D*) is the moving speed of the fixed head of the T-peel apparatus. Data region (*E*) is the range of the effective measurement value that extends beyond the midpoint in a peeling curve.

3.2.2 Signal and Noise Factors

The inclination and sampling of the peeling angle are treated as noise factors based on the assumption that the unpeeled part of the specimen shakes to the left and right during the peeling test and that the peeling force is dispersed. Furthermore, the specimen film width is considered as a signal factor based on the assumption that it exhibits direct proportionality with the peeling force. Herein, it is defined as the range of peeled film length, 100 mm, in reference to the Japanese Industrial Standards (JIS) [8-9].

3.3 Calculation of the Measurement Data

Measurement data were calculated based on the obtained peeling force from each experiment. And, the SN ratio of each experiment were calculated based on the measurement data.

To compare the experiments performed under the proposed method, SN ratio of each control factor were calculated and their optimum values were obtained. The factor effect chart of SN ratio of each factor are illustrated in Figure 5. From Figure 5, the designer determined the combination of control factors that become the optimum condition to maximize the SN ratio and the lowest condition to minimize the SN ratio.

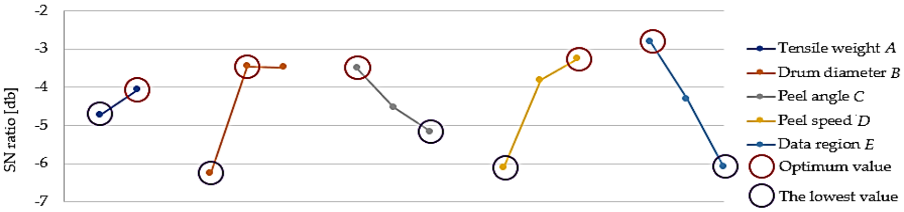


Figure 5: Factor effect chart of SN ratio

3.4 Conduct of the Supporting Experiment

Based on the optimum condition in the parameter design method, the designer conducted the supporting experiment to verify the reproducibility of the experimental result. The designer measured both the optimum and lowest conditions and calculated their corresponding SN ratio. Table 2 shows the estimated values for each condition and the result of the supporting experiment.

From Table 2, the gain difference of SN ratio between the estimated values of the parameter design method and the results from the supporting experiment was 2.476 db, which is within the 3 db standard of reproducibility of the parameter design. Thus, the reproducibility of the measurement results was confirmed.

Table 2: Estimated value of optimum condition from conventional parameter design

Parameters	Lowest condition	Optimum condition	Gain	Differential gain
Estimated value	−10.743	0.483	11.225	2.476
Supporting experiment	−10.634	−1.884	8.749	

3.5 Application of the Set-based Design Method

3.5.1 Determination of the Designer's Preference

The range of the five control factors treated as design variables, as summarized in Table 1, and the range of their SN ratio also treated as the required performance are defined herein. As for the design variables, the lowest value of the level was set as the lower limit value of the range, whereas the highest value was the corresponding upper limit value. Similarly, as for the required performance, the lowest value of the level was set as the highest SN ratio obtained by experimental measurements, whereas the highest value was set as the estimated value of the optimum condition. Additionally, the designer's preference was defined by reflecting the intention for each design variable and the required performance.

3.5.2 Application Result of the Set-based Design Method

The visualization result of the derived design solutions is shown in Figure 6. The description such as "the range solution that may exceed the SN ratio of the optimum condition" refers to the maximum value of the performance (SN ratio) exceeding 0.483 db which is the SN ratio of the optimum condition in the parameter design and the minimum value falls below −10.743 db, which is the SN ratio of the lowest condition in the parameter design.

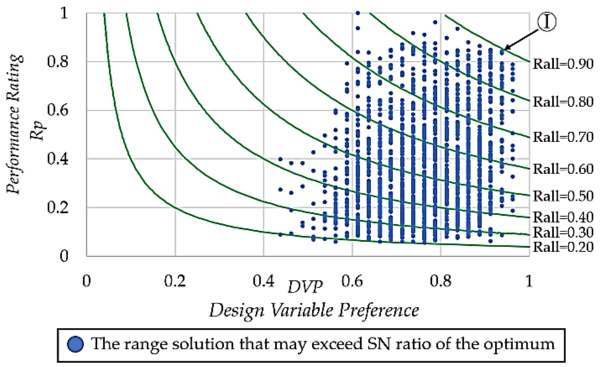


Figure 6: Visualization result of the design solutions

3.6 Discussion

As shown in Figure 6, there were 1711 calculated range solutions that possibly exceed the SN ratio of the optimum condition. In the set-based design method, a designer can select a solution among these range solutions according to their requirements. In Figure 6, for example, range solution I had the highest *Rall* among the calculated range solutions. Accordingly, the designer would select range solution I if the balance of control factor and SN ratio is the preference. As such, the designer can intentionally select a solution for an evaluation index.

Next, the effectiveness of the proposed method is quantitatively shown. The SN ratio of the design solution calculated by the proposed method was converted into antilogarithms. As there were too many solutions calculated by the proposed method in the study, only range solution I was exemplified for the calculation. The SN ratio of range solutions I vary within [0.212, 4.023]. Table 3 shows the antilogarithms of these values. Compared with the estimated value of the lowest condition in the parameter design method, the maximum SN ratio of range solutions I, showed the improved measurement ability of approximately 30 times. Likewise, compared with the estimated value of the minimum condition in the parameter design, the minimum SN ratio of range solutions I, exhibited the improved measurement ability of about 12 times. As such, the minimum SN ratio of the calculated range solution in the proposed method would not be able to improve the measurement ability of those in the conventional parameter design. However, the maximum SN ratio of the calculated range solution, the measurement ability can be improved as expected, compared to the conventional parameter design. Therefore, the proposed method indicated the possibility for more robust design than the conventional parameter design.

The above-stated discussions confirm the effectiveness of the proposed design method in searching for a design solution that reflects the designer's intention with regard to the level values outside the set values as well as the conventional parameter design.

Table 3: Result for the parameter design and comparison of antilogarithm in the proposed method

Parameter design	Range solution I	
Optimum condition	Maximum	Maximum/Lowest condition
1.118	2.525	29.943
Lowest condition	Minimum	Minimum/Lowest condition
0.084	1.050	12.451

4.0 CONCLUSION

This study proposed an uncertain design method, which is adaptive to any environment and can handle any uncertainty in the environment, by incorporating the set-based design concept into the conventional parameter design to ensure robustness. The proposed design method was shown to derive a range solution (set of solutions) that reflects the designer's intention, considering values outside the level values.

Its application on the T-peel test apparatus design, with results that were compared with those of the conventional parameter design, validated that the SN ratio of its range solution could be higher than that obtained by the optimum condition of the parameter design method. Moreover, the study showed that by employing the evaluation index, the designer could select a solution range to reflect a subjective intention. Overall, the findings of this study confirmed the feasibility of designing and developing a measurement apparatus with the proposed method by considering the designer's intention.

Nevertheless, there is a difference in the usage of variables in parameter and set-based designs. In the former, qualitative factors can be defined as control factors, whereas in the latter, design variables can be defined only through quantitative factors. Future studies will be geared on developing a robust design method that selects the structure of a measurement apparatus by defining qualitative factors as design variables.

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