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Robust parameter design (RPD)

Plan paramètre robuste (RPD)

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Foreword

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Introduction

Parameter design can be applied in product design stage to identify optimum nominal values of design parameters based on assessment of robustness of its function. Robustness assessment should be performed as a consideration of overall loss during the product's life cycle. The overall loss is composed of costs and losses at each stage of the product's life. It should include all the costs incurred during not only its production stage, but also its disposal stages.

When a product is not robust, the product causes many environmental and social economic losses (including losses to the manufacturer and users) due to its poor quality caused by functional variability throughout its usable lifetime from shipping to final disposal. Product suppliers should have responsibilities and obligations to supply robust products to the market to avert losses and damages resulting from defects in the products.

At product development and design stages, the product suppliers should therefore anticipate the defects and failures of products in the market by applying preventative measures, and also should design robust products by optimizing their design from the point of view of robustness.

At manufacturing stage, the product suppliers should manufacture their products that meet the product specifications. One can optimize manufacturing processes to produce the products that meet the specifications. However, robustness against customer's environment and products' aging can only be addressed by product design.

Parameter design methodology provides effective methods for achieving robustness through its design of specification determination, and it is a preventive counter measure against various losses in the market.

Parameter Design for Robust Products, this document, is directly targeted at losses incurred in the usage stage. Where possible, losses at other stages are also investigated so that the results of parameter design can be used to perform optimum product design for the whole of the product's life cycle.

Parameter Design for Robust Products

1 Scope

This document gives a guidance of applying the optimization method of parameter design, an effective methodology for optimization based on Taguchi Methods, to achieve robust products.

Aim of applying parameter design in product design is to prevent defects, failures and quality problems that may occur during the usage of the product, and to minimize the loss in the market. Robust product, output of parameter design, is a product which is designed such a way to minimize the user's loss caused by defects, failures and quality problems. One should note that defects, failures and quality problems are caused by functional variability of non-robust product. In the parameter design, optimum nominal values of product's design parameters can be selected by treating product's design parameters as control factors and by assessing robustness under noise factors. The use of parameter design at the development and design stages makes it possible to determine the optimum product design and specification so that the product is more robust in the market. Choice of noise factors strongly depends on the market of the product.

This document prescribes signal-to-noise ratio (hereafter SN ratio) as a measure of robustness and the procedures of parameter design to design robust products utilizing this measure. The word "robust" in this document means minimized variability of product's function under various noise conditions, that is, insensitivity of the product's function to the changes in the level of noises. For robust product, its response should be sensitive to signal, and insensitive to noises.

The robustness of a product should essentially be quantified in terms of the economical losses caused by variability of product's function at the usage stage. Accordingly, when the robustness of a product is estimated at the development and design stages, the designer should forecast and calculate the future economical losses in the market where the product will be used. However, it is often difficult to perform concrete evaluation of future losses at the development and design stages.

In practice, many product's defects and failures occur mainly due to the product's characteristics that deviate from or vary around the designed target values due to the change in usage environment and deterioration, i.e. noise conditions. The variability of product's response should be used as a measure of robustness, because market losses increase in proportion to the magnitude of variability of product's characteristics due to noise effects. The variability due to noises includes the deviation from the designed target value and the variation around the designed target value in market. SN ratio, corresponding to the inverse of the variation measure, should be used as a measure of goodness in robustness. In other words, the inverse of SN ratio is proportional to the market losses.

For the experimental plan of parameter design, direct product of inner array and outer arrays is proposed. Control factors should be assigned to inner array, and signal and noise factors should be assigned to outer array. By using a direct product plan, all the first level interactions between control factors and noise factors can be assessed and can be utilized to select the optimum level of control factors from the point of view of robustness.

Assessing robustness through SN ratio is a key of parameter design. Outer array is for evaluating SN ratio, robustness, for each combination of levels of control factors indicated by the inner array. Inner array is for comparing SN ratios and selecting optimum combination of system's design parameters. While experimental layout for inner array may have many variations, orthogonal array L_{18} is strongly recommended and then only the application of orthogonal array L_{18} is discussed in this document.

The approach of this document can be applied to any products that are designed and manufactured, including machines, chemical products, electronics, foods, consumer goods, software, new material, services. Manufacturing technologies are also regarded as products that are used by manufacturing processes.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 3534-1, *Statistics — Vocabulary and symbols — Part 1: Probability and general statistical terms*

ISO 3534-3, *Statistics — Vocabulary and symbols — Part 3: Design of experiments*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 3534-1, ISO 3534-3 and the following apply.

3.1
function:
work which a system performs in order to fulfil its objective.

Note Function can be expressed by mathematical form of input-output relation.

3.2
robustness:
degree of smallness in variability of system's function under various noise conditions.

Note System's performance can be assessed by robustness. SN ratio is a quantitative measure of robustness.

3.3
signal-to-noise ratio
SN ratio
ratio of useful effect to harmful effect in response variations.

Note 1 SN ratio is usually expressed in db value. The notation of db is used instead of dB for SN ratios of robustness measure.

Note 2 Anti-logarithm value of SN ratio, real number, is inverse of variation measure such as variance or a coefficient of variation, and inversely proportional to the monetary loss.

Note 3 The change in response caused by intentional change of signal value is useful effect. In case of the ideal function being zero point proportional, the linear slope forced through the zero point is the useful term.

Note 4 The change in response caused by noise factors is harmful effect. Effect of noise factor and deviation from the ideal function are examples.

Note 5 SN ratio should contain the variability under noise factors and the discrepancy from the ideal function under average usage condition.

3.4
sensitivity
amount of change in response caused by unit change of input.

Note 1 Sensitivity is usually expressed in db value.

Note 2 For the dynamic characteristic cases, sensitivity shows the magnitude of linear coefficient due to signal, β^2 , where β is proportional constant.

Note 3 For the nominal-the-best response, the sensitivity shows the magnitude of mean, m^2, where m is the average of response.

3.5
noise
variable which disturbs the system's function.

Note 1 User's condition contains noise and signal.

Note 2 Noise is composed of internal noise, such as aging and wear, and external noise, such as environment during usage. They are sometime called as capacity and demand respectively. Deterioration and change of internal constant of the system over time or in parts are examples of internal noises. Usage conditions and environment conditions of the product are examples of external noises. Three categories of noise factors are: 1) Environment, 2) Aging and changes over time, 3) Manufacturing Variations.

3.6
signal
input variable to the system, which is intentionally changed by user to get an intended value of response in input-output relation

Note 1 User's condition contains signal and noise. Any variable/factor at user's conditions is either a signal or a noise factor

Note 2 There are two kinds of signal; active signal and passive signal. Active signal is operated by user to get intended response, for example, rotating angle of steering wheel to change the vehicle's direction. Passive signal is used by user to know the value of input from response reading, for example, temperature in thermal measurement. In both cases, output will change by changing the value of signal but user wants to get response value in active case, and user wants to know the value of signal in passive case.

3.7
dynamic characteristics
output response which has the ideal target values depending on the value of signal.

Note The relation between dynamic characteristics and signal can be expressed by input-output functional form. Output of system's function is dynamic characteristics in many cases.

3.8
static characteristics
non-dynamic characteristics
output response which has a fixed target value.

Note Static characteristics can be categorized into three groups depending on the target value; nominal-the-best, smaller-the-better, and lager-the-better characteristics, where target value is finite value, zero, and infinity respectively.

3.9
inner array
experimental plan where design parameters are assigned as control factors and indicative factors. Each treatment run will be assessed for robustness using SN ratio and sensitivity.

Note 1 Orthogonal arrays are recommendable for inner array in parameter design, because many design parameters can be taken into consideration in one set of experiment.

Note 2 Experimental factors should be categorized by their roles and assigned separately to inner array and outer array in parameter design.

3.10
outer array
experimental plan where users' conditions are assigned as noise factors and signal factors for evaluating SN ratio and sensitivity.

Note 1 Orthogonal arrays are recommended to assign control factors, i.e. inner array in parameter design, because many design parameters (control factors) can be taken into consideration in one set of experiment.

Note 2 Experimental factors should be categorized by their roles and assigned separately to inner array and outer array in parameter design.

4 Parameter Design for Robust Products — Overview

4.1 Parameter Design for Robust Products — Requirements

Parameter Design for Robust Products (PDRP) is a rational and efficient procedure for discovering technical means to improve robustness in designing process. It is therefore necessary to provide the following two procedures:

a) A procedure for the accurate assessment and quantification of robustness

b) A procedure for the efficient assessment of multiple technical means (ideas)

This clause provides the approach to achieving the goals of PDRP, and more detailed and specific steps of the PDRP procedure are described in clauses 5 and 6.

4.2 Assessing the robustness (SN ratio) of a system

How robustness should be accurately assessed by SN ratio (item a))? Robustness is associated with many factors, so it could not be assessed by a simple measurement. To clarify hidden properties associated with robustness, the problem should be approached from the following two viewpoints.

a) Use of Ideal Function: Ideal function is the target of the system. Actual function of the system should be measured and evaluated based on the definition of ideal function. It is important to avoid defects, failure mode or quality problems for the ideal function of the system.

b) Use of Noise Factors: Noise effects should be intentionally introduced by changing noise levels and the function of the system should be measured and evaluated under those predetermined noise conditions. Evaluation of robustness strongly depends on the choice of noise factors and their levels. Apply effective noise strategies.

The function of a system is the work that the system performs in order to fulfil its objective. For example, the function of an electric lamp is to transform electrical energy into light energy, and the function of a wind turbine is to use natural wind energy to rotating energy to perform a work such as pumping water. These functions are normally expressed in the functional form of an input/output relationship between the input energy and the output energy as the work obtained. Functional form can be expressed in a number of ways. Zero-point proportional equation is common in energy transformation of real physical systems. The details will be discussed in Clause 5.

The input and the output characteristics are fixed based on system's function. Input characteristic is called the "signal" in the input/output relationship, this is because the changes in the output are acquired by intentional varying the input signal in the real usage and in the PDRP experiment. The signal is energy or information necessary to do a work and the signal factor is a user's condition for changing signal when the user of the system tries to control the output. Output is also called as response. Because of its variableness, the input signal changes 3-4 levels and can usually measure the straightness of the ideal linear relationship for a dynamic characteristic. There is no signal factor for a static characteristic, because it has only one target output.

It is important to find out the suitable measurement method of output characteristic. In time dependent phenomena, for example, detection of output characteristic is difficult. New measurement method should be developed in some cases. The output characteristic is the purpose of the system. In the case of illumination, output is quantity of light, and in the case of a water pump, it is quantity of water. The measurement method which can measure the output quantity efficiently is desirable.

Noise conditions are the sources that inhibit the system's function (i.e., its input/output relation). Examples include environmental conditions such as the temperature or humidity range in which the system is actually used, the actual supplied voltage or electrical noise conditions, the frequency of operations and/or the stress, and the length of time for which the system is in operation or left idle after it has been purchased. These noise conditions always reduce the system's function to a lower level than the level at the time of purchase. Since the purpose of PDRP is to clarify the differences in robustness by measuring the extent of this reduction, the variation of system's function under noise conditions should be clarified in the evaluation in the PDRP. This is the reason why noise conditions should be taken into the PDRP as noise factors. For the effective noise strategy, various types of noise should be examined in actual usage and environment conditions and aging assessing.

Figure 1 shows an overview of the evaluation of robustness using function and noise factors. Here, multiple data should be obtained for the objective system under the various levels of noise factor and an SN ratio is calculated from the mean and the variance of these data. SN ratio as a robustness measure should be calculated using data X_1 to X_k. Formulations of SN ratio are shown in clause 5. When more than two systems are compared, the same levels of the same noise factor should be applied for all objective systems.

	Noise levels			
	N_1	N_2	…	N_k
Evaluated system	X_1	X_2	…	X_k

N_i…Noise level
X_i…Data

Figure 1 — Robustness assessment with noise conditions

When multiple different types of noise factors are applied in an experiment, the orthogonal array can be used for determining the noise levels. In Figure 2, noise levels, N_1 to N_k, is determined by the combination of levels of each noise factor indicated by orthogonal array.

	Orthogonal array for noise factors					
	1	**2**	**3**	**4**	**…**	**k**
A : Ambient temperature, humidity					…	
B : New product and degraded product					…	
C : Usage frequency					…	
	N_1	N_2	N_3	N_4	…	N_k
Evaluated system	X_1	X_2	X_3	X_4	…	X_k

A, *B*, *C*…Noise factor

Figure 2 — Robustness assessment with noise factors assigned to an orthogonal array

4.3 Utilization of robustness assessment

The ideal function of the system and the noise strategy are the key issues for the robustness assessment of PDRP. , It is essential to measure and evaluate the variability and efficiency of basic function of the system. The intent of doing this is that the evaluation of function covers wholly the technical issues of the system to prevent the technical problems. Robustness assessment also involves assessing the effects of noise factors that inhibit the required function. The assessment results are expressed by SN ratio.

SN ratio should discriminate the true difference in robustness between designs. Since the absolute value of SN ratio is affected by the setting levels of noise factors, only relative comparison of SN ratios is meaningful to perform. Thus, it is preferable to perform benchmarking in assessing robustness.

A feature of this approach is that the only information needed to obtain the SN ratio is just the knowledge of the ideal function of the system and the noise conditions that inhibit this function, and that no detailed technical information about the system is needed. This means that SN ratios should be calculated in the same way for various systems with different technical constituents as long as the systems have the same basic function. As the robustness of systems can be accurately assessed by SN ratios, then the robustness of various systems with different design concepts can be assessed and compared.

The comparison of various systems based on different technologies or different design concepts should be performed in the same way, such as a conventional system and a competing system that uses different design concepts. This is the idea to conduct benchmarking on various designs by using SN ratios.

4.4 An efficient method for assessing technical ideas –– parameter design

Basic technologies and mechanisms should first be selected to design a system of industrial products. When there are multiple system concepts to be benchmarked, the robustness assessment introduced in the previous section can be used to select the best design concept.

After selecting the design concept, the next step is to perform a detailed design by selecting the optimum nominal values of system design parameters so that the intended function is the most robust and efficient. . The system design parameter optimization method performed at this detailed design stage is called Parameter Design for Robust Products (PDRP), which is the method recommended by this document.

Consider what sort of states might be significant. When a system is in an optimum state, it achieves the best overall performance in all conceivable usage states. More specifically, an industrial product can stably perform its intended function anytime even when it is kept under a wide range of temperature and humidity conditions, and when it is used in many different ways and in different environments. The optimum design conditions are the combination of design parameters that are set to maximize the robustness of the product. Since optimization by parameter design implies optimizing for robustness, minimized variability and maximized efficiency, judgments should be made using robustness measure, SN ratio.

The basis of optimization to apply the robustness assessment in the previous section is a criterion for optimization. This means that robustness assessment should be performed with regard to all the possible designs in design space, but in practice this is impossible. This is because a vast number of tests would have to be performed to take all possible combinations of design parameters into consideration.

As a more practical method for use in development and design stage, an experimental method using an orthogonal array is recommended where the combinations of many design parameters can be tested under limited number of experimental runs. An orthogonal array is recommended not only because it can reduce the number of experimental runs comparing with full factorial plan with same number of control factors but also because it can assign maximum number of control factors in a set under the situation of same number of experimental runs. Reliability of experimental results should be confirmed in the confirmation experiment for reproducibility checks. Clause 6 describes a specific method for performing confirmation experiment to check reproducibility.

Procedure of PDRP should be as follows;

[Step 1] Clarify the system's ideal function.

[Step 2] Select signal factor and its range,

[Step 3] Select measurement method of output response.

[Step 4] Develop noise strategy, and select noise factors and their levels.

[Step 5] Select control factors and their levels from design parameters.

[Step 6] Assign experimental factors to inner or outer array.

[Step 7] Conduct experiment and collect data.

[Step 8] Calculate SN ratio η and sensitivity *S*.

[Step 9] Generate factorial effect diagrams on SN ratio and sensitivity.

[Step 10] Select the optimum condition.

[Step 11] Estimate the improvement by the gain.

[Step 12] Conduct confirmation experiment and check the gain and “reproducibility”.

4.5 Two-step optimization (Strategy for parameter design)

Figure 3 presents an overview of PDRP as described above. The experiment in this figure includes two orthogonal arrays, one orthogonal array for control factors (inner array) and the other orthogonal array for noise factors (outer array). This is called a direct product plan. The number of experimental data corresponds to the product of the numbers of tests respectively specified in the two orthogonal arrays. For example, for the combination of L_{18} and L_{12}, the number of tests comes to 18×12=216. Something like this is very doable in case of computer simulation.

Full factorial plan may be used for outer array for noise factors instead of orthogonal array in some cases. Or, in case of physical test, it should be recommended to compound noise factors into one 2 or 3 level factor. However, it is always recommended to use an orthogonal array for inner array for design parameters, because many design parameters can be assigned to one orthogonal array.

		Outer orthogonal array for noise factors							
		1	2	3	4	…	k		
A: temperature									
B: humidity									
C: …….									
		N_1	N_2	N_3	N_4	…	N_k	Mean value	SN ratio
Inner orthogonal array for design parameters	1								
	2								
	3								
	4								
	5								
	6								
	…								
	…								