ROBUST DESIGN METHOD FOR DIVERSITY OF BA
Case Study of Seat-Swing Function Design for Railway Vehicle

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Abstract: The function of artifacts depends on Ba. Ba is defined as elements of human, artifacts and surroundings and the relationships between each of these elements. The different relationship generates the differences in function of artifacts.

Generally, artifacts are used in diverse Ba. But many artifacts are designed under average Ba at present. Therefore, this diversity of Ba results in low evaluation of artifacts under particular human or surroundings.

In order to solve this problem, the objective of the present study is to construct a method for stable evaluation under diverse Ba. First, a method of robust design was proposed. Using objective function including average and variance, the proposed design method can adapt to diverse Ba and features modeling Ba and simulation using Ba model.

Secondly use of this method was confirmed by application for the railway vehicle swing-seat design. Swing-seat has a function, which prevents hip sliding by increasing cushion angle as seat back tilts. In the present study, the diversity of sitting postures and differences in physical constitutions were defined as noise factors. Optimizing design solution (relationships between back angle and cushion angle) for the object variables (hip-sliding force) was attempted. The simulation using Ba model, which was constructed as a dynamic model of human body and seat, was performed.

As a result, optimum relationships between back angle and cushion angle were obtained using the proposed method. It was proved that the proposed design method for diversity of Ba could be useful.

Key Word: Diversity of Ba, Robust design, Design method

1. INTRODUCTION

The function of artifacts depends on Ba. Ba is defined as the elements of human, artifacts, and surroundings, and the elements of each of these elements (Figure 1). Humans use artifacts directly as an instrument for achieving an objective. The surroundings are all of the elements in the system, which are neither human nor artifacts. Generally, Ba varies with respect to the relationships between human, artifacts, and surroundings, and the relationships between each of these elements. Traditionally, design methods have been applied under average Ba, i.e. average constitution, standard and normal surroundings. However, Ba tends to vary due to change in the market, in accordance with changing fashion. Diversity of Ba is more noticeable when humans are divided into groups. Therefore, the traditional design method is evaluated lower for particular human individual despite being an average evaluation method.

Therefore, the present study examined universal design in an attempt to provide a better design method. Conceptually, universal design is highly advocated, but the design method has not yet been established.

Teramachi et al. [1] proposed a man-machine system model that forecasts the behavior of a car in an intersection as a study of individual difference. The author et al. [2] proposed a method for estimating differences in personal preference and applied this method to designing a seat. Although several studies have been conducted on individual difference, a design method that account for the diversity of Ba has rarely been reported.

However, a design method for the diversity of Ba is expected because the design method for the diversity of Ba has not been established yet.
2. PROPOSAL OF DESIGN METHOD FOR DIVERSITY OF BA

2.1. Design method for differences in artifacts

robust design method

The robust design method is a design method that evaluates by taking both average and variance into consideration. This method has mainly been used to decrease differences in artifacts during the production process.

In general, products that have got the same function often cause trouble due to dispersion of the production process and the function. This problem results in an increase changing production process or the use of high-quality materials.

These types of improvements cause increases in cost and process time. Therefore, such a plan is not well-suited to solve the dispersion. Consequently, the plan was improved in advance. Thus, it is necessary to anticipate in the design process the conditions for production and use and to design stable function under these conditions. The SN ratio, which provides nonlinear measurement, was used in the robust design. The fluctuation of data is divided into signal constituent, S, and noise constituent, N, and the ratio of these constituents is the SN ratio. The SN ratio is a stable measure of the characteristic value of function. Furthermore, as the SN ratio becomes the larger, the function becomes the more stable. In short, robust design is a method that decreases the influence of the noise factors by allowing selection of a large SN ratio.

2.2. Outline of the method for the diversity of Ba

Robust design for differences in artifacts and SN ratio were mentioned in the previous section; however, the robust design method was applied not to the diversity of Ba but to the differences in artifacts. Therefore, in the present study, the author proposed a new design method for the diversity of Ba (Figure 2). The proposed design method is divided into two phases as follows:

- Modeling of Ba
- Simulation

The difference between the traditional robust design method and the proposed design method is the addition of the modeling of Ba. This section explains the outline of the proposed design method.

Figure 2: Proposed design method

2.2.1. Outline of the modeling of Ba

In artifact designs, the ideal condition that is the most influential function is determined. Next, the measuring characteristic that is a factor of the difference between the actual function and the ideal condition is assumed. Then, the factors, which are influenced, are modeled from human, artifacts and surroundings perspectives, respectively. Finally, Ba is modeled after determining the measuring method.

2.2.2. Outline of the simulation

First, the factors that influence the function are classified into control factors and noise factors, and each level of the factors is determined. Secondly, the simulation is performed and data are obtained after every experiment condition is determined. Thirdly, the SN ratio is calculated using the data. Lastly, the optimum condition is assumed according to the SN ratio.

3. APPLICATION OF THE PROPOSED METHOD FOR RAILWAY VEHICLE SEAT DESIGN

3.1. Problem for railway vehicle seat design

Recently, many railway vehicle seats have been designed for taking into account the comfort of the passenger. For example, seatbacks have been designed to fit the human back and headrests and footrests have been incorporated into seat designs. However, these seats were designed under the assumption of Ba for one physical constitution and sitting posture; therefore, the evaluation of the seat is not always valid. In particular, since railway vehicle seats are public artifacts, providing a comfort seat for the diversity of sitting postures and differences in physical constitutions.

In actual railway vehicle seat design, a seat design that prevents hip from sliding is desired. Hip-sliding means that the hip slips forward as the passenger sits. When the passenger sits down, a sliding force (the
hip-sliding force) on the pelvis occurs, causing the hip to move forward due to the weight imbalance of each body segment. In order to prevent this hip-sliding force that occurs to a problem, a swing-seat (Figure 3-1) function is used [3]. At present, this function is designed according to average values, and the relationship between the seatback and the seatcushion do not account for the diversity of Ba. Thus, this function should be improved.

3.2. Purpose and objective of the present study
After modeling the railway vehicle seat design the proposed design method based on the robust design method, the present study attempts to confirm the proposed method.

3.3. Application for the railway vehicle swing-seat function

3.3.1. Modeling of Ba
(1) Determination of the ideal condition
In order to design the railway vehicle swing-seat function for the diversity of Ba, it is necessary to clarify the relationships between human, artifacts and surroundings according to the index as the ideal condition (the object value of the function). In this case, the hip-sliding force, one of the comfort indexes, is examined. Therefore, the ideal condition is defined that the hip-sliding force is zero.

(2) Clarification of the measuring characteristic
(a) Measuring characteristic
In this study, the measuring characteristic is defined as the hip-sliding force.
(b) Determination and clarification of the factors that influence the ideal condition
The factors that influence the ideal condition are the diversity of sitting postures, the differences in physical constitutions, back angle (B.A.) and cushion angle (C.A.).

• Diversity of sitting postures
In a previous study [4] concerning the evaluation on the railway vehicle, three sitting postures were reported: the standard posture and the hip-sliding postures (Figure 3-2). The standard posture is a sitting posture in which the pelvis is maintained in contact with the seatback. The hip-sliding postures are sitting postures in which the hip is forward, the pelvis rotates, and the pelvis and waist are maintained away from the seatback. Moreover, the hip-sliding postures are classified into a sitting posture that maintains the hip and the waist stretched (the stretched waist sitting posture) and a sitting posture that maintains the hip and waist bent (the bent waist sitting posture).

• Differences in physical constitutions
The effect of differences in physical constitutions is dependent upon the length of each body segment and the body weight.

(3) Modeling of the factors
In the present study, the human and artifact models were constructed taking into account diversity of
sitting postures and differences in physical constitutions. In addition, a model describing the human-artifact relationship was constructed. In the case, surroundings (The height of the tip of the seatcushion) were fixed. Together these models comprised the Ba model. The method of concretely constructing these models is described below.

(a) Construction of the human model (the body model)(Figure 3-3)

In order to design for diversity of sitting postures and differences in physical constitutions, it is necessary to divide the body into diverse segments. This division was performed according to anatomic and sitting posture characteristics. The body model consisted of five body segments connected by four joints.

• Weight of each segment

Previous body measuring values [5], [6] were used to determine the weight of each segment in the present study. The respective weights of the thorax and waist segments were determined according to a model proposed by Satoh [7].

(b) Construction of the artifact model (the seat model)(Figure 3-4)

The artifact model used in the present study is the seat model for the railway vehicle. The artifact model was constructed to estimate the hip-sliding force, therefore, the seat model was defined as consisting of the seatback and the seatcushion in order to determine the sitting postures of the body model. The seat model consisted in two dimensions. The seatback and the seatcushion were joined to form a rigid link model that assumes no change in shape position or angle under the addition of force. The seatcushion rotated at the tip of the seatcushion. The height of the tip of the seatcushion was 0.4 m.

(c) Construction of the human-artifact model (the body-seat system model)(Figure 3-5)

It is possible to estimate the hip-sliding force and the diversity of the sitting postures. Therefore, the human-artifact model was represented using a two-dimensional model constructed on the sagittal plane.

In the human-artifact model, the frictional force was assumed to act at contact points between the passenger and the seat. The present study assumed that the frictional force affected the angles of both the seatback and the seatcushion. In this model, the coefficient of friction was defined as 0.3. The coefficients of friction for the seatback and the seatcushion were assumed to be equal.

(4) Determination of the method used to measure the measuring characteristic

Using the body-seat model, it is possible to determine all other body angles. Thus, the equations of hip-sliding force for each sitting posture were calculated. The ankle angle ($\theta_{An}$) and hip angle ($\theta_{Hi}$) were determined geometrically from the body measurements.

3.3.2. Simulation

The factors that influence the ideal condition are diversity of sitting postures, differences in physical constitutions, B.A. and C.A. These factors were classified according to the level after being classified as either a control factor or a noise factor.

(1) Determination of the control factors, the noise factors and the levels.

(a) Determination of the control factors and levels

• Determination of the control factors

In order to prevent the hip-sliding force, the improvement of the swing-seat function was investigated. The B.A. and C.A. were the control factors since these were the design variables of the swing-seat function. It is necessary to optimize C.A. for every B.A. because the B.A. moves together with the C.A. of the swing-seat function. Thus, in the present study the C.A. was simulated for every B.A. by referring to the robust design.

• Determination of the control factor levels

Fifty-one control factor levels were defined for the actual design $0^\circ$ to $50^\circ$ in one degree increments.

(b) Determination of the noise factors and the levels

• Determination of the noise factors

It is necessary to optimize relationships between B.A. and C.A. in the diversity of Ba. Therefore, in simulation the noise factors were defined as diversity of sitting postures and differences in physical constitutions, because sitting postures and physical constitutions were presumed to be the noise factors for the ideal condition (zero hip-sliding force).

• Determination of sitting posture levels

As mentioned above, sitting postures consisted of the standard posture and the hip-sliding postures. The hip-sliding postures consist of the stretched waist
sitting posture and the bent waist sitting posture. The noise factor levels were the two levels that consist of the standard posture and the stretched waist sitting posture. Next, the noise factor levels were the three levels that consisted of the standard posture, the stretched waist sitting posture and the bent waist sitting posture.

**Determination of the physical constitution levels**

In order to analyze differences in physical constitutions, the physical constitution levels were defined as shown in Table 1. These levels were defined such that Level 2 represents the average body dimensions and body weight, and Level 1 is $-\sqrt{3}/2\sigma$ of Level 2 and Level 3 is $+\sqrt{3}/2\sigma$ of Level 2.

**Experiment conditions**

In order to compare the traditional design method with the proposed method, simulation was performed using average values (Simulation 1). Simulation that takes into account diversity of sitting postures and differences in physical constitutions as the noise factors (Simulation 2) was performed. Simulation 2-1 was performed under two sitting posture levels: the standard posture and the stretched waist sitting posture. Simulation 2-2 was performed under three sitting posture levels: the standard posture, the stretched waist sitting posture and the bent waist sitting posture.

(a) Simulation using average values (Simulation 1)

Simulation 1 was performed under the standard sitting posture for the average physical constitution. Under this condition, a line graph was produced showing several optimums C.A. for the smallest hip-sliding force for each B.A. This graph was called the prevention hip-sliding curve.

(b) Simulations taking into account sitting postures and physical constitutions (Simulation 2)

In Simulation 2, sitting postures and physical constitutions were taken into account. Thus, the optimum relationships between B.A. and C.A. were obtained for each condition. Each optimum solution was determined as the largest SN ratio produced under each condition.

**Simulation 2-1**

The control factor was C.A. and the noise factors were the sitting postures and the physical constitutions. The sitting posture levels were the standard sitting posture levels and the stretched waist sitting posture levels. Three physical condition levels were examined.
Table 1: Physical constitution levels

<table>
<thead>
<tr>
<th></th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thorax length [mm]</td>
<td>200.6</td>
<td>201.3</td>
<td>220.0</td>
</tr>
<tr>
<td>Lumbar length [mm]</td>
<td>202.2</td>
<td>212.0</td>
<td>221.8</td>
</tr>
<tr>
<td>Pelvis length [mm]</td>
<td>151.1</td>
<td>184.3</td>
<td>219.0</td>
</tr>
<tr>
<td>Lower length [mm]</td>
<td>404.3</td>
<td>434.1</td>
<td>463.9</td>
</tr>
<tr>
<td>Body weight [kg]</td>
<td>48.97</td>
<td>58.10</td>
<td>69.23</td>
</tr>
</tbody>
</table>

Simulation 2-2

Three sitting posture levels were examined, which consist of the standard posture, the stretched waist sitting posture and the bent waist sitting posture. The others conditions were the same as those for Simulation 2-1.

(3) Calculation of the SN ratio

The SN ratio was calculated as the difference in the object of the measuring characteristic. In this simulation, a hip-sliding force near zero is desired. Because of the existence of both plus and minus forces, the SN ratio in this case was calculated as nominal-the-better characteristic. The SN ratio ($\eta$) was calculated as shown in the following equation (3).

\[
\eta = -10 \log V_f
\]

\[
\eta = -10 \log \frac{\sum Y_i^2}{n}
\]

\[
V_f = \sum Y_i^2
\]

\[
\eta = -10 \log V_f
\]

The sum of variance represents the size of the error data of the ideal condition. The average $Y^2$ was $m$, the variance was $\sigma^2$, thus expected value of the $Y^2$ ($E(Y^2)$) was

\[
E(Y^2) = m^2 + \sigma^2
\]

Therefore, the SN ratio evaluated both the average $m$ and the fluctuation of the error $\sigma$.

(4) Assumption of optimal conditions

In the present study, the optimum solution was defined as the maximum SN ratio.

3.4. Simulation results

3.4.1. Diversity of sitting postures

Figure 3-6 shows that the C.A. was smallest for the bent waist sitting posture and was larger for the stretched waist sitting posture and larger still for the standard sitting posture. As the sitting postures changed the hip-sliding force also changed. The elements were the hip position, thorax angle ($\theta_T$), and the mass ratio, which was composed of the lumber segment and the pelvis segment. As these elements changed the hip-sliding force was changed.

Due to the change in also the mass ratio of the hip-sliding postures, the load on the cushion increased and the hip-sliding forces also increased. Since the $\theta_T$ of the bent waist sitting posture was larger than that of the stretched waist sitting posture, the hip-sliding force of the bent waist sitting posture was smaller than that of the stretched waist sitting posture.

The physical constitutions, B.A. and C.A. were fixed and the hip position was changed (Figure 3-7). Figure 3-7 shows a linear relationship between $\theta_A$ and the hip-sliding force. This figure also shows a nonlinear relationship between hip position and the hip-sliding force. Thus, if a nonlinear relationship exists, the design solution will not be optimum if designed for the average passenger.

3.4.2. Comparison between the design by average method and the design by SN ratio method

For a linear function between a factor and the measuring characteristic, the distribution of the factor was mapped using the function (Figure 3-8). Figure 3-8 shows the same distribution before mapping and after mapping. Therefore, the optimum solution obtained using the SN ratio is equal to the average since the distribution of the measuring characteristic becomes symmetric. For a nonlinear function between a factor and the measuring characteristic, the distribution of the factor was mapped using the function. Figure 3-8 shows the distribution obtained after mapping is diverges from linear compared to that obtained before mapping. Therefore, the optimum
solution obtained using the SN ratio is not equal to that obtained using the average because the distribution of the measuring characteristic does not become symmetric. As the dispersion becomes larger, the SN ratio becomes smaller because the SN ratio is equivalent to Equation (3). Thus, the optimum value obtained as the maximum SN ratio takes the dispersion into account.

4. CONCLUSION

In the present study, a design method that takes into account diversity of Ba was proposed. The proposed method was applied to the railway vehicle swing-seat design. In addition, the optimum relationships between B.A. and C.A. were proposed. The proposed design method for diversity of Ba was found to yield different results than the traditional design method. The proposed design method enabled the design of a railway vehicle swing-seat took into account both diversity of sitting postures and differences in physical constitutions by quantitative analysis.

The proposed design method is as follows: Figure 4.

First, the ideal condition is determined. Secondly, the relationships between elements and those between each element and human, artifacts and surroundings are clarified. Models are then constructed. The human model is constructed from an ergonomics point of view. When the artifact model is constructed, the function and specifications and the structure of the Ba under constraints are clarified. When the surrounding model is constructed, the surroundings are classified into groups according to how each artifact is used, and each group is constructed.

Thirdly, the dynamics method is used to determine the equation. The elements are classified as either control factors or noise factors. Finally, the experimental conditions are determined and simulation is performed. In order to evaluate the average and the dispersion, the optimum design solution is assumed using the SN ratio.

The present study proposed a new design method...
based on the robust design method in order to construct a design method that accounts for diversity of Ba. The proposed method could be useful if the relationships between the factors and the measuring characteristic are nonlinear.

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