# Dehydration Dynamics Model with Monte Carlo Method for a Front-loading Washer/dryer

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In this study, we aimed to improve the efficiency of an anti-vibration design for front-loading washer/dryers and propose a dehydration dynamics model that combines a mechanical model with a random algorithm. In addition to the anti-vibration structure, front-loading washer-dryers are equipped with dehydration start control where dehydration is repeated until the level of vibration detected during dehydration falls below the threshold. The proposed model focuses on the probability distribution of clothing behavior during dehydration and models the clothing behavior by using a random number that follows the probability distribution. Then, we present the reusability of the probability distribution and the difference from a mechanical model that does not consider clothing. In this way, in the upstream design without the actual machine, the anti-vibration structure and dehydration start control could be simultaneously designed, improving the efficiency of the anti-vibration design.

Keywords: Vibration Control, Simulation-based design, Washing machine, Uncertainty Modeling

## 1 INTRODUCTION

The front-loading washer/dryer has an outer tub for water supported by an anti-vibration structure that consists of springs and dampers. Inside of the outer tub is a rotating drum. During dehydration, as the drum rotates, the clothing experiences a centrifugal force and is pressed against the inner wall of the drum. As the drum rotates at a fast speed, dehydration takes occurs. At this time, if the distribution of clothing is unbalanced inside the drum, unbalanced centrifugal force causes an exciting force, and the drum and the surrounding outer tub vibrate together. Because of this, front-loading washer/dryers are equipped with dehydration start control to reduce vibration during dehydration.

The dehydration start control works as follows. When the detected imbalance and the vibration level of the outer tub are determined to have exceeded the threshold, the drum rotation is reduced or stopped for a moment to restart the dehydration process (retry) to correct the imbalance. Because this retry is repeated until the detected vibration level reaches below the threshold, ultimately, the imbalance is reduced, and vibration and noise are reduced. However, if the retry is repeated too many times, the dehydration time becomes longer because restarting needs time of modifying the imbalance and entanglement of clothes. Thus, to reduce the vibrations of a front-loading washer/dryer, not only an anti-vibration structure but also an optimal design that includes the dehydration start control is desirable.

In terms of vibration problems of washers, many studies proposed vibration analysis methods and optimization methods for an anti-vibration structure. In studies of vibration analysis methods, a 2D dynamic model of the anti-vibration structure [1], component-mode synthesis methods that feature rubber feet [2], and a rigid–flexible coupling simulation method that features sheet metal [3] have been presented. The anti-vibration suspension model is also applied for mobilities [4][5]. In studies on optimization methods, in addition to anti-vibration systems, such as a quad horizontal damper system in top loading washing machines [6] and vibration control by semi-active dampers [7][8], design methods, such as a genetic algorithm [9] and response surface method [10], have been proposed. Other studies included a sensor that identified the fabric [11], durability of products [12], and data consistency assessment of drum and panel structures [13][14]. However, these studies did not consider the behavior of clothing; thus, evaluation of the dehydration start control was performed toward the end of the design when the actual machine was completed. At this stage, even if the number of retries exceeds the standard, there is little freedom in changing the anti-vibration structure, making improvements difficult.

Meanwhile, in studies that consider clothing behavior [15][16], clothing in water was modeled by thin elastic plates, and a fluid analysis was performed. Because these studies targeted the amount of clothing that could move within the water in a vertical-axis washing machine, these are not applicable for conditions in which clothing cannot move in the water, such as when the ratio of clothing relative to the drum capacity is high or with front-loading washer/dryers where clothing tends to collect at the bottom of the drum due to gravity. As a modeling method of uncertainty in the field of rotor dynamics, a method that provided a probability distribution [17][18] has been proposed. The authors [19] focused on the probability distribution of clothing behavior and showed that the dehydration start control could be modeled regardless of the amount of clothing by using a random algorithm. However, this method did not provide a concrete method to generalize clothing behavior and mechanically model the anti-vibration structure. Therefore, a specific method to simultaneously design the anti-vibration structure and the dehydration start control in the upstream design process without an actual machine is still required.

In this study, we aimed to improve the efficiency of the anti-vibration design for front-loading washer/dryers, and we propose a dehydration dynamics model that combines a mechanical model with a random algorithm. The proposed model is able to assess the impact of the design parameters of the anti-vibration structure on the number of retries by using a mechanical model and the probability distribution for the vibration level obtained in a preliminary experiment. In this report, we show that the probability distribution obtained in the experiment can be defined as a $\beta$ distribution by using two types of front-loading washer/dryers with different diameters $D$ and depths $L$ for the drum as example calculations. Next, the number of retries obtained in the proposed model is shown to have a higher sensitivity to the damping coefficient of the anti-vibration structure than the vibration level obtained with the mechanical model that does not consider clothing. Improved points of the present model over our past research [16] are the first is that parameters of anti-vibration are integrated to model and the second is that a probability distribution is defined as a beta distribution. Based on these results, we discuss the utility of the present method in the upstream design process without using an actual machine.

## 2 Front-loading washer/dryer

### *2.1 Anti-vibration support structure*

A front-loading washer/dryer has an outer tub for water elastically supported within a cabinet by springs above and suspensions with a rubber bush on both sides (FIGURE 1). Inside this outer tub is a drum that holds clothing. The drum is rotary driven by a motor located on the back of the outer tub. Inside the drum, there is a lifter to stir the clothing. The opening of the outer tub is connected to a cabinet with rubber bellows and is sealed against water. The outer tub is equipped with a vibration detection mechanism to detect the amount of imbalance and vibrations of the outer tub. In this study, we examined two machines with a similar drum capacity but different drum diameters, $D$, and depths, $L$, which were differentiated by a drum aspect ratio of $\alpha = D/L$.

### *2.2 Dehydration start control*

The dehydration start control can be divided into three motions: (A) the clothing is pressed against the drum by the centrifugal force, (B) passes through resonance, and (C) dehydration (FIGURE 2). In (A) where clothing is pressed against the drum, first, the drum is rotated to untangle the clothing. This is followed by the drum rotating in one direction while the lifter stirs the clothing, and a centrifugal force presses clothing against the inner wall of the drum. During this time, an imbalance occurs if the mass distribution of clothing pressed against the inner wall of the drum is uneven. If the vibration level detected by the vibration detection device is lower than the predetermined threshold, it moves to (B), the resonance passing stage. However, if the vibration level is above the threshold, the drum rotation is slowed or stopped for a moment, and dehydration is restarted (retry) to correct the imbalance. Similarly, during (B), the resonance passing stage, the detected vibration level and the threshold are constantly compared, and the rotation is increased toward the target rotation. Once the target rotation is reached, dehydration is performed for a given amount of time at a constant rotation in the (C) dehydration stage. This is followed by the drum being slowed or stopped to finish the dehydration.

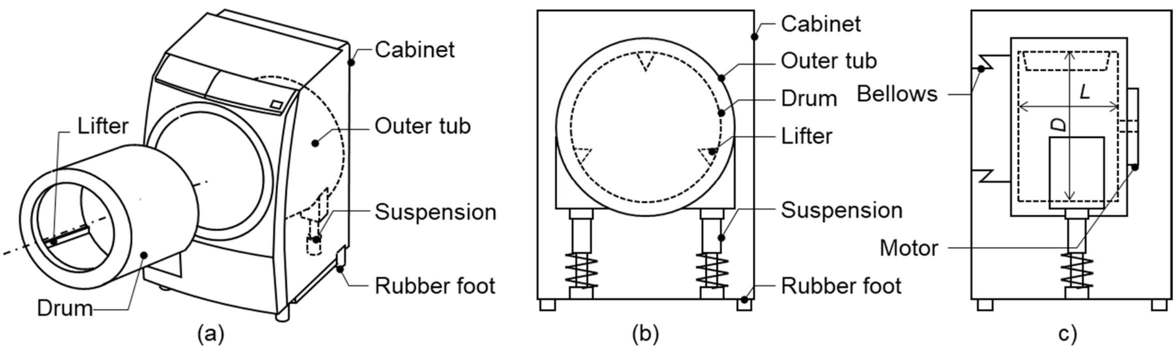


FIGURE 1: Anti-vibration structure of a front-loading washer/dryer. (a) shows disassembled perspective view. (b) shows front view. (c) shows side view.

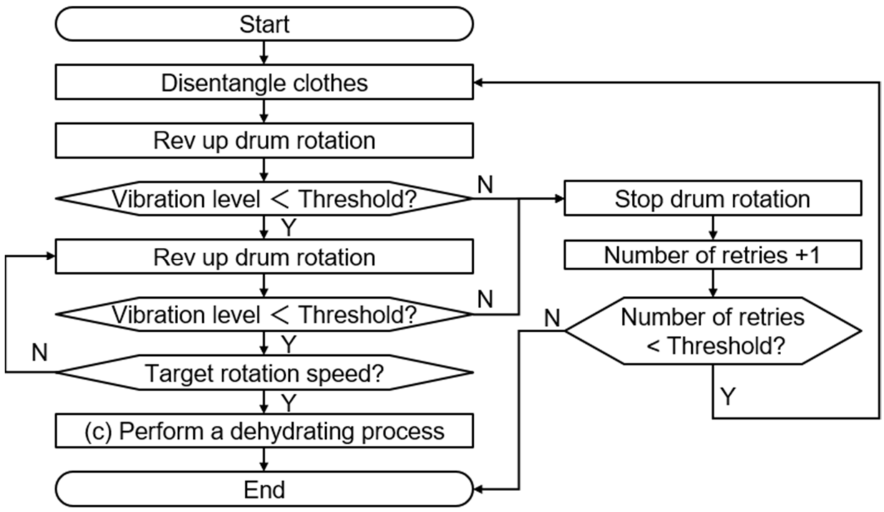


FIGURE 2: Example of the dehydration start control in a front-loading washer/dryer. A is when clothing is pressed against the drum, B is when it passes through the resonance, and C is dehydration.

## 3 Dehydration dynamics model

The present model consists of three parts—the imbalance model, mechanical model, and control model—to design the anti-vibration structure and dehydration start control simultaneously (FIGURE 3(a)). With the imbalance model, the imbalance level, $m \sim F''$ was randomly generated according to the probability distribution of clothing behavior, $F''$ (FIGURE 3(b)). This was followed by the mechanical model equivalent to the imbalance response function converting the imbalance level, $m$, to the vibration level, $x$, of the outer tub and the cabinet to obtain probability distribution, $F'$. With the control model, the area above the threshold of the probability distribution, $F'$, was removed to obtain the probability distribution, $F$. Details of each model are described below.

### *3.1 Imbalance model*

Because the clothing behavior is difficult to formulate, first, feature values correlated with the imbalance in clothing distribution was measured as the imbalance level, $m$, and the probability distribution, $G''$, was obtained from its frequency distribution using a Gaussian kernel density estimation. Measurement of the imbalance level, $m$, was performed in the following three steps using a clothing set that combined various types of clothing. In Step 1, we randomly placed one item of clothing at a time, which was grouped by arbitrary types to reach a predetermined mass. In Step 2, we used the dedicated control software that disabled the threshold and repeated stage (A) of FIGURE 2 (pressing clothing) 15 times after the washing process. In Step 3, we stopped the operation and removed the clothing from the drum. Vibration data obtained from this included 15 per operation. By repeating Steps 1 to 3 five times, we obtained a total of 75 data points. With these 75 data points, we prepared the probability distribution, $G''$, via the Gaussian kernel density estimation.

Here, when we assumed that the data from $n$ numbers of samples $z_1, z_2, \ldots, z_i, \ldots, z_n$ follow an independent and the same Gaussian distribution, the kernel density function of the Gaussian distribution for each data, $K(z)$, was expressed as:

$$K(z) = \frac{1}{\sqrt{2\pi}} e^{\frac{-z^2}{2}} \tag{1}$$

If the kernel density function, $K(z)$, of Equation (1) was stacked, the kernel density estimate of variable $x$, $f_K(x)$, became:

$$f_K(x) = \frac{1}{nh} \sum_{i=1}^{n} K\left(\frac{x - z_i}{h}\right) \tag{2}$$

where $h$ is the bandwidth (width of stacked distribution), and the standard deviation σ of

Equation (3) was used:

$$h = \frac{1.06\sigma}{n^{\frac{1}{5}}} \tag{3}$$

Next, the acceptance–rejection method was used to randomly generate the imbalance level, $m$, that follows probability distribution $G''$ obtained from the experiment. First, random number $u$ that follows a uniform distribution was generated, and then, random number $y$ that follows a uniform distribution was generated. At this time, if the random number, $y$, was below the Gaussian kernel density estimation, $f_K(u)$, it was accepted as $m = u$, whereas other values were rejected, and random number $x$ was generated again. By repeating this process, a set of imbalance levels, $m$, that follows the probability distribution of $F''$ was obtained.

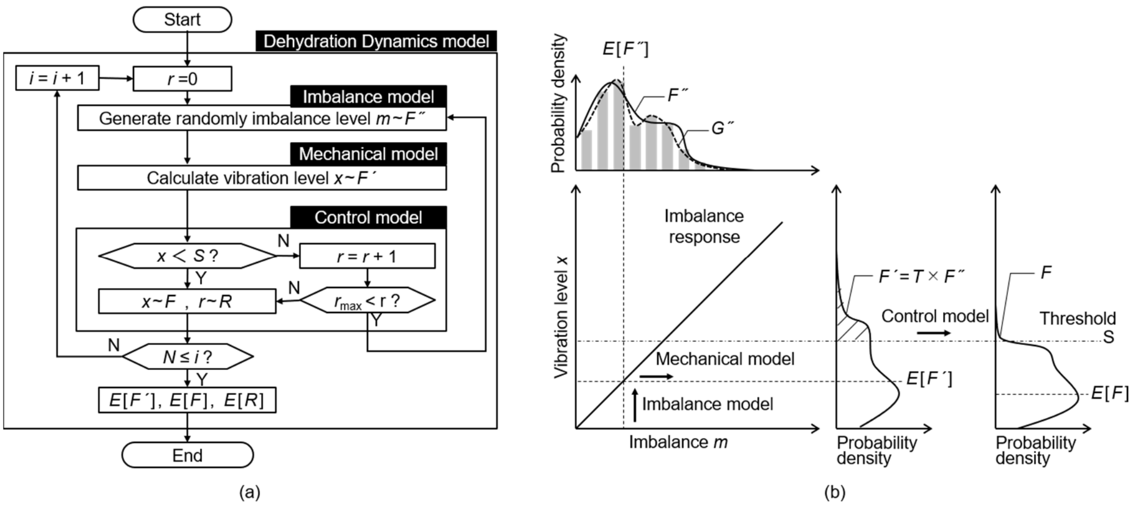


FIGURE 3. Dehydration dynamics model. (a) shows algorithm model. (b) shows relationship between probability distributions and imbalance response.

### *3.2 Mechanical model*

To examine the relationship between the design parameters of the anti-vibration structure and the number of retries, the mechanical model was defined by the two degrees-of-freedom spring mass damper model, where motion was restricted to one direction (FIGURE 4(a)). If the outer tub/drum and cabinet were masses = $m_1$ and $m_2$ and displacements = $x_1$ and $x_2$, the composite spring constant of suspension = $k_1$, the composite damping coefficient = $c_1$, the composite spring constant of the feet = $k_2$, the composite damping = $c_2$, the imbalance = $m$, and the drum rotation speed = $\omega$. Then, the state expression of the equation of motion is written as Equation (4):

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}\begin{bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{bmatrix} + \begin{bmatrix} c_1 & -c_1 \\ -c_1 & c_1 + c_2 \end{bmatrix}\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} + \begin{bmatrix} k_1 & -k_1 \\ -k_1 & k_1 + k_2 \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} mr\omega^2 \sin \omega t \\ 0 \end{bmatrix} \quad (4)$$

Parameters of masses, damping, and stiffnesses are determined based on the behavior of the actual machine. If the vibration displacement of the outer tub, $A_1(m, \omega)$, is expressed using imbalance $m$ and drum rotation speed $\omega$, the vibration displacement of the outer tub $x_1$ normalized by the maximum value $x_1$ for imbalance $M$, which is the reference, is expressed as:

$$x_1 = \frac{A_1(m,\omega)}{max\{A_1(m=M,\omega)\}}. \quad (5)$$

The amplitude of transfer force on floor $f_t$ is expressed as Equation (6):

$$f_t = k_2 x_2 + c_2 \dot{x}_2 \quad (6)$$

It is normalized by reference imbalance $M$ and drum rotation speed $\Omega$ using amplitude $A_2$ of vibration displacement $x_2$ of the cabinet is expressed with an amplitude via Equation (7):

$$f_t = \frac{A_2(m,\omega)\sqrt{k_2 + c_2\omega^2}}{A_2(m = M, \omega = \Omega)\sqrt{k_2 + c_2\Omega^2}}. \quad (7)$$

The vibration level, $x$, used as the output was the maximum value of the outer tub displacement, $x_1$, $x_{1\max}$ (FIGURE 4(b)). Due to high damping of the second mode for the outer tub displacement ($m = m_1 = m_2 = 1.0$, $c_1 = 10$, $c_2 = 2.5$, $k_1 = 500$, $k_2 = 2000$), the first peak $x_{1\max}$ only appears in Fig. 4 (b). Japanese houses often have wooden floors that easily vibrate; therefore, the floor transfer force with drum rotation speed, $\Omega$, over a long period of time, $f_{t900}$, is also output as an observation value.

To focus on the vertical vibration of drums, the simple 2D model is employed in this study. However, when 3D motion like a whirling-swing coupling vibration, it is necessary to use the 3D dynamic model.

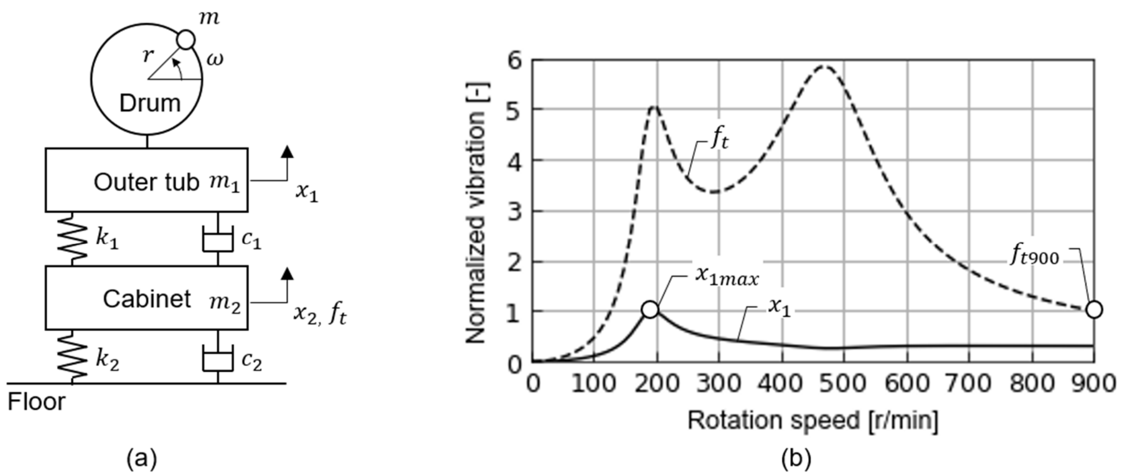


FIGURE 4: Mechanical model. (a) shows two-degree-of-freedom mass–spring–damper model. (b) shows vibration responses ($m = m_1 = m_2 = 1.0$, $c_1 = 10$, $c_2 = 2.5$, $k_1 = 500$, $k_2 = 2000$).

### 3 .3 Control model

With the control model, vibration level $x$ was below the threshold, $S$. Alternatively, a number of retries, $r$, was added, and the process was restarted using the imbalance model until the number of retries exceeded its upper limit, $r_{max}$. By repeating this process $N$ times, vibration level $x$~$F'$ before the retry and vibration level $x$~$F$ after the retry as each set of $N$ were obtained along with the number of retries, $r$~$R$. The representative value of the probability distribution for these inputs and outputs is the average (expected value): $E[F']$, $E[F'']$, $E[R]$. In the present model, $N = 10{,}000$ and $r_{max} = 20$ are given.

### 3.4 Validity

Validity was assessed using the difference between the experimental value and calculated value for the probability distribution of vibration levels before and after the retry. The experimental value before the retry was probability distribution $G''$ from Section "Imbalance model". The experimental value after the retry was obtained by randomly adding one item of clothing each for each operation and running the washer five times with three dehydration runs each. Clothing had five levels of arbitrary combinations at 1, 3, 5, 7, and 11 kg, and the experiment was conducted with the machines with drum aspect ratios, $\alpha$, of 2.0 and 1.3.

To obtain the difference in the probability distribution, KL divergence [20] was used. If probability distributions $P$ and $Q$ consisting of $n$ discrete values were applied, the KL divergence, $D_{KL}(P||Q)$, was expressed using Equation (8) :

$$D_{KL}(P \parallel Q) = \sum_i P(i) \log_2 \frac{P(i)}{Q(i)} \qquad (i = 1,2,\dots,n). \tag{8}$$

KL divergence takes a value between 0 and 1, and a value closer to 0 means less divergence. Probability distributions $P(i)$ and $Q(i)$ were normalized by dividing with the area.

The result showed that the KL divergence, $D_{KL}(G''||F'')$, from the probability distribution obtained with the acceptance–rejection method, $F''$, to the probability distribution obtained with experiment $G''$, and was almost under any condition (Table 1). The KL divergence, $D_{KL}(G||F)$, from probability distribution obtained in the calculation, $F$, to probability distribution $G$ after the retry obtained with the dehydration start control in the experiment was higher than $D_{KL}(G''||F'')$ but smaller than $D_{KL}(G''||G)$ or $D_{KL}(F''||F)$, which were equivalent to changes in the probability distribution because of the dehydration start control or their ratio. Additionally, the trends in $D_{KL}(G''||G)$ and $D_{KL}(F''||F)$ were consistent. Therefore, we confirmed the validity of the proposed model because the difference between the experimental and calculated probability distributions was small for the probability distribution and its changes before and after the retry.

Table 1. KL divergence. $G''$ is the probability distribution of the imbalance level obtained in the experiment. $F''$ is the probability distribution of the imbalance level obtained with the acceptance–rejection method. $G$ is the probability distribution of the vibration level obtained with the washer operation. $F$ is the probability distribution of the vibration level obtained via the calculation.

| Drum aspect ratio $\alpha$ | | | 2.0 | | | | | 1.3 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Mass of clothes | 1 kg | 3 kg | 5 kg | 7 kg | 11 kg | 1 kg | 3 kg | 5 kg | 7 kg | 11 kg |
| $D_{KL}(G''\|\|F'')$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $D_{KL}(G\|\|F)$ | 0.28 | 0.28 | 0.09 | 0.35 | 0.13 | 0.13 | 0.12 | 0.07 | 0.18 | 0.07 |
| $D_{KL}(G''\|\|G)$ | 2.93 | 5.12 | 3.10 | 6.31 | 0.81 | 3.25 | 5.38 | 4.11 | 4.39 | 2.24 |
| $D_{KL}(F''\|\|F)$ | 2.62 | 5.65 | 3.63 | 5.95 | 0.67 | 4.39 | 5.64 | 4.55 | 4.95 | 2.32 |

## 5 Results and discussions

### *5.1 Calculation results*

First, to show the reusability of probability distribution $G''$ from clothing behavior, we compared probability distribution $G''$ with the parametric $\beta$ distribution. Here, $\beta$ distribution $f(x)$ is given by:

$$f(x) = \frac{x^{a-1}(1-x)^{b-1}}{\Gamma(a)\Gamma(b)}. \quad (9)$$

Parameters $a$ and $b$ were positive real numbers, and $\Gamma(a)$ and $\Gamma(b)$ were gamma functions. In the range of $0 \leq x \leq 4$, parameters $a$ and $b$, with which KL divergence from probability distribution $G''$ to the $\beta$ distribution become the minimum, were applied. As a result, probability distribution $G$ and the $\beta$ distribution were consistent under all conditions (FIGURE 5). This showed that regardless of the amount of clothing or drum aspect, $\alpha$, probability distribution $G''$ can be recreated with the $\beta$ distribution in the range of parameters $a$ = 1.7–2.4 and $b$ = 4.0–13.2.

Next, we determined the influence of the design parameters of the anti-vibration structure on the number of retries. Here, as design parameters, the ratios for the standard damping coefficient of suspension, 0.5, 0.75, 1.00, 1.50, and 2.00, were applied. As a result, compared to the mechanical model shown in Equation (5), the sensitivity had a higher response (FIGURE 6). The proposed model determines the impact of damping coefficient, $c_1$, based on the relationship between probability distribution $F'$ and threshold $S$. In contrast, the mechanical model does not consider clothing behavior and has a constant impact. These are the likely reasons for the higher response. However, the floor transfer force did not show as much difference as the number of retries between the proposed model and the mechanical model. Because outer tub displacement $x_{1max}$ correlated to the floor transfer force is capped by threshold $S$, compared to the number of retries that has a room up to the $r_{max}$, the changes in the probability distribution were smaller. The floor transfer force had a trade-off relationship with damping coefficient $c_1$.

***5.2 Discussion***

The ability to reproduce probability distribution $G''$ with a $\beta$ distribution indicates that the design parameters of the anti-vibration structure and response of the number of retries can be examined by using multiple $\beta$ distributions in the case where probability distribution $G''$ cannot be obtained for clothing behavior in the upstream design process without an actual machine. Therefore, probability distribution $G''$ is impacted by the rotation pattern of the drum and the shape of the drum lifter, and it is desirable to obtain it by using an actual machine. However, understanding the rough trend in the upstream design is more useful for the anti-vibration design than moving onto the downstream stage without estimating the number of retries.

The results showed that the response of the number of retries to damping coefficient $c_1$ had a higher sensitivity than the outer tub displacement $x_{1max}$ of the mechanical model. This indicates that small changes in the anti-vibration design have a major impact on the dehydration start control. Consequently, the optimal solution obtained with the mechanical model alone may be a localized solution when including the solution range of the actual usage, including the dehydration start control. Additionally, because there is limited freedom to change the anti-vibration structure in the design downstream, in the worst case, development has to be restarted. For example, even if reduction of the floor transfer force was prioritized and a solution that minimizes damping coefficient $c_1$ from the Pareto Curve was obtained, the number of retries could drastically increase in the design downstream and may not meet the standard.

The proposed model is highly useful for allowing the simultaneous design of an anti-vibration structure with dehydration start control in the upstream design.

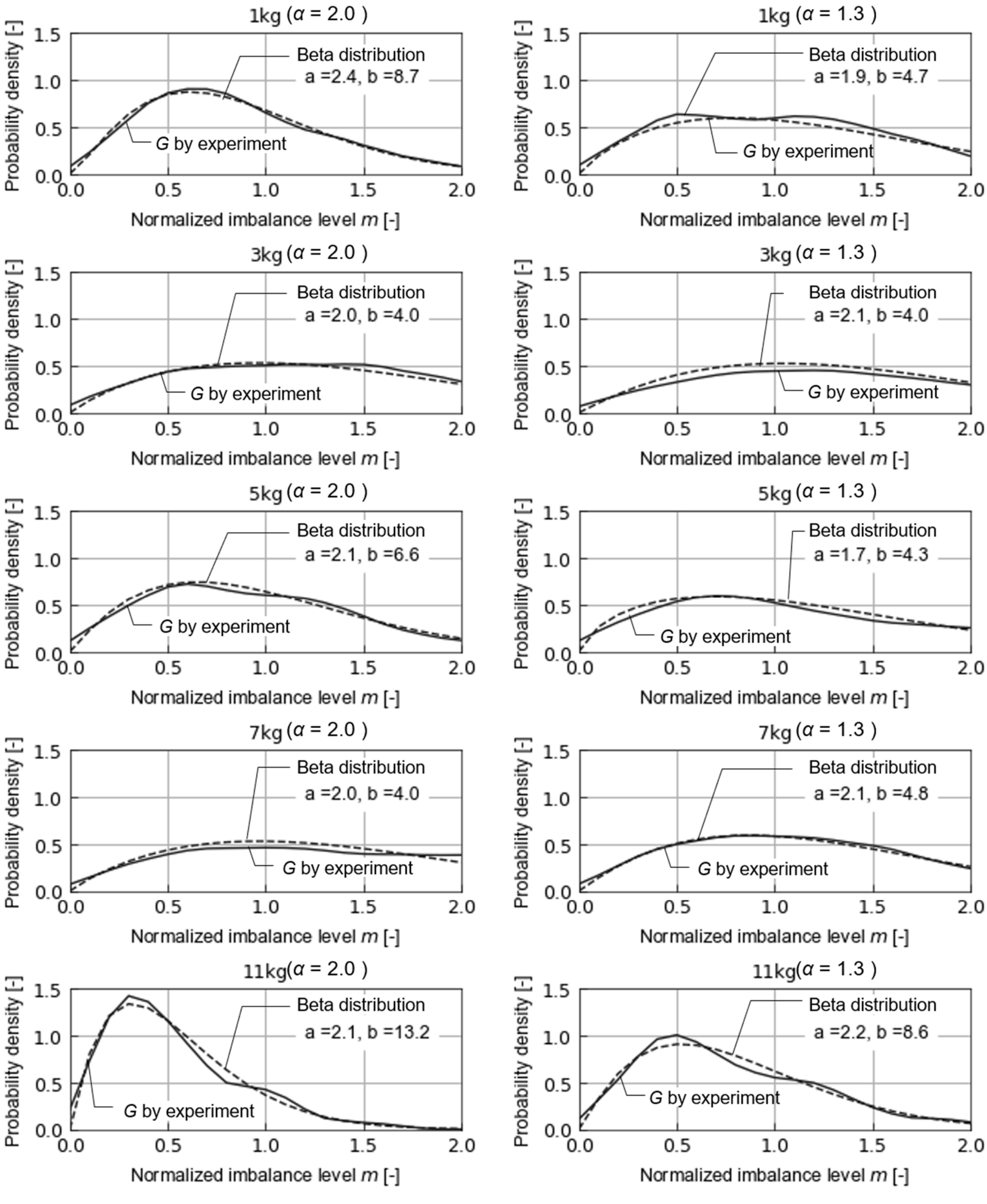


FIGURE 5. Comparison of probability distribution $G''$ obtained from the experiment and $\beta$ distribution. Imbalance level $m$ was normalized by dividing with threshold of each condition. For the $\beta$ distribution ($0 \leq x \leq 4$), parameters $a$ and $b$ were used.

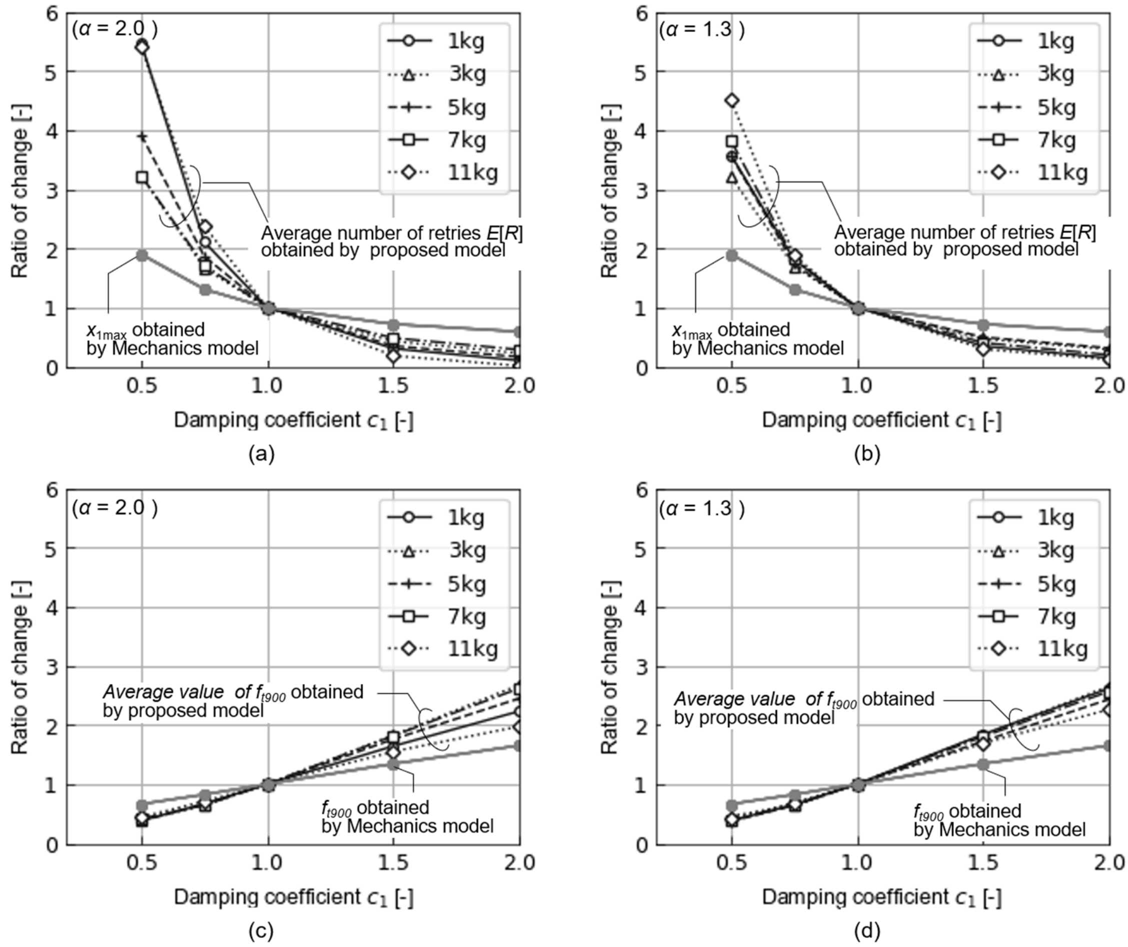


FIGURE 6. Comparison of the proposed model and the mechanical model. The standard was the damping coefficient $c_1 = 1.0$. (a) and (b) show the average retry number, $E[R]$, obtained in the proposed model and the outer tub displacement, $x_{1max}$, obtained with the mechanical model. (c) and (d) show the average floor transfer force, $f_{t900}$, obtained with the proposed model and $f_{t900}$ obtained with the mechanical model.

## 6 Conclusions

To improve the efficiency of the anti-vibration design of front-loading washer/dryers, we propose a dehydration dynamics model that combines a mechanical model with a random algorithm. The proposed model focuses on the fact that clothing behavior during dehydration has a certain probability distribution and randomly generates the amount of imbalance that follows this probability distribution. This was followed by inputting the amount of imbalance into the mechanical model and obtaining the vibration displacement of the outer tub and probability distribution of the floor transfer force. If it was higher than the threshold for the vibration displacement, it was retried from the generation of the imbalance, and the number of retries was added. To verify the utility of the proposed model, the calculation was performed with two machines with drum aspect ratios of $\alpha$ = 2.0 and 1.3 (drum diameter divided by the depth) with clothing weights of 1, 3, 5, 7, and 11 kg. The following conclusions were reached:

(1) The KL divergence equivalent to the difference of the experimental and calculated probability distribution was almost 0 at the imbalance level before the retry and 0.07–0.35 at the vibration level after the retry. This shows the validity of the probability distribution obtained by the proposed model.

(2) The imbalance level obtained from the experiment could be reproduced with the $\beta$ distribution in the parameter ranges of $a$ = 1.7–2.4 and $b$ = 4.0–13.2.

(3) The average number of retries was more sensitive to the design parameter of the anti-vibration structure, damping coefficient, compared to the outer tub displacement obtained via the mechanical model.

(4) Thus, the present model can assess the impact of design parameters of the anti-vibration structure on the number of retries by providing multiple $\beta$ distributions in the upstream design process without using a real machine. Therefore, we showed the utility of simultaneously designing the anti-vibration structure and dehydration start control.

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