Dynamic simulation of baby carriage under running condition: analyzing vibration when passing over a level difference

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Abstract
Baby carriage vibrations cause unpleasant sensations for both the babies and carriage operators. This study analyzed the baby carriage vibration generated by passing over a level difference on a road surface because this situation introduces a large physical burden and significant stress. The purpose of this study is to develop simulation models in order to improve the performances of baby carriages under operating conditions efficiently. Furthermore, experiments were conducted using a real baby carriage to verify the accuracy of the simulation models. We focused on vibrations in the front leg because characteristic vibrations were generated in this part. Baby carriage models, such as the rigid body model (modeled as a rigid body other than the elastic deformation of suspension) and the elastic connection model (modeled the movement of joints around the legs), have been developed. However, the accuracy of these models are insufficient because these are not able to model high-frequency vibrations and the trend in the vibration peaks when the baby carriage passes over the level difference. Additionally, we developed the front leg elastic body model considered the elastic deformation of front legs based on the finite segment method. In the front leg elastic body model, front legs were divided into fifths, which were connected by translational and rotational springs because the time is required for analysis using the general finite element method. This model was able to provide the trend similar to the experimental result. Finally, the vibration reduction design for a baby carriage was considered by using the developed simulation model.

Keywords: Dynamic analysis, Simulation, Modeling method, Multibody dynamics, Elastic deformation, Measuring vibration, Stroller

1. Introduction

Baby carriages are commonly used to transport babies because they alleviate the physical stress that results from carrying a child (Koh et al., 2019). The safety of baby carriage is investigated in various field (Dols et al., 2013; Fowler et al., 2016; Ridenour, 2001). One of the factors related to the safety and comfort of a baby carriage is the vibration generated during its operation. The vibration generated by rough road surfaces is transferred the baby riding in a carriage, as well as the operator of the carriage. This causes significant stress for the baby and negatively affects operability for the operator (Muraki et al., 2013).

Recent designs for baby carriages have incorporated technology for vibration reduction and shock absorption. However, such methods have been limited to the development of cushioning and suspension systems, while improvements to the base structure of carriages have largely been ignored. Previous studies have developed vibration testing systems for baby carriages (Kawashima, 2011) and conducted modal analysis on a baby carriage (Miyauchi et al., 2015). However, none of these studies have considered the vibration of baby carriages operating on real road surfaces. Additionally, only sensory evaluations have been conducted to evaluate baby carriage vibration. To the best of our
knowledge, no studies have analyzed this vibration quantitatively.

In this study, for the purpose of reducing baby carriage vibration, a simulation model was developed to perform design and performance evaluation efficiently. To analyze baby carriage vibration under running conditions, multibody dynamics (MBD) (Schiehlen, 1997) that can handle large movements, including vibrations, were adopted. It is necessary to consider the combination of multiple conditions in a system with many parts, such as a baby carriage. In such cases, MBD are useful for analyzing dynamic characteristics. We developed the simulation model that can analyze the baby carriage vibration running on road having grooves (Kamio and Aihara, 2017). This study focused on the carriage passing over a level difference on a road surface because this situation introduces a large physical burden and significant stress. To analyze the large vibration and the elastic deformation when a baby carriage passes over the level difference, this study developed the advanced simulation model. Furthermore, to clarify the vibrations generated during baby carriage operation, experiments with humans pushing carriages were conducted. To verify the accuracy of the developed simulation model, the results of simulations and experiments were compared. Finally, the reduction of baby carriage vibration was considered based on the developed model.

2. Development of a simulation model

This study developed a simulation model that can analyze the baby carriage vibration under running conditions during design and development. A power input of a human arm is simulated to replicate actual environment, and the contact between the carriage wheels and the road surface is calculated. Model development and numerical calculations were performed using the general-purpose MBD software RecurDyn (FunctionBay, Inc., 2019). This software operates based on recursive formulation theory and is able to analyze various model characteristics, including elastic deformation.

2.1 Overview of the model

Figure 1 shows a comprehensive view of the simulation model developed in this study. This model consists of a baby carriage and a road section with a level difference (modeled as two rectangular bodies). The X-axis represents the horizontal direction, the Y-axis represents the vertical direction, and the Z-axis represents the direction of carriage movement. In this study, acceleration in the Y-axis was considered as the baby carriage vibration. The height of the level difference is 15 mm, which is the average height difference between a sidewalk and roadway. This model does not consider the asperity of a road surface.

Figure 2 shows a model of an operator’s arm, which consists of springs and bodies. Arms holding and pushing the carriage handle were modeled using elastic bodies (i.e., springs). When arms are modeled by rigid bodies, it is impossible the carriage to pass over the level difference because it cannot absorb the impact and transfer the force. Such Springs and bodies can model the movement of the operator’s elbow joints when a baby carriage contacts a level difference. Additionally, massless objects were placed at the tips of the springs. These objects were applied the translational motion...
equivalent to pushing a baby carriage. Rotational springs were placed on these bodies to restrict rotational movement. Table 1 lists translational and rotational spring parameters used to model carriage operator’s arm. The spring characteristics were determined by referring to the movement of an operator and measurement results from our experiments. In this study, verified the validity of the developed simulation models for one condition because the actual usage environment of baby carriage is various. The walking speed when pushing a baby carriage was assumed to be in the range of 500–900 mm/s by preliminary experiments. This study adopted a walking speed of 600 mm/s because the baby carriage motion was able to be measured stably when baby carriage running on this speed in experiments. Additionally, it has been clarified that the simulation model can be analyzed using the same parameter values even if the driving speed is changed (Kamio and Aihara, 2017).

In this model, the contact stiffness between carriage wheels and the road surface was defined and the contact forces, which depend on the interference levels between two objects, were calculated. The contact force \( F \) is defined by Eq. (1), where \( F_n \) is the normal force and \( F_f \) is the frictional force. The normal force is generated in the direction perpendicular to the contact surface.

\[
F = F_n + F_f \tag{1}
\]

The normal force \( F_n \) and the frictional force \( F_f \) are calculated by Eq. (2) and (3), where \( k \) is the spring coefficient, \( c \) is the damping coefficient, \( \mu \) is friction coefficient, and \( x \) is the displacement based on interference levels.

\[
F_n = kx + cx \tag{2}
\]

\[
F_f = \mu F_n \tag{3}
\]

Table 2 lists the numerical values for the contact calculation between the carriage wheels and the road surface. The contact stiffness was determined based on experimental results because it directly affects the amplitude of vibration.

### 2.2 Baby carriage model

Figure 3(a) shows the baby carriage model constructed by referencing a typical baby carriage. The baby carriage model consists of a handle, seat frame, armrests, legs, and wheels. This model size is approximately 460 mm in width, 780 mm in depth, and 1160 mm in height. The wheel size is approximately 70 mm in radius and 25 mm in width. The cushion and hood were not modeled because we focused on the basic structure of a baby carriage. Additionally, to model...
the weight of a baby, a mass of 10 kg was placed on the seat frame. This weight was chosen because the maximum target age for this type of baby carriage is 16 months and the weight of a baby at this time is approximately 10 kg (DISABLED WORLD, 2019).

Figure 3(b) shows a system schematic view of the baby carriage model. All parts are modeled as rigid bodies, and the legs, armrest, handle, and seat frame are connected rigidly. Wheels are connected to shafts by rotational joints at the points where offset amount is 0 mm. The suspensions were modeled using linear springs between shafts and connectors. These springs have the spring constant of 12 N/mm and damping coefficient of 1 Ns/mm. First of all, this study developed the baby carriage that parts are connected rigidly other than suspensions (rigid body model).
2.3 Modeling of joints

Folding baby carriages have become mainstream because users prioritize space saving (Sehat and Nirmal, 2017). Therefore, a baby carriage provides some clearances between each of its parts to allow for folding movements. These clearances introduce additional vibration. Such vibration can have a significant effect on an entire structure, especially in small and complicated systems. Additionally, the legs receive a large force at the time of contact with a level difference, and the movement of part joints is significant. Therefore, we created an additional model incorporating movements between the parts around legs. Figure 4(a) shows the modeled joints of the baby carriage. The joints between legs and armrests, and between legs and connectors are connected by rotational springs to model movement around the legs in the X-axis rotational direction. In this paper, the baby carriage model using rotational springs to model movements between the parts around legs is referred to as the elastic connection model. Figure 4(b) shows a system schematic of the elastic connection model, and Table 3 lists rotational spring parameters used in this model. These parameters were determined based on experimental results and the movement of carriage.

2.4 Modeling of elastic deformation

The frames of baby carriages are hollow structures for weight reduction. Consequently, they have low rigidity and can easily become elastically deformed. Additionally, the configuration of the carriage leg is one of the important factors when considering the stability and foldability of a baby carriage. Therefore, we developed another baby carriage model including elastic deformation of front legs because these legs are elastically deformed when the carriage contacts a level difference. The general finite element method is effective for modeling elastic deformation (Argyris et al., 1979).

Table 3  Spring coefficients and damping coefficients of rotational springs used to connect between legs and armrests, and between legs and connectors.

|                     | Armrest - Leg | Leg - Connector |
|---------------------|---------------|-----------------|
| Spring coefficient [N/mm] | 8.0 × 10^7    | 2.5 × 10^6      |
| Damping coefficient [Ns/mm] | 1             | 10              |

Fig. 5  Comparison of the finite element model and the finite segment model to determine the spring coefficients for the finite segment model. The finite segment model simulates elastic deformation by connecting multiple rigid bodies using springs (elastic deformation occurs at the connection points).
However, for dynamic analysis with contacts, this method has extreme time requirements. Therefore, when the finite element method is used, it is not feasible to perform a parameter study to improve the performance of baby carriages.

To reduce analysis time when considering elastic deformation, we simulated elastic deformation by connecting multiple rigid bodies using springs. The front legs were divided into fifths, which were connected by translational and rotational springs. This simulates elastic deformation of front legs because deformation occurs at the connection points. This model is referred to as the finite segment method (Connelly and Huston, 1994). The time required for analysis using this model is much less than that required when using the finite element method. The spring coefficients used in the finite segment model were determined based on comparisons to a simplified finite element model. Figure 5(a) shows the finite element model and finite segment model, as well as the schema used for comparison. The front legs in the finite element model are meshes with tetragonal elements. The element size is 3 mm, the number of nodes is 9943, and the number of elements is 29738. The top of leg is fixed by a rotational spring, similar to the elastic connection model. The lower end of leg is subjected to a force of 300 N/m. To determine the spring coefficients for the finite segment model, we compared the displacements of two models when they were subjected the force. Figure 5(b) shows analysis results of the finite element model and the finite segment model. We determined that the spring coefficients used in the finite segment model are appropriate based on the strong agreement of these results. Table 4 lists spring constants and damping coefficients of the translational and rotational springs used in the finite segment model. In this study, the baby carriage with the finite segment model added to the elastic connection model is referred to as the front leg elastic body model.

### 3. Experiment

To experimentally measure the vibration generated during baby carriage operation, experiments using a real baby carriage were conducted. The results obtained through the experiments were used to verify the accuracy of the developed simulation models. The experimental apparatus and conditions are described below.
3.1 Experimental apparatus

Figure 6 shows the baby carriage and the level difference used in our experiments. A standard baby carriage was used in this study. The height of the seat is 450 mm and the weight of the carriage is 5.4 kg. The seat cushion and hood were removed because these parts were not included in the simulation models. A ferrous plate was placed on the ground to replicate a level difference on a road surface. The height of this plate was 15 mm, which is consistent with the simulations.

Accelerometers were attached to measure the vibration of the baby carriage. Figure 7 shows the sampling points on the baby carriage for experiments, where point I is the shaft between paired wheels, point II is the lower-front leg, and point III is the armrest with the legs connected. The vibrations at these points were measured simultaneously. The X-, Y-, and Z-axes were the same as those in simulation models.

3.2 Experimental conditions

To simulate a real environment, the baby carriage was pushed by human arms. The driving speed was controlled by limiting the step size of the operator and controlling step timing using a metronome. The driving speed was controlled to be 600 mm/s, and a mass of 10 kg was placed on the seat to match simulations.

In experiments, the movement of the baby carriage varied slightly with each trial. The movement when passing over a level difference varies depending on the movement of wheels. As shown in Figure 8, the movement when the front left and right wheels contact the level difference at the same time does not jump significantly. We adopted results of this movement as the movement of baby carriage passing over a level difference judging qualitatively based on video captured from the side.

4. Experimental and simulation results

4.1 Experimental results

Figure 9 shows experimental results for accelerations of sampling points. The first vibration peak (at approximately 0.1 s) was generated when wheels passed over the level difference. This vibration increases as the parts move closer to the road surface. However, for the lower-front leg, one can see vibration peaks that were not generated at the shaft and armrest (at approximately 0.2 s). The front leg is connected to the shaft through the suspension and a connector. We can conclude that the characteristic vibrations of lower-front legs are caused by the rotational movements between the parts around front legs and the elastic deformation of suspensions. Therefore, our analysis focused on the vibration of the lower-front leg.
Fig. 9 Experimental results for accelerations of sampling points during the running test. For lower-front leg, there are vibration peaks that were not generated at the shaft and armrest (at approximately 0.2 s). It is assumed that the characteristic vibrations of lower-front legs are caused by the rotational movements between the parts around front legs and the elastic deformation of suspensions.

Fig. 10 Comparison of the vibration waveforms at the front leg between simulation results and experimental result. The rigid body model and the elastic connection model are insufficient for modeling the movement of a baby carriage passing over a level difference. In the front leg elastic body model, high-frequency vibrations are modeled similar to the experimental result.
4.2 Simulation results

To validate the developed simulation models, we compared vibration waveforms of experimental and simulation results. This study focused on vibration of the front leg caused by contact with a level difference. Figure 10 shows simulation results for each type of models and the experimental result. The driving speed in simulations was controlled through stable by translational motion. In contrast, the driving speed in the experiment fell below the set speed (600 mm/s) when the carriage passed over the level difference because a human was driving it. Therefore, we made measurement time dimensionless based on the time required to drive over the level difference and compared the resulting vibration waveforms.

Figure 10(a) shows the analysis result for the rigid body model, and Fig. 10(d) shows the experimental result. The rigid body model is not able to model high-frequency vibration because it contains no elastic deformation outside the suspension. Based on this result, the rigid body model is insufficient for modeling the movement of a baby carriage passing over a level difference.

Figure 10(b) shows the analysis result for the elastic connection model. High-frequency vibrations are captured by modeling the part joints around the legs. However, the trend in vibration peak values does not match the experimental result. Based on this result, the accuracy of the elastic connection model is insufficient for modeling the movement of a baby carriage passing over a level difference.

Figure 10(c) shows the analysis result for the front leg elastic body model. High-frequency vibrations increase overall when using this model. Additionally, one can see that the high-frequency vibrations between points B and C are caused by vibration of the clearances around the leg, whereas the high-frequency vibrations between points D and E are caused by the elastic deformation of the front leg. In the experimental result (Figure 10(d)), the time that takes to pass over the level difference (point A to E) is shorter than the front leg elastic body model because the simulation models does not model the force that the operator gives to the carriage handle when contacting the level difference.

We will now consider the feasibility of this model. Figure 11 shows the comparison between absolute value of acceleration peaks of the front leg elastic body model and the experimental result. The average error is approximately 4 %. It is assumed that this error is included by the contact stiffness between the wheels and road surface. However, the trend in the vibration peaks is in good agreement with the experimental result. Therefore, this model is valid for performing the design and development of baby carriages when passing over a level difference.

![Fig. 11 Comparison of absolute value of acceleration peaks between the simulation result using the front leg elastic body model and the experimental result. The average error is approximately 4 %. The trend in the vibration peaks is in good agreement with the experimental result.](image-url)
5. Vibration reduction design based on the developed simulation model

In this section, to show the usage example of the developed model, a design for the vibration reduction of a baby carriage passing over a level difference is considered focusing the carriage legs. Evaluation of the generated vibration is performed based on the absolute value of the vibration peaks, similar to the previous section. For the purpose of analyzing the effects of structural materials, we connected the front legs to the rear legs using linear springs. Figure 12 shows installation positions of the linear spring between the front and rear legs. By adding a damping element in this manner, it can be assumed that the impact when contacting a level difference is reduced.

Figure 13(a) shows the vibration reduction rate of each vibration peaks due to installation positions of linear springs (spring constant of 100 N/mm). Each rates of vibration peaks before installing springs are defined 100 %. The structural damping coefficient is constant. One can see that the vibration is unchanged when the spring attached at positions a or b. In contrast, there is a significant reduction in vibration when the spring attached at position c, which is the position closest to the wheels. Figure 13(b) shows a comparison of vibration waveforms between carriages with and without an added structural element. One can see that the absolute values of the vibration peaks are smaller after adding the spring.

This study focused on the angle between the front and rear leg. Figure 14 shows the changes in the angle between the front and rear legs. Figure 14(a) is the case without a spring (before changing the structure), and Figure 14(b) is the...
case where a spring is added at position c. These results demonstrate that the movement of the front legs is restricted and that there is very little vibration, even when the front wheels ride over a level difference. It is assumed that the baby carriage vibration can be reduced changing structure of it. In this way, the developed simulation model is able to analyze the influence of vibration generated under running conditions by altering the carriage structure.

6. Conclusions

In this study, to reduce baby carriage vibrations, MBD simulation models were developed to perform design and performance evaluations efficiently. A baby carriage operating on real road surfaces was analyzed, and a level difference on a road surface, which generates large vibrations, was considered. Additionally, experiments with a human pushing on a carriage were conducted. The validity of the MBD simulation models was investigated by comparing the simulation results to the experimental result. The key points of this study can be summarized as follows.

(1) To clarify the model elements necessary for analyzing the baby carriage vibration generated by passing over a level difference, this study developed three type of baby carriage models: the rigid body model (modeled as a rigid body other than the elastic deformation of suspension), the elastic connection model (modeled the clearances between parts around the legs), and the front leg elastic body model (modeled the elastic deformation of the front legs).
(2) To measure the vibration generated during baby carriage driving experimentally, experiments using a real baby carriage were conducted. It is clarified that the characteristic vibrations are generated on the front leg compared the shaft between wheels and armrest.
(3) The feasibility of the developed simulation model was verified by comparing the simulation results to the experimental result. When comparing acceleration peaks of the front leg elastic body model to the experimental result, the trend in the vibration peaks is in good agreement.
(4) As a usage example for the developed simulation model, baby carriage vibration when adding a damping element between the front and rear legs was analyzed.

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