Control system for semi-active in-car crib with joint application of regular and inverted pendulum mechanisms

Takeshi KAWASHIMA*
* Department of Mechanical Engineering, Kanagawa Institute of Technology
1030 Shimo-ogino, Atsugi-city, Kanagawa, 243-0292, Japan
E-mail: kawashima@eng.kanagawa-it.ac.jp

Received 25 December 2014

Abstract
To reduce the collision shock and injury risk to an infant in an in-car crib (or in a child safety bed) during a car crash, it is necessary to keep the force acting on the crib constant and below a certain allowable value. To this end, we propose a semi-active in-car crib with joint application of regular and inverted pendulum mechanisms. The crib is supported like a pendulum by arms, and the pendulum system is supported like an inverted pendulum by arms. This system not only reduces the impulsive force but also transfers the force to the infant’s back using a spin control system, i.e., the force acts perpendicularly on the crib. The spin control system was developed previously. In the present study, an acceleration control system is developed. One of the characteristics is that this system has the merits of both a regular pendulum-style in-car crib and an inverted pendulum-style in-car crib. The regular pendulum-style one is suitable when moderate impulsive forces are involved because the crib moves smoothly soon after the force begins to affect the crib. The inverted pendulum-style one is suitable when large impulsive forces are involved because the arm that is initially tilted backward, which constitutes the inverted pendulum, is difficult to move under weak forces. Therefore, the proposed in-car crib is able to increase the acceleration of the crib gradually and maintain it around the target value. This paper focuses on the control system. The control law is introduced, and the robustness is examined using numerical simulation.

Key words: Mechanical engineering, Motion control, Impact control, Shock control, Occupant crash protection, Passive safety device, Child restraint system, Impact relaxation, Pendulum, Inverted pendulum

1. Introduction

In Japan, people typically spend a large amount of time commuting to the workplace. In particular, young workers with babies face many difficulties. This has resulted in a decrease in the birth rate and a shortage of young workers. To solve this problem, it is necessary to establish a social environment in which parents with a baby are able to work comfortably. This study focuses on young parents who are able to find a daycare center only in or near their workplace. The goal is to develop equipment that ensures a baby’s safety in a car, thereby reducing the mental burden of the parents. Thus, for a bed-type child-seat, which can be used for a neonatal infant, we propose an in-car crib (or a child safety bed) with joint application of regular and inverted pendulum mechanisms, which not only reduces the impulsive force by moving the crib but also transfers the force to the infant’s back using a spin control system, i.e., the force acts perpendicularly on the crib.

The risk of brain damage (encephalopathy) due to decreased arterial oxygen saturation can be reduced by using an in-car crib. In particular, abdominal compression can be avoided, which is not the case when a child car seat is used. However, with an in-car crib, the collision impact is directed to the infant’s side, and the resultant motion of the body is relatively complex. For this reason, in previous research, use of a spin control system was proposed for the crib so that the impact falls on the infant’s back. This control technique was developed as an actively controlled regular
pendulum-type bed for an ambulance (Kawashima, 2002). The present study focuses on the development of a crib movement system.

For crib movement systems, pendulum mechanisms have been proposed by many engineers. In the literature concerning a patent designed by Sawaishi (2004), a child car seat is described as a rotating seat like a pendulum aimed at reducing the impact on a baby pressed against the seatbelt and redirecting the force toward the seat. When a child car seat is supported in this manner, the initial acceleration acting on the seat can be reduced almost completely by moving the seat. However, this acceleration cannot be reduced further after the pendulum has rotated (Kawashima, 2012, 2013). Therefore, regular pendulum-style in-car cribs are unsuitable when large impulsive forces are involved. In our proposed in-car crib, the acceleration of the crib can be kept almost constant during collision. This is one of the main advantages of the proposed system. A child car seat that is rotated by electromagnets installed on the seat and base to reduce impact forces and redirect the force toward the child’s hip has been registered as a utility model by Tamura (2000). In addition, the patent of a child car seat that is rotated to a safety position before collision by using predictive information of a vehicle crash to reduce harm to the baby has been made available to the public by Ohno, et al. (2001). In these two systems, the child car seat is moved by an actuator using power at or before collision. In our proposed system, the rotation of the arms supporting the crib is semi-actively controlled by the braking mechanism, resulting in a reduction in the impulsive force. That is, our proposed system saves energy, which is a significant advantage for a vehicle with limited power. This is another major advantage of the proposed system.

An inverted pendulum-style active in-car crib was previously proposed to reduce the impulsive force acting on the crib to an allowable value during crib movement in a car crash (Kawashima, 2010). The crib is supported by two arms constituting an inverted pendulum. In a vehicle cabin, the space for crib movement is limited. To minimize the impulsive force in such restricted spaces, the force acting on the crib must be kept constant from the initial stage until the final collision stage. The arm is initially tilted backward because of the difficulty of movement of the inverted arm. Therefore, the acceleration of the crib can be maintained at less than the vehicle deceleration until the arms are upright. In addition, a semi-active shock control system is applied to keep the acceleration constant. Although this system is effective in a car crash with strong impulsive forces, it is not effective in a car crash with weak forces, because the crib does not move in the latter case (Kawashima, 2012, 2013).

To combine the characteristics of the regular pendulum-style in-car crib and the inverted pendulum-style in-car crib, we propose an in-car crib that involves joint application of the regular and inverted pendulum mechanisms. The conceptual diagram is shown in Fig. 1. In this system, the acceleration of the crib increases gradually and is maintained at less than the vehicle deceleration. That is, this system has the advantages of both the regular pendulum mechanism and the inverted pendulum mechanism (Kawashima, 2012, 2013).

Fig. 1 Conceptual diagram of the in-car crib with joint application of regular and inverted pendulum mechanisms to reduce the collision shock and injury risk to an infant in the crib during a car crash.
We also propose a semi-active control system. First, we developed a control algorithm that adjusts only the damping coefficient of the joint between the base and the arm, which constitutes an inverted pendulum. We confirmed its effectiveness using numerical simulation. The results indicate that the acceleration of the crib increases gradually and is maintained at around the target value of 26 G when the deceleration of the base fixed on the vehicle seat is 30 G (Kawashima, 2012). Next, we developed a control algorithm that adjusts the friction torques of the joint between the base and the arm constituting the inverted pendulum and the joint between the arm constituting the inverted pendulum and the regular pendulum. We confirmed its effectiveness using numerical simulation. The results indicate that the acceleration of the crib increases gradually and is maintained at around the target value of 25 G when the deceleration of the base fixed on the vehicle seat is 30 G (Kawashima, 2013).

In this system, the arm that is tilted backward, which constitutes the inverted pendulum, is supported by a stopper. Each joint is set with large damping under normal conditions for a comfortable ride. And a forward stopper is also installed for safety. In addition, each joint is designed to set with large friction torque as a fail-safe in case the control system breaks down.

This paper focuses on the control system. The control law is introduced, and the robustness is examined using numerical simulations.

For the impact control system, a method was derived for calculating the seatbelt tension to maintain the acceleration of the thorax, the deformation of the thorax, and the migration length of the occupant in the cabin within tolerance limits in a car crash for a nonlinear human-vehicle system (Balandin, et al., 2001). For occupant protection in modern-day automobiles, a crushable zone is designed in the vehicle body, and a seatbelt and air bags are installed. In addition, use of a child-seat is obligatory when infants are in the car. However, these are passive or open-loop systems, and the expected result is not always obtained, because of effects such as disturbance. Therefore, an impact control system that feeds back the condition is required in order to obtain a definite result. In terms of active impact control, studies have investigated an optimal control system, an H infinity control system (Wang, et al., 2005a), a system using feed-forward input (Wang, et al., 2005b), and a gain-scheduled control system (Wang, et al., 2007). Additionally, an active knee bolster has been developed by applying the impact control method for occupant injury protection (Kato, et al., 2007).

Regarding a semi-active impact control system in which the actuator can be miniaturized and the power consumption can be small, the author has studied a system that uses the actuator for semi-active control using a braking mechanism (Kawashima, 2005). An active seatbelt has been proposed that uses a semi-active actuator, and its effectiveness has been confirmed by an experiment using a model (Kawashima, 2008). A knee bolster applied for semi-active impact control has also been studied (Narukawa, et al., 2012).

Although child restraint systems with moving mechanisms are not considered in the present technical standards, this paper shows the degree of reduction in the deceleration of the crib when the moving mechanism and the control system are applied.

2. Nomenclature

Symbols, representative values, and descriptions used in this paper are as follows:

\[ A_1 = -22.5 \text{ G} \] Acceleration of the crib after the vehicle stops.
\[ A_2 = 20.0 \text{ G} \] Relaxation value of the acceleration of the crib relative to vehicle acceleration in the initial stage of the car crash.
\[ A_3 = 5.00 \text{ G} \] Relaxation value of the acceleration of the crib relative to vehicle acceleration during vehicle movement, i.e., acceleration of the crib relative to the base.
\[ D_1 \] Friction torque of the joint between the base and arm 1, which constitutes the inverted pendulum. This is the control input.
\[ D_{ref} \] Reference friction torque of the joint between the base and arm 1. This is the basic control input.
\[ \Delta D_1 \] Friction torque of the joint between the base and arm 1, derived using sliding mode control theory. This is the feedback control input.
\[ D_2 \] Friction torque of the joint between arm 1, which constitutes the inverted pendulum, and arm 2, which
constitutes the regular pendulum. This is the control input.

\( D_{2} \) : Reference friction torque of the joint between arms 1 and 2. This is the basic control input.

\( \Delta D_{2} \) : Friction torque of the joint between arms 1 and 2, derived using sliding mode control theory. This is the feedback control input.

\( l_{1} = 600 \text{ mm} \) : Length of arm 1, which constitutes the inverted pendulum.

\( l_{2} = 400 \text{ mm} \) : Length of arm 2, which constitutes the regular pendulum.

\( M = 13.0 \text{ kg} \) : Mass of the crib including the mass of the infant.

\( m = 1.00 \text{ kg} \) : Mass of the joint between arm 1, which constitutes the inverted pendulum, and arm 2, which constitutes the regular pendulum.

\( m_{1} = 5.00 \text{ kg} \) : Mass of arm 1, which constitutes the inverted pendulum.

\( m_{2} = 1.50 \text{ kg} \) : Mass of arm 2, which constitutes the regular pendulum.

\( T_{1} = 0.05 \text{ s} \) : Time until acceleration of the crib becomes constant.

\( T_{2} = 0.0944 \text{ s} \) : Time when the vehicle stops.

\( T_{3} \) : Time when the crib stops.

\( \dot{X} = -30.0 \text{ G} \) : Acceleration of the vehicle, i.e., acceleration of the base.

\( \theta_{1} \) : Angular displacement of arm 1, which constitutes the inverted pendulum.

\( \dot{\theta}_{1} \) : Target angular displacement of arm 1.

\( \Delta \theta_{1} \) : Error of angular displacement of arm 1 with respect to the target angular displacement \( \theta_{1r} \).

\( \theta_{2} \) : Absolute angular displacement of arm 2, which constitutes the regular pendulum.

\( \dot{\theta}_{2} \) : Target absolute angular displacement of arm 2.

\( \Delta \theta_{2} \) : Error of absolute angular displacement of arm 2 with respect to the target angular displacement \( \theta_{2r} \).

3. Analytical model

The analytical model of the proposed system is shown in Fig. 2. The crib and the arms were assumed to be single mass particle. The friction torque of each joint is adjusted by the controller.

![Analytical model of the in-car crib with joint application of regular and inverted pendulum mechanisms.](image)

The equation of motion for the model shown in Fig. 2 can be derived as follows:

\[
\left\{ \frac{1}{3} m_{1} + m + m_{2} + M \right\} \dot{\theta}_{1} + \frac{1}{2} m_{2} + M \cos(\theta_{1} + \theta_{2}) \dot{\theta}_{2} \dot{\theta}_{2} + \frac{D_{1} + D_{2}}{l_{1}} - \frac{1}{2} \left( \frac{1}{2} m_{1} + m + m_{2} + M \right) g \sin \theta_{1} = - \frac{1}{2} \left( \frac{1}{2} m_{1} + m + m_{2} + M \right) \cos \theta_{1} \cdot \dot{X} \quad (1a)
\]
4. Control law

We developed a semi-active controller that adjusts the movement of the crib to reduce the crib acceleration to the target acceleration, which is selected by considering the cabin space, by adjusting the friction torque of each joint using the braking mechanism. In this paper, the deceleration of the base is assumed to be constant at 30 G. It is reduced by the crushable zone of the vehicle body in a car crash. A collision is assumed to occur over a short time of approximately 0.0944 s when the vehicle decelerates at -30 G from 100 km/h. Thus, the control system requires high-frequency feedback. Therefore, each control input for the friction torque consists of the pre-calculated basic control input and the sliding mode control input to compensate for the effects of disturbances and model errors.

The objective of the controller is to reduce the acceleration of the crib. Therefore, the acceleration of the crib should be set as the control target. However, the accelerations are not the state variables. Thus, we set as the target the trajectory of displacement of each arm, which is calculated using the desired horizontal acceleration of the crib. The basic control input is preliminarily derived by solving the dynamic equation under the condition of the calculated trajectory; it is then stored in the memory of the system, with the control inputs calculated under other conditions. The sliding mode control input is calculated using the control law to correct the error of the arm displacement with respect to the target trajectory. The sliding mode control is suitable for this application, because the sliding mode control law can be easily derived for the nonlinear model, and the well-designed law is robust for the model error and disturbances.

First, the target trajectory of each arm is derived. This should be calculated using the desired resultant acceleration of the crib. However, this calculation becomes complicated in some cases, for example, nonlinearity of calculation of the square. Therefore, it can be calculated from the desired horizontal acceleration of the crib relative to the base as follows:

\[
0 \leq t < T_1 : \quad a_{wr} = A_r \left( t/T_1 - 1 \right)^2 + A_e
\]

\[
T_1 \leq t < T_2 : \quad a_{wr} = A_r
\]

\[
T_2 \leq t < T_3 : \quad a_{wr} = A_e
\]

An example of this is shown in Fig. 3. The desired absolute horizontal acceleration of the crib is \( \ddot{X} + a_{wr} \). The acceleration of the crib relative to the base \( A_r \) is decided considering the empty space for the crib movement in the cabin. The allowable acceleration for the infant is also considered in the actuality. In this study, the relaxation value \( A_e \) is decided by assuming 0.9 m of empty space for the crib movement in the cabin using the trial and error method.

![Fig. 3 Example of desired relative horizontal acceleration of the crib for designing the controller](image-url)
The target trajectory of each arm is derived using the relationships of each arm configuration under the condition that the angular velocities of both arms are assumed to be equal to shorten the movement of the crib. Example trajectories are shown in Fig. 4.

![Fig. 4 Example target trajectories of each arm for the control.](image)

The horizontal and vertical velocities of the crib derived by the calculation are shown in Fig. 5. This figure shows that the vertical velocity of the crib, \( V_{yr} \), is smaller than the horizontal velocity, \( V_{xr} \). This confirms that the vertical acceleration can be ignored.

![Fig. 5 Example of relative horizontal velocity and vertical velocity of the crib derived by calculation.](image)

The basic control inputs of each joint are calculated using Eq. (1) and the derived trajectories of the arms. Example basic inputs are shown in Fig. 6.

![Fig. 6 Example basic control inputs to rotate each arm according to the target trajectory.](image)

The basic control inputs are open-loop control inputs. Therefore, feedback control inputs are derived to compensate for the effects of disturbance or model errors by applying sliding mode control theory. The errors of angular displacements of the arms, \( \Delta \theta_1 \) and \( \Delta \theta_2 \), and the control input derived using sliding mode control theory, \( \Delta D_1 \) and \( \Delta D_2 \), are set as follows:
The equations of motion for the errors are derived by eliminating the high-order terms of the errors in the inertia terms as follows:

\[
\begin{align*}
\Delta \theta_1 &= \theta_1 - \theta_{1r}, \quad \Delta \theta_2 = \theta_2 - \theta_{2r}, \\
\Delta D_1 &= D_1 - D_{1r}, \quad \Delta D_2 = D_2 - D_{2r}
\end{align*}
\] (3)

(4)

Next, the state equation is arranged from these equations as follows:

\[
\frac{d[\Delta \theta]}{dt} = [f] + [B][u]
\] (6)

Here, \([\Delta \theta] = [\Delta \theta_1 \quad \Delta \theta_2 \quad \Delta \dot{\theta}_1 \quad \Delta \dot{\theta}_2]^T\) is the state variable vector and \([u] = [\Delta D_1 \quad \Delta D_2]^T\) is the control input vector.

The hyper-plane for the sliding mode control is selected as follows:

\[
[s] = [G][\Delta \theta] = 0, \quad [G] = \begin{bmatrix} G_{11} & 0 & G_{12} & 0 \\ 0 & G_{21} & 0 & G_{22} \end{bmatrix}
\] (7)

The sliding mode control law is obtained as follows (Hashimoto, 1993):

\[
[u] = -\alpha F([\theta], t) \left[ \frac{s}{s + \delta} \right]
\] (8)

Here, the smooth function is used instead of the switching function to suppress the chatter of the control input. Additionally, \(1 < \alpha, \ 0 < \delta, \ 0 < [u_{eq}] < F([\theta], t), \ \{s^*\} = ([G][B])^{-1}[s], \ [G] = \partial_i\{s^*\}/\partial_i[\theta], \ \det([G][B]) \neq 0\), and \([u_{eq}] = -([G][B])^{-1}[G]\{f\}\). In this study, \(\alpha = 1.1\) and \(\delta = 1.0\) are used.

5. Numerical simulation

The effectiveness of the proposed control law was confirmed using numerical simulation. The parameters described in Section 2 were used. Equation (1) was solved using the Runge-Kutta method. The sampling period of the control was 1 ms, and the sampling period of the Runge-Kutta method was 0.1 ms. Disturbances were applied to confirm the effectiveness of feedback control inputs. The amplitude and frequency of the disturbances were 20 rad/s and 100 Hz, respectively. An example simulation result is shown in Figs. 7a and 7b.

These figures show that the acceleration of the crib gradually increased from approximately 8 G and was maintained at almost 25 G while the effect of disturbance was canceled. The arms rotated cooperatively, and the rotating angles were less than 45°. The maximum acceleration of the crib was 25.25 G, whereas the maximum acceleration of the crib without the feedback control was 25.73 G. Thus, the effectiveness of the feedback control was verified.
Figure 8 shows the time history of the percentage of the feedback control inputs when the frequency of disturbance was set to 25 Hz. The maximum acceleration of the crib was 25.25 G, whereas the maximum acceleration of the crib without the feedback control was 26.08 G. The ratios change at the low frequency compared with the result of Fig. 7b because of the low disturbance frequency. Thus, it was verified that the feedback control works well at various disturbance frequencies.

Fig. 7a Simulation result for semi-active control in the case of $M = 13.0 \text{ kg}$, $m = 1.00 \text{ kg}$, $m_t = 5.00 \text{ kg}$, $l_1 = 600 \text{ mm}$, $m_2 = 1.50 \text{ kg}$, $l_2 = 400 \text{ mm}$, the initial angle of arm 1 of −30 deg, the vehicle deceleration of $\ddot{X} = -30 \text{ G}$ for 0.0944 s and the set control reference of $-\ddot{X} - A = 25 \text{ G}$ with disturbances. The amplitude and frequency of the disturbances were 20 rad/s$^2$ and 100 Hz, respectively. The solid line, the broken line, the bold line, the thin line, and the dotted line show the time history of the angular displacement of arm 1, the angular displacement of arm 2, the acceleration of the crib, the friction torque between the base and arm 1 as the control input, and the friction torque between arm 1 and arm 2 as the control input, respectively. The unit [hNm] means hectonewton-meter.

Fig. 7b Simulation result for semi-active control. The bold line and the solid line show the time history of the ratio of the feedback control input of the joint between the base and arm 1 to the basic control input and the ratio of the feedback control input of the joint between arm 1 and arm 2 to the basic control input, respectively.

Fig. 8 Simulation result for semi-active control in the case of with disturbances. The amplitude and frequency of the disturbances were 20 rad/s$^2$ and 25 Hz, respectively. The bold line and the solid line show the time history of the ratio of the feedback control input of the joint between the base and arm 1 to the basic control input and the ratio of the feedback control input of the joint between arm 1 and arm 2 to the basic control input, respectively.
Figures 9a and 9b show the simulation result in case that the amplitude and frequency of the disturbance were set to 200 rad/s^2 and 100 Hz, respectively. The maximum acceleration of the crib was 25.81 G, whereas the maximum acceleration of the crib without the feedback control was 26.93 G. Figure 10 shows the time history of the percentage of the feedback control inputs when the frequency of disturbance was set to 25 Hz. The maximum acceleration of the crib was 27.15 G, whereas the maximum acceleration of the crib without the feedback control was 33.07 G. From these results, it was verified that the feedback control works well at various disturbance magnitudes, although the large input is required.

Fig.9a Simulation result for semi-active control in the case of $M = 13.0$ kg, $m = 1.00$ kg, $m_1 = 5.00$ kg, $l_1 = 600$ mm, $m_2 = 1.50$ kg, $l_2 = 400$ mm, the initial angle of arm 1 of $-30$ deg, the vehicle deceleration of $X = -30$ G for 0.0944 s and the set control reference of $-X + A = 25$ G with disturbances. The amplitude and frequency of the disturbances were 200 rad/s^2 and 100 Hz, respectively. The solid line, the broken line, the bold line, the thin line, and the dotted line show the time history of the angular displacement of arm 1, the angular displacement of arm 2, the acceleration of the crib, the friction torque between the base and arm 1 as the control input, and the friction torque between arm 1 and arm 2 as the control input, respectively. The unit [hNm] means hectonewton-meter.

Fig.9b Simulation result for semi-active control. The bold line and the solid line show the time history of the ratio of the feedback control input of the joint between the base and arm 1 to the basic control input and the ratio of the feedback control input of the joint between arm 1 and arm 2 to the basic control input, respectively.

Fig.10 Simulation result for semi-active control in the case of with disturbances. The amplitude and frequency of the disturbances were 200 rad/s^2 and 25 Hz, respectively. The bold line and the solid line show the time history of the ratio of the feedback control input of the joint between the base and arm 1 to the basic control input and the ratio of the feedback control input of the joint between arm 1 and arm 2 to the basic control input, respectively.
The maximum acceleration of the crib was 25.22 G when the sampling period of the feedback control was 1 ms and without disturbances; when the sampling period of the feedback control was 0.1 ms, the maximum acceleration of the crib was 25.06 G; when the sampling period was 10 ms, the maximum acceleration of the crib was 25.45 G ($\delta = 2.0$ in the control law). Thus, it was verified that the control performance was improved as the sampling period was decreased.

In terms of parameter change, basic robustness of the sliding mode control was expected. However, the mass of the infant can be measured by a force sensor installed on the crib. Therefore, to achieve effective control, the reference control input is calculated on the basis of the measured infant mass before the vehicle starts moving. In a car crush, vehicle deceleration greater than 30 G is reduced to 30 G by the crushable zone of the vehicle body, and reference control input depending on the deceleration is selected for deceleration less than 30 G. For example, the simulation result when the crib mass, including the mass of the infant, was $M = 8.00\text{ kg}$ is shown in Figs. 11a and 11b. The maximum acceleration of the crib was 25.29 G. The time history of the acceleration of the crib was similar to the result shown in Figs. 7a and 7b. Thus, the effectiveness of the proposed control system was confirmed.

Fig. 11a Simulation result for semi-active control in case of $M = 8.00\text{ kg}$, $m = 1.00\text{ kg}$, $m_1 = 5.00\text{ kg}$, $l_1 = 600\text{ mm}$, $m_2 = 1.50\text{ kg}$, $l_2 = 400\text{ mm}$, the initial angle of the arm 1 of $-30\text{ deg}$, the vehicle deceleration of $\ddot{X} = -30\text{ G}$ for 0.0944 s and the set control reference of $\ddot{r}A_X = 25\text{ G}$ with disturbances. The amplitude and frequency of the disturbances were 20 rad/s$^2$ and 100 Hz, respectively. The solid line, the broken line, the bold line, the thin line, and the dotted line show the time history of the angular displacement of arm 1, the angular displacement of arm 2, the acceleration of the crib, the friction torque between the base and arm 1 as the control input, and the friction torque between arm 1 and arm 2 as the control input, respectively. The unit [hNm] means hectonewton-meter.

Fig. 11b Simulation result for semi-active control. The bold line and the solid line show the time history of the ratio of the feedback control input of the joint between the base and arm 1 to the basic control input and the ratio of the feedback control input of the joint between arm 1 and arm 2 to the basic control input, respectively.
6. Conclusions

To improve the safety of infants in cars, we proposed an in-car crib with joint application of regular and inverted pendulum mechanisms to reduce collision shock and injury risk due to a car crash. A controller adjusts the friction torques of two revolution joints using control inputs, which consist of the basic control input derived from the reference acceleration of the crib and the sliding mode control input, which compensates for disturbances and parameter changes. In this paper, we examined the characteristics of the proposed control system using numerical simulations. We found that the acceleration of the crib increased gradually from approximately 8 G and was maintained at around the reference value of 25 G when the vehicle deceleration was 30 G. The maximum acceleration depends on the distance of horizontal movement of the crib in the cabin. Therefore, the reference value of the control system must be set by considering both the length of arm 1 and the amount of space available for crib movement. We also verified the effectiveness of the feedback controller for various controller sampling periods, disturbance frequencies, disturbance magnitudes and infant masses.

For further improvement of the controller performance, it is necessary to develop the control law tracking the target trajectory of the acceleration directly. This is the challenge for the feature.

Acknowledgment

This work was supported by a Grant-in-Aid for Scientific Research (C) (JSPS KAKENHI Grant Number: 24560279).

References


Kawashima, T., Basic research on inverted pendulum style child bed, Proceedings of the 5th Asian Conference on Multibody Dynamics (2010), No.59750, Kyoto, Japan.


Sawaishi, T., The rotary type and impact absorption type child-seat and the rolling mechanism for the child-seat,


