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

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Abstract. To reduce the risk of injury to an infant in an in-car crib (or in a child safety bed) collision shock during a car crash, it is necessary to maintain a constant force acting on the crib below a certain allowable value. To realize this objective, we propose a semi-active in-car crib system with the joint application of regular and inverted pendulum mechanisms. The arms of the proposed crib system support the crib like a pendulum while the pendulum system itself is supported like an inverted pendulum by the arms. In addition, the friction torque of each arm is controlled using a brake mechanism that enables the proposed in-car crib to decrease the acceleration of the crib gradually and maintain it around the target value. 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 impulse force acts is made to act perpendicularly on the crib. The spin control system was developed in our previous work. This work focuses on the acceleration control system. A semi-active control law with acceleration feedback is introduced, and the effectiveness of the system is demonstrated using numerical simulation and model experiment.

1. Introduction

In Japan, people typically spend a large amount of time commuting to the workplace. In particular, young workers with infants face many difficulties. This has resulted in the decrease in the birth rate and a shortage of young workers. To solve this problem, it is necessary to establish a social environment where parents of infants are able to live comfortably. This study focuses on young parents who are able to find a daycare center only in or near their workplace. The objective is to develop equipment that ensures an infant's safety in a car, thereby addressing the concern of parents regarding safety of their infants. 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 is made to act 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 our previous research, the use of a spin control system was proposed for the crib so that the impact is directed to the infant's back. This control technique was developed as an actively controlled regular pendulum-type bed for an ambulance by the author [1]. The present study focuses on the development of a crib movement system.

For crib movement systems, pendulum mechanisms have been proposed by many engineers. Sawaishi [2] designed a child car seat to behave like a pendulum-like rotating seat, which was 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 deceleration acting on the seat can be reduced almost completely by rotating the seat. However, this deceleration cannot be further reduced after the pendulum has rotated [3], [4]. Therefore, the regular pendulum-style in-car cribs are unsuitable when large impulsive forces are involved. In our proposed in-car crib, the deceleration of the crib can be increased gradually and kept almost constant during collision. This is one of the main advantages of the proposed system. Tamura [5] has registered a child car seat that is rotated by electromagnets installed on the seat and base, which reduce the impact forces and redirect the force toward the child's hip, as a utility model. In addition, the patent of a child car seat, which rotates to a safety position prior to collision by using predictive information before a vehicle crash to reduce harm to the baby, has been made available to the public by Ono [6]. In both systems, the child car seat is moved by an actuator using power at or before collision. However, in our proposed system, the rotation of the arms supporting the crib is semi-actively controlled by the braking mechanism, resulting in a reduction of the impulsive force experienced by the crib. 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 by the author [7]. The crib is supported by two arms constituting the inverted pendulum. In a vehicle cabin, the space for crib movement is limited. Therefore, to minimize the impulsive force in such restricted spaces, the force acting on the crib must be kept constant from the initial to the final collision stage. The arm is initially tilted backward to counter the difficulty in movement of the inverted arm. Therefore, the deceleration of the crib can be maintained below the vehicle deceleration until the arms are vertical. In addition, a semi-active shock control system is applied to keep the deceleration constant. Although this system is effective in a car crash with strong impulsive forces, it is rather ineffective in car crashes with weak forces, because the crib does not move in the latter case [3, 4].

To combine the advantages of the regular pendulum-style in-car crib and the inverted pendulum-style in-car crib, we propose an in-car crib that involves the joint application of regular and inverted pendulum mechanisms. The conceptual diagram is shown in Figure 1. In this system, the deceleration of the crib increases gradually and is maintained below the vehicle deceleration, thereby resulting in system that has advantages of both the regular pendulum mechanism and the inverted pendulum mechanism [3, 4].

We also propose a semi-active control system. First, we developed a control algorithm that adjusts only the damping coefficient of the joint connecting the base and the arm which acts as an inverted pendulum. We confirmed the effectiveness of the system using numerical simulations. The simulation results indicate that the deceleration of the crib increases gradually and is maintained at around the target value of 26 G ("G" is a unit of the acceleration based on the gravitational acceleration: 1 G = 9.806 m/s^2) when the deceleration of the base affixed to the vehicle seat is 30 G [3]. Subsequently, we developed a control algorithm that adjusts the friction torques of the joint connecting the base and the arm which acts as an inverted pendulum, and the joint connecting the arm which acts as an inverted pendulum and the arm which acts as a regular pendulum. We confirmed the effectiveness of the modified system using numerical simulations. The results indicate that the deceleration of the crib increases gradually and is maintained at around the target value of 25 G when the deceleration of the base affixed to the vehicle seat is 30 G [4]. The robustness of the system was also examined using numerical simulations [8].

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

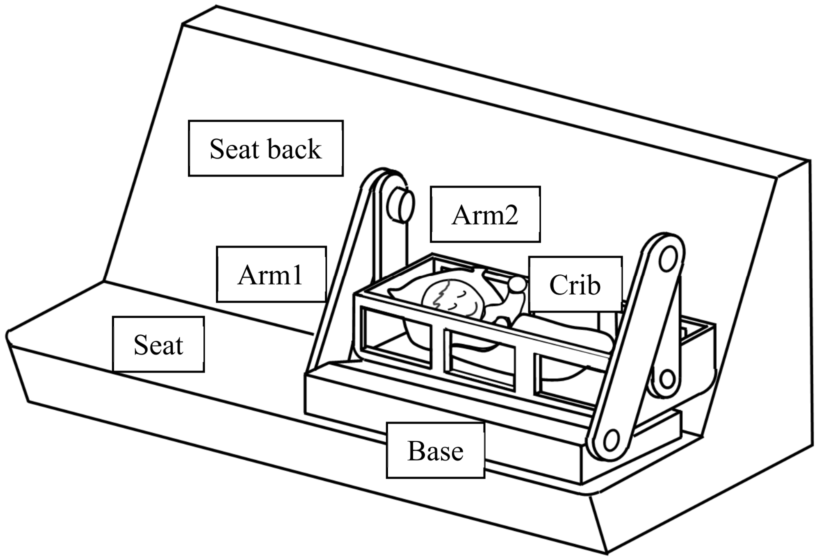

Figure 1. Conceptual diagram of the proposed in-car crib system.

This work focuses on the acceleration control system, which is directly able to control the acceleration affecting the crib. We also introduce the control law and the effectiveness is examined using numerical simulation and model examination.

For the impact control system, a method was proposed for calculating the seatbelt tension to required maintain the acceleration of the thorax, the deformation of the thorax, and the migration length of the occupant in the cabin within the tolerance limits in a car crash for a nonlinear human-vehicle system [9]. To add to occupant safety in modern-day automobiles, a crushable zone is designed in the vehicle body, and seatbelts and air bags are installed in the cabin. In addition, use of a child-seat is obligatory when infants are present in the car. However, these are passive or open-loop systems, and do not always perform as expected, because of effects such as disturbance. Therefore, an impact control system that feeds back the state variables is required in order to obtain a definite result. In terms of active impact control, several studies have investigated an optimal control system, an H infinity control system [10], a system using feed-forward input [11] and a gain-scheduled control system [12]. In addition, an active knee bolster has been developed by applying the impact control method for occupant injury protection [13].

A semi-active impact control system, wherein the actuator can be miniaturized and the power consumption can be small, has been studied by the author; the system utilizes the actuator for semi-active control using a braking mechanism [14]. An active seatbelt has been proposed that uses a semi-active actuator, and its effectiveness has been confirmed experimentally using a model [15]. A knee bolster applied for semi-active impact control has also been studied [16].

Although child restraint systems with moving mechanisms are not considered in present technical standards, this paper demonstrates the extent to which the deceleration of the crib can be reduced when the moving mechanism and the control system are applied.

2. Nomenclature

Symbols, representative values, values of experimental model in parentheses and descriptions used in this paper are as follows:

a_x : Horizontal acceleration of the crib.

$A_{xr} = -25.0$ G ($A_{xr} = -1.70$ G): Target horizontal acceleration of the crib during vehicle movement.

$A_{xr} = -20.0$ G ($A_{xr} = -1.70$ G): Target horizontal acceleration of the crib after the vehicle stops.

$C_2 = 0$ ($C_2 = 0$): Damping coefficient of the joint between arm 1, which acts as an inverted pendulum, and arm 2, which acts as a regular pendulum.

D_1 : Friction torque of the joint between the base and arm 1, which acts as an inverted pendulum. This is the control input.

$l_1 = 600$ mm ($l_1 = 400$ mm): Length of arm 1, which acts as an inverted pendulum.

$l_2 = 400$ mm ($l_2 = 250$ mm): Length of arm 2, which acts as a regular pendulum.

$M = 13.0$ kg ($M = 0.200$ kg): Mass of the crib including the mass of the infant.

$m = 1.00$ kg ($m = 0.500$ kg): Mass of the joint between arm 1, which acts as an inverted pendulum, and arm 2, which acts as a regular pendulum.

$m_1 = 5.00$ kg ($m_1 = 0.400$ kg): Mass of arm 1, which acts as an inverted pendulum.

$m_2 = 1.50$ kg ($m_2 = 0.100$ kg): Mass of arm 2, which acts as a regular pendulum.

$\ddot{X} = -30.0$ G ($\ddot{X} \approx -1.90$ G): Acceleration of the vehicle, i.e., acceleration of the base.

θ_1 : Angular displacement of arm 1, which acts as an inverted pendulum.

θ_2 : Absolute angular displacement of arm 2, which acts as a regular pendulum.

3. Analytical model

The analytical model of the proposed system is shown in Figure 2. The crib and the arms are assumed to be a single mass particle.

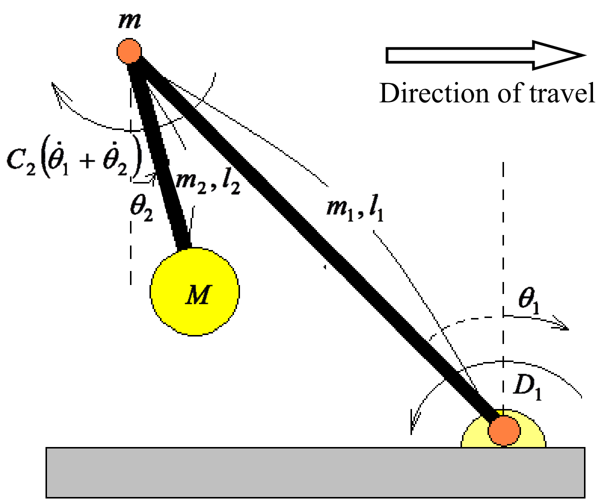

Figure 2. Analytical model of the proposed in-car crib system.

In this study, $\theta_2 = \theta_1 + \pi / 6$ is assumed for simplicity, that is to say, arm 2 is linked with arm 1. Thus, the system has one degree of freedom, and the friction torque between the base and arm 1 D_1 can be adjusted by the controller.

The equation of motion for the model shown in Figure 2 under the above assumption can be derived as follows:

$$
\begin{aligned}
&\left[\left(\frac{1}{3}m_1+m+m_2+M\right)l_1^2+\left(\frac{1}{3}m_2+M\right)l_2^2+2\left(\frac{1}{2}m_2+M\right)l_1l_2\cos(2\theta_1+\pi/6)\right]\ddot{\theta}_1\\
&-2\left(\frac{1}{2}m_2+M\right)l_1l_2\sin(2\theta_1+\pi/6)\dot{\theta}_1^2+4C_2\dot{\theta}_1\\
&-\left(\frac{1}{2}m_1+2m+m_2+M\right)l_1 g\sin\theta_1+\left(\frac{1}{2}m_2+M\right)l_2 g\sin(\theta_1+\pi/6)\\
&=-\left[\left(\frac{1}{2}m_1+m+m_2+M\right)l_1\cos\theta_1+\left(\frac{1}{2}m_2+M\right)l_2\cos(\theta_1+\pi/6)\right]\ddot{X}-D_1
\end{aligned}
\tag{1}
$$

4. Control law

To control the acceleration of the crib directly, the equation of motion (1) is differentiated as follows:

$$
\begin{aligned}
&\left[\left(\frac{1}{3}m_1+m+m_2+M\right)l_1^2+\left(\frac{1}{3}m_2+M\right)l_2^2+2\left(\frac{1}{2}m_2+M\right)l_1l_2\cos(2\theta_1+\pi/6)\right]\dddot{\theta}_1\\
&-4\left(\frac{1}{2}m_2+M\right)l_1l_2\left(2\sin(2\theta_1+\pi/6)\ddot{\theta}_1+\cos(2\theta_1+\pi/6)\dot{\theta}_1^2\right)\dot{\theta}_1+4C_2\ddot{\theta}_1\\
&-\left[\left(\frac{1}{2}m_1+2m+m_2+M\right)l_1\cos\theta_1-\left(\frac{1}{2}m_2+M\right)l_2\cos(\theta_1+\pi/6)\right]g\dot{\theta}_1\\
&=-\left[\left(\frac{1}{2}m_1+m+m_2+M\right)l_1\cos\theta_1+\left(\frac{1}{2}m_2+M\right)l_2\cos(\theta_1+\pi/6)\right]\dddot{X}\\
&+\left[\left(\frac{1}{2}m_1+m+m_2+M\right)l_1\sin\theta_1+\left(\frac{1}{2}m_2+M\right)l_2\sin(\theta_1+\pi/6)\right]\ddot{X}\dot{\theta}_1-\dot{D}_1
\end{aligned}
\tag{2}
$$

The derived equation reassembles the state equation, given by the following:

$$\dot{\boldsymbol{\theta}}=\mathbf{f}+\mathbf{B}u \tag{3}$$

Here, $\boldsymbol{\theta}=\{\theta_1 \quad \dot{\theta}_1 \quad \ddot{\theta}_1\}^{\mathrm{T}}$ is the state variable vector and $u=\dot{D}_1$ is the control input.

For applying the sliding mode control theory, the hyper-plane $s=0$ is selected as follows:

$$a_x-A_{xr}=0 \tag{4}$$

Here, a_x is the horizontal acceleration of the crib which is defined as follows:

$$a_x=\ddot{X}+\sqrt{l_1^2+l_2^2+\sqrt{3}l_1l_2}\left(\cos(\theta_1-\phi)\ddot{\theta}_1-\sin(\theta_1-\phi)\dot{\theta}_1^2\right) \tag{5a}$$

$$\phi=\arctan\left(\frac{l_2}{2l_1+\sqrt{3}l_2}\right) \tag{5b}$$

Then, the sliding mode control law can be obtained as follows [17]:

$$u=-\alpha F(\boldsymbol{\theta},\quad t)\frac{s^*}{\left|s^*+\delta\right|} \tag{6}$$

Here, the smooth function $s^*/|s^*+\delta|$ is used instead of the switching function $s^*/|s^*|$ to suppress the chatter of the control input. Additionally, $\alpha > 1$, $0 < |u_{eq}| < F(\boldsymbol{\theta},\ t)$, $s^* = (\mathbf{GB})^{\mathrm{T}} s$, $0 < \delta$, $\mathbf{G} = \partial s/\partial \boldsymbol{\theta}$, $u_{eq} = -(\mathbf{GB})^{-1}\mathbf{Gf}$ is the equivalent control input and $\det(\mathbf{GB}) \neq 0$. In this study, $\mathbf{G}$ is as follows:

$$\mathbf{G} = \sqrt{l_1^2 + l_2^2 + \sqrt{3} l_1 l_2}\left\{-\left(\sin(\theta_1-\phi)\ddot{\theta}_1 + \cos(\theta_1-\phi)\dot{\theta}_1^2\right) \quad -2\sin(\theta_1-\phi)\dot{\theta}_1 \quad \cos(\theta_1-\phi)\right\} \tag{7}$$

5. Numerical simulation

The effectiveness of the proposed control law was confirmed using numerical simulation. The parameters described in Section 2 were used in the simulation. Equation (1) was solved using the Runge-Kutta method. The sampling period of the control was set to 1 ms, and the sampling period of the Runge-Kutta method was set to 0.1 ms. In addition, the parameters in the control law of equation (6) were set to $\alpha = 25.0$ and $\delta = 0.01$ in this study, and D_1 was obtained by integrating $u = \dot{D}_1$, that is to say, $D_1 = D_1 + u \times 0.001\mathrm{s}$.

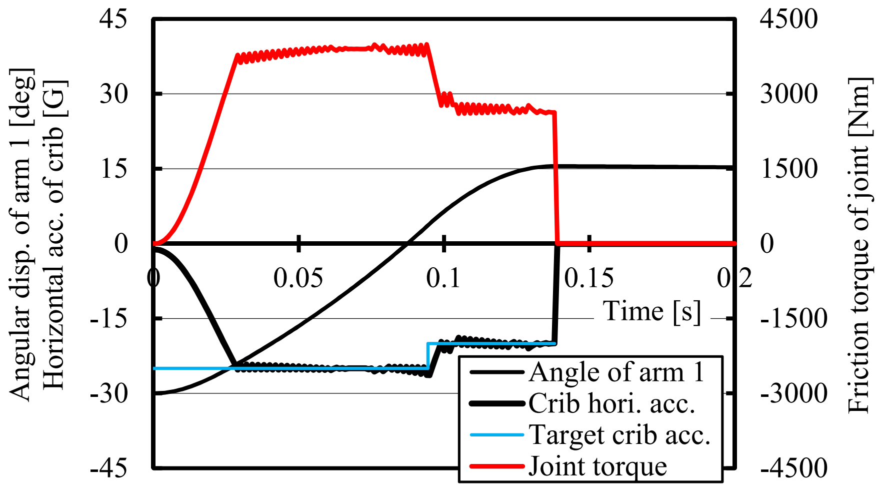

Figure 3. Simulation result with the application of acceleration feedback control.

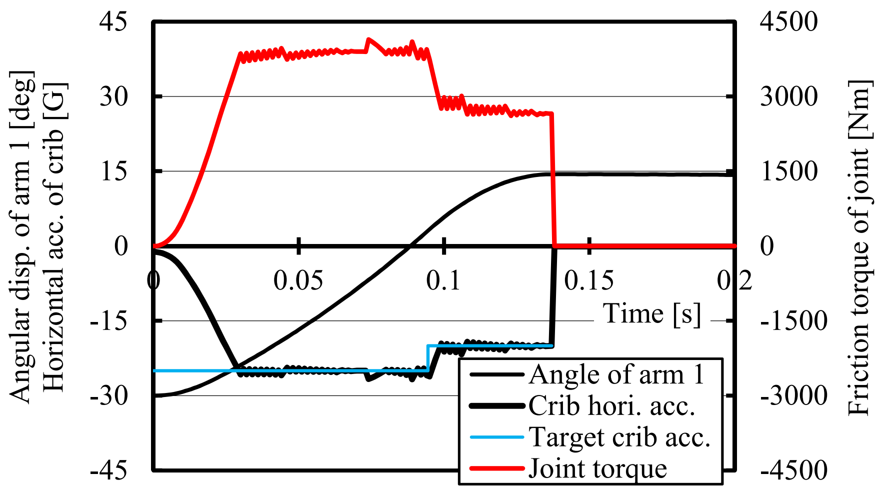

Figure 4. Simulation result with disturbance and with the application of acceleration feedback control.

A representative example of the simulation result is shown in Figure 3. The result in the case that disturbances were applied to confirm the robustness of control law is shown in Figure 4. The amplitude and frequency of the disturbances were 100 rad/s^2 and 100 Hz, respectively. The black solid line indicates the change in the angular displacement of arm 1, the black bold line indicates the change in the horizontal acceleration of the crib, the blue thin line indicates the target horizontal acceleration of the crib, and the red solid line indicates the friction torque of the joint between the base and arm 1 as the control input.

The figures show that the acceleration of the crib gradually decreased because the change of control input is limited to 250 Nm per sampling period of the control, and it was almost maintained at the target acceleration of -25 G during vehicle movement and was almost maintained at the target acceleration of -20 G after the vehicle comes to a halt, then it stepped up to almost zero at 0.138 s because the crib stopped. The crib acceleration varies if the friction torque of the joint is constant, and the crib collides to the seatback of the front seat if the torque is smaller. From Figure 4, the effect of disturbance was also almost canceled. Thus, the effectiveness of the feedback control was verified.

6. Model experiment

The effectiveness of the proposed control system was confirmed by a model experiment. Especially, the feasibility of the controller with the feedback of short sampling period of 1 ms in short collision time was verified.

6.1. Track for small scale crash testing facility

The track is a channel with 600 mm width, 130 mm depth, and 25 m length. Twenty-seven linear induction motors (LIM) with a maximum thrust of 588 N are installed at 0.9 m intervals. The speed of the carriage is controlled by changing the driving frequency of the LIM using two inverters. In this study, the carriage is decelerated by LIMs connected to the power supply in reverse instead of the concrete wall after it is accelerated in order to ensure the reproducibility of the deceleration. A photograph of the track is shown in Figure 5.

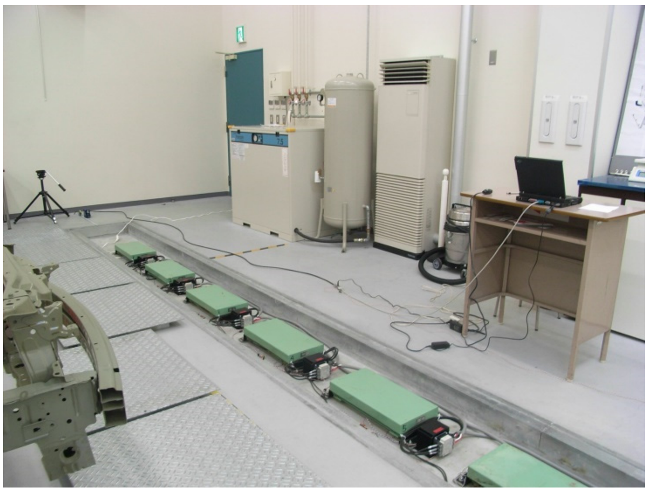

Figure 5. Small scale crash testing facility track.

6.2. Carriage for small scale crash testing facility

The lightweight carriage running on the track is fabricated using aluminum. An aluminum plate of 3 mm thickness, 350 mm width, and 900 mm length is installed under the same sized steel plate installed at the bottom of the carriage to be driven by the LIMs. The clearance between the aluminum plate and the upper surface of the LIMs is adjusted to about 4 mm. The area covering the LIMs becomes almost constant by making the length of the plate 900 mm, and a constant thrust is expected although the effect of the magnetic leakage at the edge of the LIMs remains. The carriage is installed with four rubber wheels for supporting the dead weight; the carriage is also installed with four small rubber wheels rotating on vertical shafts and contacting the wall of the channel in order to prevent weaving.

6.3. Experimental model of the in-car crib

A photograph of the experimental model of the in-car crib installed on the carriage is shown in Figure 6.

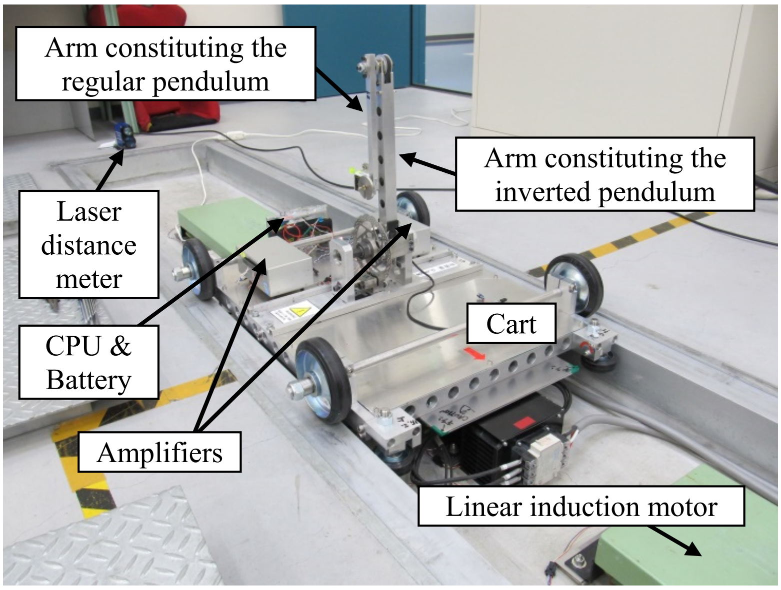

Figure 6. Experimental model of the in-car crib installed on the carriage.

Arm 1 is installed to resemble an inverted pendulum through the rotating joint on the carriage. The friction torque of the joint is controlled by a bicycle disk brake unit that uses two multilayer piezoelectric actuators (AE0505D16DF manufactured by NEC TOKIN Co.) arranged in series. The angular displacement is measured by a magnetic rotary encoder (JR205A2048CAF manufactured by TAIHO PRODUCT Co., Ltd.). Arm 2 is installed to resemble a regular pendulum with the upper end of arm 1 through a link mechanism. In this experimental model, arm 2 is always kept in the vertical position for simplicity. A weight is used as the crib model and a small wireless motion recorder (MVP-RF10 manufactured by MicroStone Co.) for sensing the horizontal acceleration of the crib model is installed at the lower end of arm 2. Two accelerometer modules (MMA7361) are also installed at the lower end of arm 2 and on the carriage for the feedback control. The control input is calculated by a micro-computer (Arduino Due) and the actuators are controlled via two piezo-drivers (M-2501 manufactured by MESS-TEK Co., Ltd.). The displacement of the carriage is measured using a laser distance meter (LDM301 manufactured by JENOPTIK). The angular displacement and the control input is transmitted to the computer set up on the floor by radio using digital wireless control units (WCU-C2543uDH manufactured by Keitsu Electric Co., Ltd.) in order to record the control results.

6.4. Model experiment

A car crash was simulated by decelerating the carriage by about 19 m/s^2. The accelerations were measured at 1 ms intervals and the friction torque of the joint between arm 1 and the carriage was controlled in 1 ms intervals. The angular displacement of arm 1 and the control input were also transmitted to the computer on the floor by radio at 1 ms intervals. The displacement of the carriage was measured at 10 ms intervals.

Journal of Physics: Conference Series **744** (2016) 012019 doi:10.1088/1742-6596/744/1/012019

A representative examples of the experimental result are shown in Figures 7 and 8. These results are not the same experiment but under the same conditions, because only two variables can be transmitted to the computer on the floor in this experimental facility. The red thin lines in both figures, black bold, blue solid lines in Figure 7, orange bold and green solid lines in Figure 8 indicate the change of the velocity of the carriage, the angular displacement of arm 1, the friction torque of the joint as the control input, the horizontal acceleration of the crib model, and the acceleration of the carriage, respectively. The blue solid line in Figure 8 indicates the target acceleration of the crib. The noise of acceleration signals were reduced by using the low-pass filter. The parameters in the sliding mode control law of equation (6) were set to $\alpha = 10.0$ and $\delta = 0.1$ in this experiment.

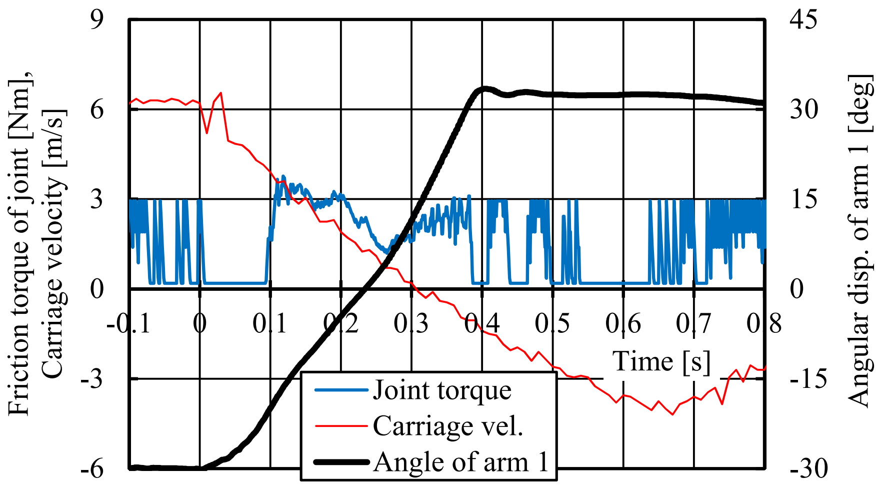

Figure 7. Experimental result in the case where the acceleration feedback control was applied (1).

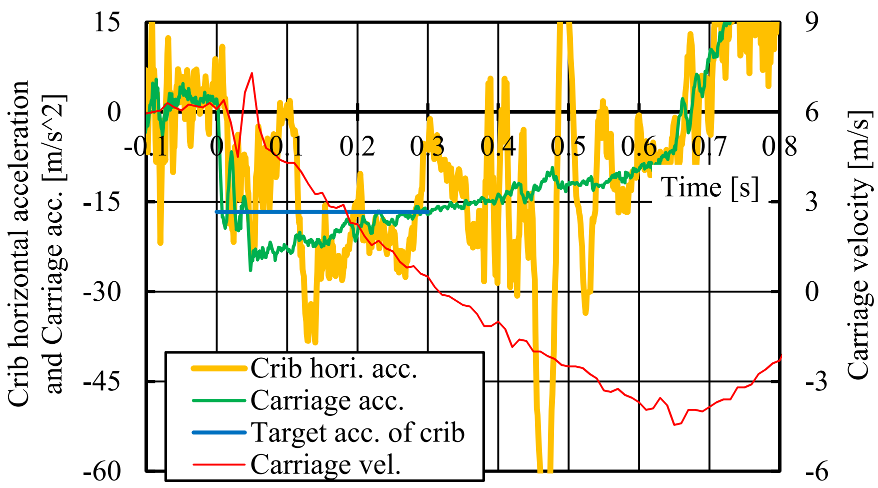

Figure 8. Experimental result in the case where the acceleration feedback control was applied (2).

The deceleration of the carriage gradually decreased, although it was assumed to be constant. The horizontal deceleration of the crib model until 0.11 s was lower than the target deceleration because of small friction torque of the joint in order to counter the difficulty in movement of the inverted arm initially tilted backward. Then it increased to the target acceleration with the increase of the friction torque and it kept at near the target acceleration from 0.11 s to 0.30 s, at which the carriage was stopped, although it fluctuated and the crib model deceleration exceeded the carriage deceleration occasionally.

The fluctuation was caused by the backlash of the link mechanism joining arm 2 with arm 1. The large change in the horizontal acceleration of the crib model around 0.47 s was caused by the collision of arm 1 with the stopper, after the carriage was stopped at 0.30 s and run in the reverse direction. The average horizontal deceleration of the crib model from 0 s to 0.30 s was 16.5 m/s^2 under the condition that the average deceleration of the carriage was 19.2 m/s^2, although the crib acceleration did not keep constant at the target acceleration of 16.7 m/s^2. That is to say, the average horizontal deceleration of the crib model was smaller than the average deceleration of the carriage and almost equal to the target deceleration until the carriage was stopped. In addition, the angular displacement of arm 1 was varied according to the friction torque of the joint. Then, the feasibility of the controller with the feedback of short sampling period of 1 ms in short collision time was verified. Therefore, it was confirmed that the proposed control system was effective.

For comparison, the experimental result without control is shown in Figure 9. The orange bold, green solid and black thin lines indicate the change of the horizontal acceleration of the crib model, the acceleration of the carriage and the angular displacement of arm 1, respectively. The horizontal deceleration of the crib model was almost smaller than the carriage deceleration during the crib movement because the arm 1 rotated fast for small friction torque of the joint. However, the arm 1 collided to the front stopper and the crib model deceleration became large suddenly before the carriage was stopped. Therefore, it was clarified that the control system was necessary and the target acceleration of the crib should be set in consideration of the moving distance of the crib in the cabin.

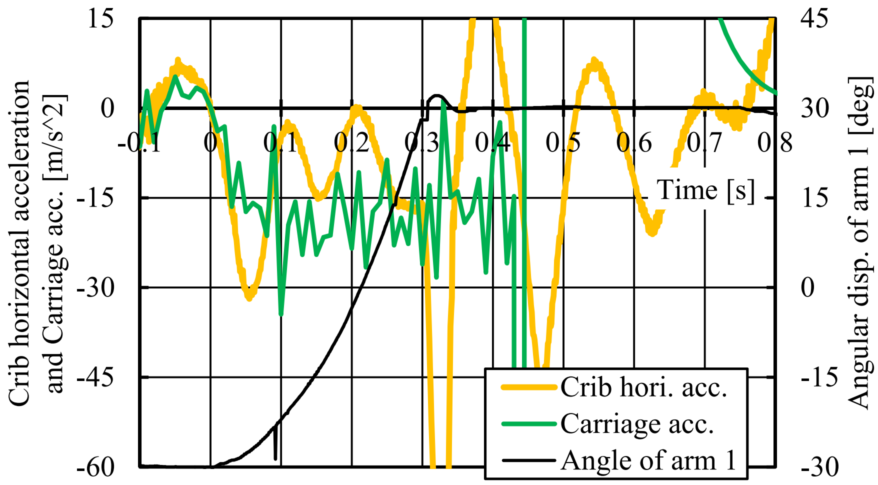

Figure 9. Experimental result in the case without control.

7. Conclusions

For the in-car crib with joint application of regular and inverted pendulum mechanisms, a semi-active acceleration control system, which could control the acceleration affecting the crib directly, was proposed using the sliding mode control theory. And, the numerical simulations and the model experiments were conducted in order to confirm the effectiveness of the proposed control system.

As the simulation result, the horizontal acceleration of the crib gradually decreased because the change of control input is limited, and it was almost maintained at the target acceleration during vehicle movement and was also almost maintained at the target acceleration after the vehicle came to a halt, then it stepped up to almost zero because the crib stopped. Therefore, the effectiveness of the proposed control system was clarified.

As the experiment result, the average horizontal acceleration of the crib model was smaller than the average acceleration of the carriage and almost equal to the target acceleration until the carriage was stopped, although the horizontal acceleration of the crib model fluctuated. In addition, the angular displacement of arm 1 was varied according to the friction torque of the joint. Therefore, the feasibility of the controller with the feedback of short sampling period of 1 ms was verified and the effectiveness of the proposed control system was confirmed.

Maintaining the horizontal acceleration of the crib at the target acceleration is a novel feature subject, achieved by improving the experimental model and the control law.

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

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