Experiment on a Semi-Active In-Car Crib with Joint Application of Regular and Inverted Pendulum Mechanisms Using Scale Model

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Abstract: To reduce the collision shock and risk of injury to an infant in an in-car crib (or in a child safety bed) during a car crash, it is necessary to limit the 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 crib is supported by arms similar to a pendulum, and the pendulum system itself is supported by arms similar to an inverted pendulum. In addition, the arm acting as a regular pendulum is joined with the arm acting as an inverted pendulum through a linking mechanism for simplicity, and the friction torque of the joint connecting the base and the latter arm is controlled using a brake mechanism, which enables the proposed in-car crib to gradually increase the deceleration of the crib and maintain it at 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 is made to act perpendicularly on the crib. The spin control system was developed in our previous work. The present work focuses on the acceleration control system. A semi-active control law with acceleration feedback is introduced using the sliding mode control theory. Especially, a feedback system of the crib acceleration relative to the vehicle is proposed for the high-vibrational environment. Further, a control experiment using scale model is conducted to confirm the effectiveness, and some results are reported.

Key words: shock control; occupant crash protection; passive safety device; child restraint system; impact relaxation

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Nomenclature

$A_r = -4.50\ m/s^2$ Desired crib horizontal acceleration relative to the base, or the reference input.

$C_2 = 0.00$ Nms/rad 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. This is the control input.

$l_1 = 0.385$ m Length of Arm 1.

$l_2 = 0.250$ m Length of Arm 2.

$M = 0.200$ kg Mass of the crib including the mass of the infant.

$m = 0.500$ kg Mass of the joint between Arms 1 and 2.

$m_1 = 0.450$ kg Mass of Arm 1.

$m_2 = 0.100$ kg Mass of Arm 2.

$\ddot{X} = 19.0\ m/s^2$ Acceleration of the vehicle, i. e. , acceleration of the base. This is assumed to be a constant.

$\ddot{x}_c$ Horizontal acceleration of the crib.

θ_1 Angular displacement of Arm 1.

$\theta_{10} = -\pi/6$ Initial angular displacement of Arm 1.

$\theta_{12} = -\pi/6$ Difference between angular displacements of Arms 1 and 2, that is, $\theta_{12} = \theta_1 - \theta_2$.

θ_2 Absolute angular displacement of Arm 2.

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0 Introduction

This study focuses on equipment used to ensure the safety of an infant in a car. To reduce the collision shock and injury risk to an infant in an in-car crib (or a child safety bed) during a car crash, it is necessary to limit the force acting on the crib to below a certain allowable value. That is to say, the impact force affecting the infant within a short period of time is changed to a smaller force that affects the infant for a longer period of time by moving the crib forward. However, the cabin space of a vehicle is limited. Therefore, the force must be maintained at a constant level. To realize this objective, we propose a semi-active in-car crib with a joint application of regular and inverted pendulum mechanisms, as shown in Fig. 1. The crib is supported by Arm 2, which acts like a pendulum, and the pendulum system itself is supported by Arm 1, which acts like an inverted pendulum. Arm 2 rotates at a difference of 30° with Arm 1 using a simple linking mechanism. In addition, the friction torque of the joint connecting the base and Arm 1 is controlled using a braking mechanism. Therefore, the proposed in-car crib is able to gradually increase the deceleration of the crib and maintain it at around the target value. In addition, our proposed system is able to save energy using a semi-active control system, which is a significant advantage for a vehicle with a limited amount of power.

In this project, an in-car crib, which is a bed-type child-seat, is applied because the risk of

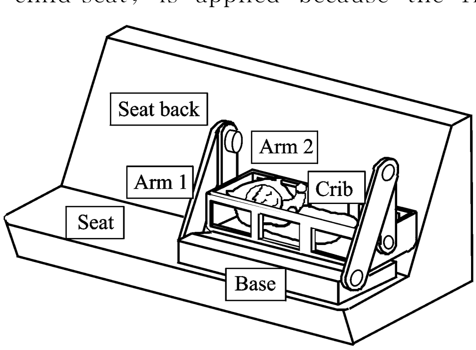


Fig. 1 Conceptual diagram of the in-car crib with a joint application of regular and inverted pendulum mechanisms

brain damage (encephalopathy) from a decrease in arterial oxygen saturation can be reduced. In particular, abdominal compression can be avoided, which is not the case when achild car seat is used. In addition, it can also be used for neonatal infants.

However, with an in-car crib, a collision impact is directed toward the infant's side, and the resulting motion of the body is relatively complex. For this reason, the use of a spin control system was proposed for the crib, allowing the impact to fall on the infant's back, i. e. , the force acts perpendicularly on the crib. The author developed this control technique as an actively controlled regular pendulum-type bed for use in-ambulances[1]. The present study therefore focuses on the development of a crib movement system.

Many different pendulum mechanisms have been proposed for crib movement systems. In a patented design by Sawaishi[2], a child car seat is described as a rotating seat, similar to a pendulum, which is 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 moving the seat. However, this deceleration cannot be reduced further after the pendulum has rotated[3]. Therefore, regular pendulum-type in-car cribs are unsuitable when large impulsive forces are involved. In our proposed in-car crib, the deceleration of the crib can be maintained at almost a constant level during a collision, which is one of the main advantages of the proposed system. A child car seat that is rotated using electromagnets installed on the seat and base to reduce the impact forces and redirect the force toward the child's hip has been registered as a utility model by Tamura[4]. In addition, a patent for a child car seat that is rotated to a safe position before a collision using predictive information of a vehicle crash to reduce harm to the baby was developed by Ono et al[5]. With these two systems, the child car seat is moved by an actuator using power during or before a collision. In our proposed system, the rotation of the arms supporting the crib is controlled semi-actively using a 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 a limited amount of power.

An inverted pendulum-type active in-car crib was previously proposed to reduce the impulsive force acting on the crib to an allowable level during crib movement in a car crash. This crib is supported by an arm, which also acts like an inverted pendulum. In a vehicle cabin, the space for the crib movement is limited. To minimize the impulsive force in such a restricted space, the force acting on the crib must be maintained at a constant level, 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 deceleration of the crib can be maintained at less than the vehicle deceleration until the arm reaches an upright position. In addition, a semi-active shock control system is applied to maintain the deceleration at a constant level. Although this system is effective during a car crash with strong impulsive forces, it is not effective during a car crash with weak forces because the crib does not move[3].

To combine the advantages of a regular pendulum-type in-car crib and an inverted pendulum-type in-car crib, we propose an in-car crib that involves the joint application of both regular and inverted pendulum mechanisms. In this system, the deceleration of the crib increases gradually, and is maintained at below the vehicle deceleration, thereby resulting in a system with advantages of both a regular pendulum mechanism and an inverted pendulum mechanism[3].

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 acting as an inverted pendulum. We confirmed the effectiveness of the system using numerical simulations. The results indicate that the deceleration of the crib increases gradually and is maintained at around the target value of $26g$ when the deceleration of the base fixed on the vehicle seat is $30g$. Subsequently, we developed a control algorithm that adjusts the friction torque of the joint connecting the base and the arm acting as an inverted pendulum. We also confirmed the effectiveness of the modified system through numerical simulations. The results indicate that the deceleration of the crib increases gradually and is maintained at around the target value of $25g$ when the deceleration of the base fixed on the vehicle seat is $30g$[3]. We then developed a control algorithm that adjusts the friction torque of the joint connecting the base and the arm acting as an inverted pendulum, as well as the joint connecting this arm and the arm acting as a regular pendulum. We again confirmed the effectiveness of the modified system through numerical simulations. The results indicate that the deceleration of the crib increases gradually and is maintained at around the target value of $25g$ when the deceleration of the base fixed on the vehicle seat is $30g$. The robustness of the proposed control system was also examined based on numerical simulations[6].

On the other hand, we derived a semi-active acceleration control law for controlling the acceleration of the crib directly, but it is not required for the generation of the arm trajectory. The semi-active control system was built using a dynamic equation for the jerking of the crib. The effectiveness was confirmed using software for a multibody dynamics simulation[7].

For this work, a semi-active control law was proposed for controlling the crib horizontal acceleration relative to the vehicle. Further, the effectiveness was investigated by model examination, and some of the results are reported.

In our systems, Arm 1, which is tilted backward and acts as an inverted pendulum, is supported by a stopper. The controlled joints are set for a large damping under normal conditions for a comfortable ride. Moreover, a forward stopper is also installed for safety. In addition, the controlled joints were designed to exhibit a large friction torque as a fail-safe in case of a breakdown of the control system.

For the impact control system, Balandin et al. proposed a method calculating the seatbelt tension required to maintain an acceleration of the thorax, a deformation of the thorax, and the migration length of the occupant in the cabin within the tolerance limits during a car crash for a nonlinear human-vehicle system[8]. To add to the occupant safety of a modern vehicle, a crushable zone is designed for the vehicle body, and seatbelts and air bags are installed in the cabin. In addition, the use of a child-seat is obligatory when an infant is present. However, these are passive or open-loop type systems, and do not always perform as expected owing to certain types of disturbances. Therefore, an impact control system that provides feedback regarding the condition of the crib is required to obtain a definitive result. In terms of active impact control, Wang et al. investigated an optimal control system, an H infinity control system[9], a system using feed-forward input[10], and a gain-scheduled control system[11]. In addition, an active knee bolster applying an impact control method for protecting the occupants from injury has been developed[12].

A semi-active impact control system, in which the actuator can be miniaturized and the power consumption can be reduced, has also been studied by the author[13]. The system utilizes an actuator for semi-active control using a braking mechanism. In addition, an active seatbelt that uses a semi-active actuator was proposed, and its effectiveness was confirmed experimentally using a model[14]. Narukawa et al. studied a knee bolster applied for semi-active impact control[15].

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

1 Semi-active Control Law

First, a semi-active control law for controlling the crib horizontal acceleration relative to the base (or the vehicle or the carriage in the model experiment) is derived using the sliding mode control theory.

1.1 Analytical model

To develop the control law, an analytical model is derived, which is shown in Fig. 2. The crib and joint are assumed to be a single mass particle. In this study, Arm 2 rotates at a difference of 30° from Arm 1, that is, $\theta_{12}=\theta_1-\theta_2$. In addition, the torque of the joint connecting Arm 1 to the base, $-D_1$, is only controlled using a brake mechanism. And the deceleration of the vehicle, that is, of the base is assumed to be constant because of the crushable zone installed on the vehicle body.

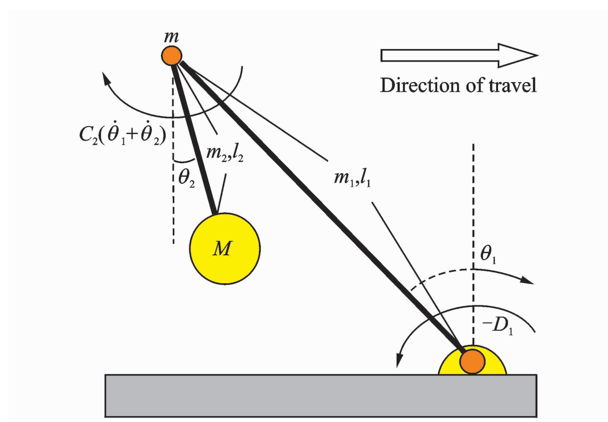


Fig. 2 Analytical model of the proposed in-car crib with joint application of regular and inverted pendulum mechanisms

1.2 Semi-active sliding mode control law

The equation of motion for the model shown in Fig. 2 is derived first for applying the sliding mode control theory. Then, it is differentiated to derive the control law with acceleration feedback as follows

$$\left[\left(\frac{m_1}{3}+m+m_2+M\right)l_1^2+\left(\frac{m_2}{3}+M\right)l_2^2+2\left(\frac{m_2}{2}+M\right)l_1\ l_2\cos(2\theta_1-\theta_{12})\right]\dddot{\theta}_1-4\left(\frac{m_2}{2}+M\right)l_1\ l_2\left[2\sin(2\theta_1-\theta_{12})\ddot{\theta}_1+\cos(2\theta_1-\theta_{12})\dot{\theta}_1^{\,2}\right]\dot{\theta}_1+4C_2\ddot{\theta}_1-\left[\left(\frac{m_1}{2}+m+m_2+M\right)l_1\cos(\theta_1)-\right.$$

$$\left(\frac{m_2}{2}+M\right) l_2\cos\left(\theta_1-\theta_{12}\right)\Big] g\dot{\theta}_1 =$$

$$\Big[\left(\frac{m_1}{2}+m+m_2+M\right) l_1\sin(\theta_1)+$$

$$\left(\frac{m_2}{2}+M\right) l_2\sin(\theta_1-\theta_{12})\Big]\ddot{X}\dot{\theta}_1+\dot{D}_1 \qquad (1)$$

The state equation is then arranged from this equation as follows

$$\{\dot{\theta}\}=\{f\}+\{B\}\dot{D}_1 \qquad (2)$$

where $\{\theta\} = \{\theta_1 \quad \dot{\theta}_1 \quad \ddot{\theta}_1\}^{\mathrm{T}}$ is the state variable vector, $f_1=\dot{\theta}_1$, $f_2=\ddot{\theta}_1$,
$f_3=\{[(m_1/2+m+m_2+M)l_1\sin(\theta_1)+(m_2/2+M)l_2\sin(\theta_1-\theta_{12})]\ddot{X}\dot{\theta}_1-4C_2\ddot{\theta}_1+4(m_2/2+M)l_1\ l_2[2\sin(2\theta_1-\theta_{12})\ddot{\theta}_1+\cos(2\theta_1-\theta_{12})\dot{\theta}_1{}^2]\dot{\theta}_1+[(m_1/2+m+m_2+M)l_1\cos(\theta_1)-(m_2/2+M)l_2\cos(\theta_1-\theta_{12})]g\dot{\theta}_1\}/\bar{M}$, $B_1=B_2=0$, $B_3=1/\bar{M}$, and
$\bar{M}=(m_1/3+m+m_2+M)l_1^2+(m_2/3+M)l_2^2+2(m_2/2+M)l_1\ l_2\cos(2\theta_1-\theta_{12})$.

The hyper-plane for the sliding mode control is selected to control the crib horizontal acceleration relative to the base directly as follows

$$s=(\ddot{x}_C-\ddot{X})-A_{\mathrm{r}}=$$

$$\sqrt{l_1^2+l_2^2+2\,l_1\ l_2\cos(\theta_{12})}\,[\cos(\theta_1-\phi)\ddot{\theta}_1-$$

$$\sin(\theta_1-\phi)\dot{\theta}_1^2]-A_{\mathrm{r}} \qquad (3)$$

where $\phi=\arctan[l_2\sin(\theta_{12})/(l_1+l_2\cos(\theta_{12}))]$.

The semi-active sliding mode control law is obtained as follows[16]

$$\dot{u}=-\alpha F(\{\theta\} \quad t)\frac{s^*}{|s^*|+\delta},\ u=\int\dot{u}\mathrm{d}t$$

$$\text{if } \dot{\theta}_1\cdot u<0,\ \text{then } D_1=u,\ \text{else } D_1=0 \qquad (4)$$

Here, a smooth function is used instead of a sign function (the signum function) to suppress the chatter of the control input. Additionally, $1<\alpha$, $0<|u_{\mathrm{eq}}|<F(\{\theta\} \quad t)$, $u_{\mathrm{eq}}=-(\{G\}\{B\})^{-1}\{G\}\{f\}$, $\{G\}=\partial s/\partial\{\theta\}$, $\det(\{G\}\{B\})\neq 0$, $s^*=(\{G\}\{B\})^{\mathrm{T}}s$ and $0<\delta$. Each element of $\{G\}$ is

$$G_1=-\sqrt{l_1^2+l_2^2+2\,l_1\ l_2\cos(\theta_{12})}\,[\cos(\theta_1-\phi)\ddot{\theta}_1-\sin(\theta_1-\phi)\dot{\theta}_1^2],$$

$$G_2=-\sqrt{l_1^2+l_2^2+2\,l_1\ l_2\cos(\theta_{12})}\,\sin(\theta_1-\phi)\cdot 2\dot{\theta}_1,$$

$$G_3=\sqrt{l_1^2+l_2^2+2\,l_1\ l_2\cos(\theta_{12})}\,\cos(\theta_1-\phi).$$

The effectiveness of the controller was confirmed by the numerical simulations conducted using the real-size model shown in Fig. 3. Fig. 4 shows the simulation result with a sinusoidal disturbance, with an amplitude of 1.00g and a frequency of 120 Hz, added to the vehicle deceleration for 0.1 s. Figs. 4(a—e) indicate the changes in vehicle acceleration, torque of joint, which is the control input, angular displacement of Arm 1, the horizontal in-car crib acceleration, and relative horizontal in-car crib acceleration, respectively.

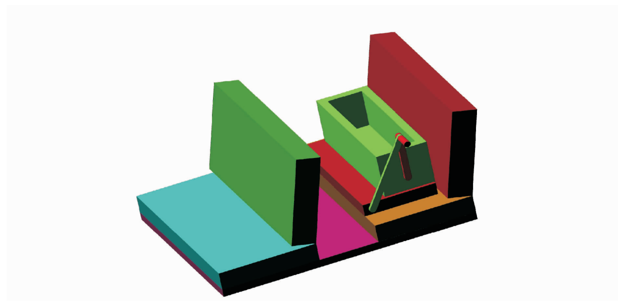


Fig. 3 Simulation model (Adams, MSC Software)

It is confirmed that the relative crib acceleration is insensitive to the high frequency disturbance, although the absolute crib acceleration is disturbed. Therefore, stable control is expected by the proposed control law.

2 Experiment

The performance of the proposed control system was confirmed by a model experiment. In particular, the effectiveness of the controller with feedback from a short sampling period of 1 ms during a short collision time was verified.

2.1 Track for small scale crash testing facility

The track is a channel with the dimensions of 600 mm in width, 130 mm in depth, and 25 m in 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. Here, the carriage is decelerated by LIMs connected to the power supply in reverse instead of the concrete wall after it is accelerated for ensuring the reproducibility of the deceleration. A photograph of the track is shown in Fig. 5.

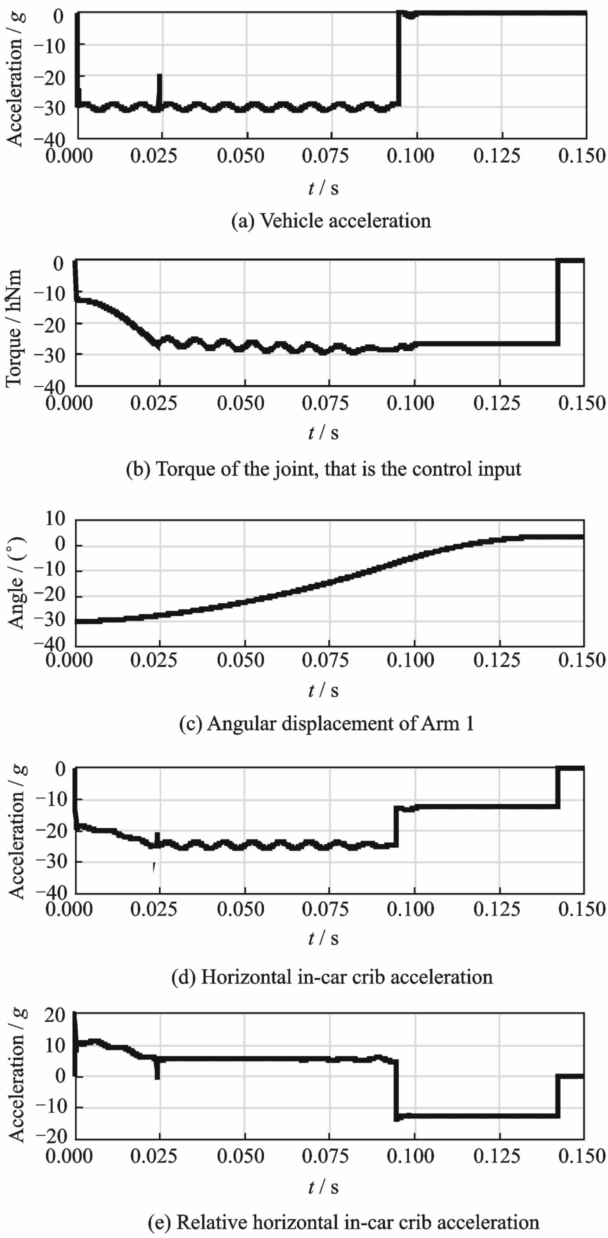


Fig. 4 Simulation results with the proposed control and disturbance

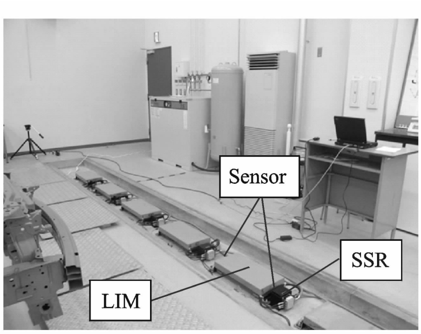


Fig. 5 Track of the small-scale crash testing facility

2.2 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.

When an infrared ray distance measuring sensor, installed in front of and behind the LIM, detects the carriage, a solid-state relay (SSR) is switched on and electric power is supplied to the LIM. The carriage is then driven.

A representative example of the experiment results of the carriage running test is shown in Fig. 6. Figs. 6(a,b) indicate the changes in carriage velocity and acceleration, respectively. From these figures, it was confirmed that the carriage with a weight of 30 kg was decelerated at −19 m/s^2 from the velocity of 6.5 m/s after it was accelerated by this system. The carriage was decelera-

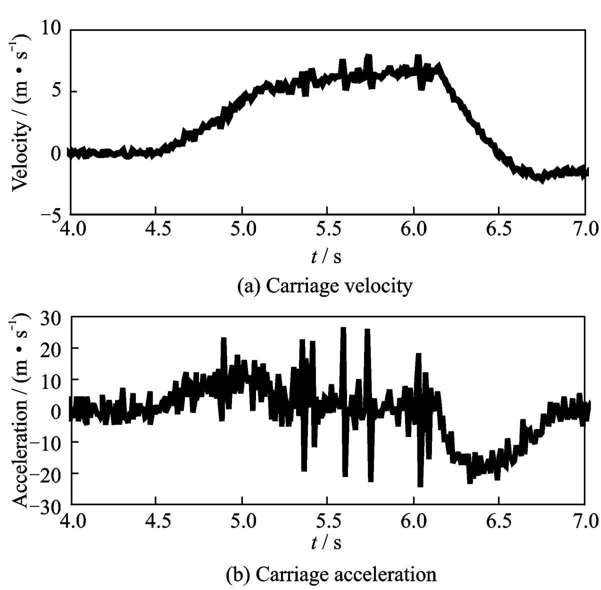


Fig. 6 Representative results of the carriage running test

ted immediately after it was accelerated to prevent large vibration of the carriage. Also, a little delay occurred in the acceleration result for the strong low-pass filter for smoothing sets of data.

2.3 Experimental scale model of the in-car crib

A photograph of the experimental model of the in-car crib installed on the carriage is shown in Fig. 7. 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.) for the feedback control. Arm 2 is installed to resemble a regular pendulum with the upper end of Arm 1 through a link mechanism to keep the phase constant for the simplicity of control and to reduce the moving distance of the crib. 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. An accelerometer module (MMA7361) is also installed on the carriage. The control input is calculated by a micro-computer (Arduino Due) and the actuators are controlled by two piezo-drivers (M-2501 manufactured by MESS-TEK Co., Ltd.). The displacement of the carriage is measured using a laser distance meter

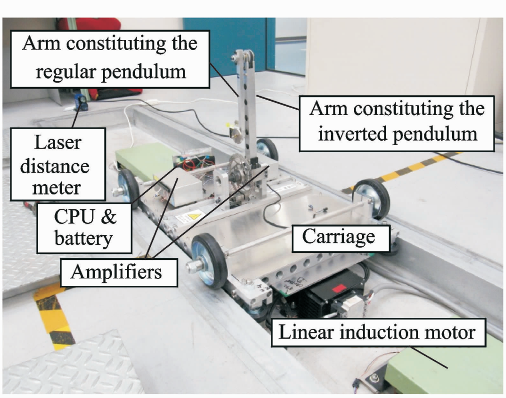


Fig. 7 Experimental scale model of the in-car crib with joint application of regular and inverted pendulum mechanisms installed on the carriage

(LDM301 manufactured by JENOPTIK). The angular displacement and the control input are transmitted to the computer by radio using digital wireless control units (WCU-C2543uDH manufactured by Keitsu Electric Co., Ltd.) in order to record the control results.

2.4 Model experiment

A car crash was simulated by decelerating the carriage at $-19\ m/s^2$. The state variables were measured in 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 by radio in 1 ms intervals. The displacement of the carriage was measured in 10 ms intervals by the laser distance meter.

2.4.1 Experimental result for the fixed in-car crib case

An example of the experimental result for the fixed in-car crib case is shown in Fig. 8. The joint connecting Arm 1 and the base was fixed by the maximum friction torque. Figs. 8(a—d) indicate the changes in carriage (cart) velocity, angular displacement of Arm 1, carriage acceleration and horizontal in-car crib acceleration, respectively.

It is confirmed that Arm 1 remained at rest from Fig. 8(b), and it follows that the changes in carriage acceleration and crib acceleration are almost same from Figs. 8(c,d), although the crib acceleration oscillated due to the backlash of the joints.

2.4.2 Experimental result for the in-car crib moving almost freely case

An example of the experimental result for the in-car crib moving almost freely case is shown in Figs. 9(a—d). The minimum friction torque acted on the joint connecting Arm 1 and the base.

From Fig. 9(b), Arm 1 was moving to the front stopper and collided with it. From Fig. 9(d), it is confirmed that the crib deceleration can be reduced to approximately $10\ m/s^2$ while the crib is moving, although the large deceleration

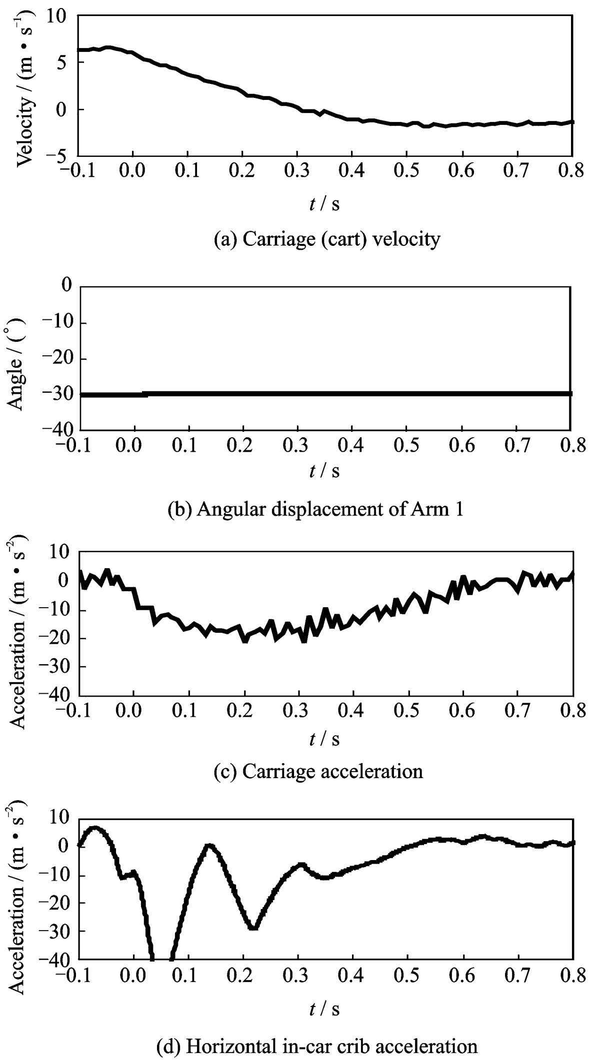


Fig. 8 Experimental results for the fixed crib case

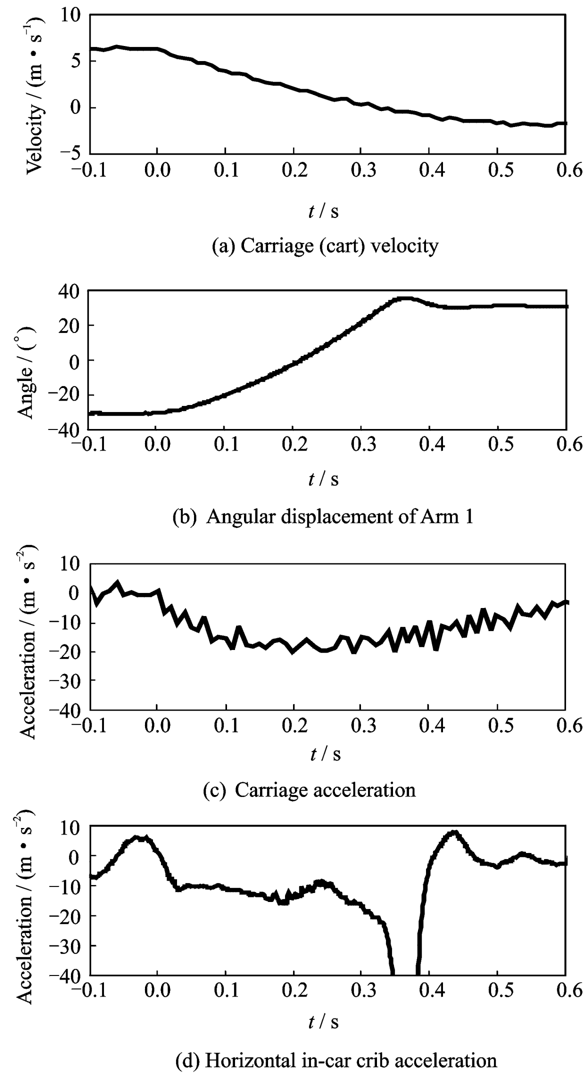


Fig. 9 Experimental results for the in-car crib moving almost freely case

occurred during the collision with the front stopper.

2.4.3 Experimental result with semi-active control

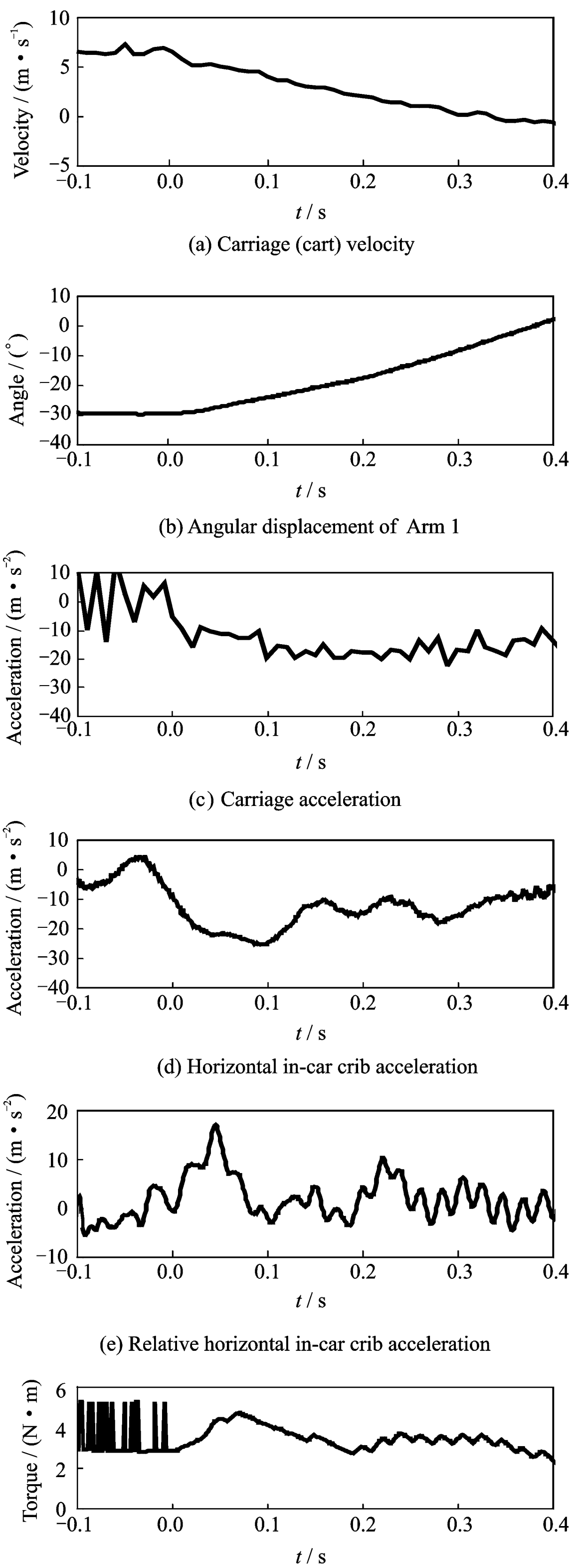
A representative example of the experimental results with the proposed semi-active control is shown in Fig. 10. Figs. 10(e,f) indicate the changes in the crib horizontal acceleration relative to the base, and control input, respectively.

The parameters in the sliding mode control law of Eq. (4) were set to $\alpha=8$ and $\delta=0.01$ in this experiment, and the reference input was set to $A_r=-4.50$ m/s^2.

The changes in carriage velocity and crib horizontal acceleration, for the three cases, are summarized in Figs. 11(a,b), respectively. The thin, solid, and thick lines indicate the experimental results for the case of the fixed crib (joint fixed), the crib moving almost freely (joint torque released), and the crib controlled (joint torque controlled), respectively.

From Fig. 11(a), it is clarified that the reproducibility of the carriage deceleration is ensured.

From Fig. 10(e), it is clarified that the relative acceleration of the crib is mainly a positive value, this means that the crib acceleration can be reduced, although it did fluctuate, and from Fig. 11(b), the oscillation of crib acceleration for the crib controlled case is suppressed as compared with the acceleration for the fixed crib case and a collision with the front stopper is avoided as compared with the result for the crib moving case.



(a) Carriage (cart) velocity

(b) Angular displacement of Arm 1

(c) Carriage acceleration

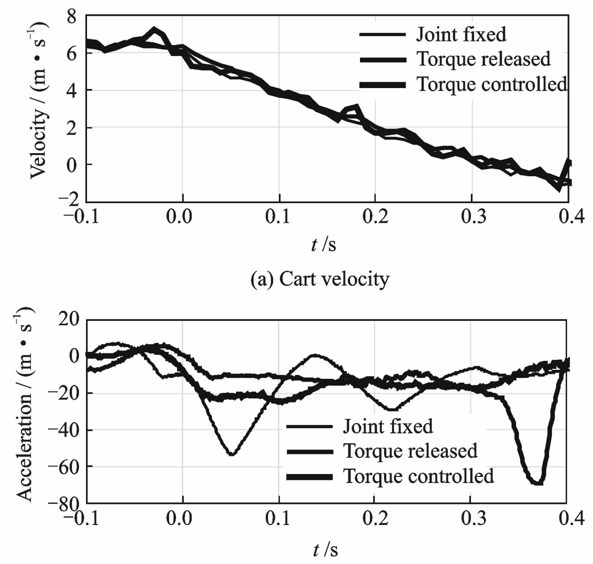
(d) Horizontal in-car crib acceleration

(e) Relative horizontal in-car crib acceleration

(f) Torque of the joint, that is the control input

Fig. 10 Experimental results for the case where acceleration feedback control was applied

Therefore, it is concluded that crib deceleration can be reduced by the proposed control system. The average of the crib horizontal acceleration relative to the base until 0.3 s, when the carriage velocity becomes zero, is −3.42 m/s^2. The average acceleration of the carriage until 0.3 s, measured by the laser distance meter, is −22.3 m/s^2 and the average horizontal acceleration of the in-car crib, measured by the small wireless motion recorder, is −16.8 m/s^2. From these average values, it is also confirmed that the crib horizontal acceleration can be reduced from the carriage acceleration, then the proposed control system, with feedback from a short sampling period of 1 ms, is effective, although the relative crib acceleration did not reach the target value.



(a) Cart velocity

(b) Crib horizontal acceleration

Fig. 11 Experimental results summarized for the three cases

3 Conclusions

For the in-car crib with joint application of regular and inverted pendulum mechanisms, a semi-active relative acceleration control system, which could control the horizontal in-car crib acceleration relative to the base directly, was developed using the sliding mode control theory. Further, a model experiment was conducted to confirm the effectiveness of the proposed control system with feedback from a short sampling period of 1 ms. The results indicated that the crib acceleration can be reduced without a collision with the front stopper, and the effectiveness is confirmed.

Furthermore, future challenges are: improvement of the experimental scale model to keep the crib deceleration constant, the refinement of the sensing and control system, and an experiment that confirms the effectiveness of the system after the carriage stops following a collision between the carriage with a wall, using an impact attenuator.

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