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Vehicle Occupant's Protection in Front- and Rear-end Collisions Using Sliding Mode Control

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Abstract

The United Nations Global Status Report on Road Safety (WHO 2015), reflecting information from 180 countries, indicates that the worldwide total number of road traffic deaths has plateaued at 1.25 million per year. Although there has been progress toward improving road safety legislation and in making vehicles safer, the report shows that the pace of change is too slow. Urgent action is needed to achieve the ambitious target for road safety reflected in the newly adopted 2030 Agenda for Sustainable Development: halving the global number of deaths and injuries from road traffic crashes by 2020. Therefore, much effort is needed in the area of active and passive safety research development of ground vehicles. The current research presents the sliding mode control of vehicle occupant-seat frame on front- and rear-end collisions. To reduce the injury level of the occupants' head and chest as well as safety belt force and neck torque, a nonlinear occupant model is derived and used to develop a sliding mode control algorithm that supplements other safety restraint systems. Simulation results for various crash conditions are compared to conventional restraint systems with and without safety belt force limiter for the nonlinear occupant's model. The study shows that the chest and neck injury criteria in front- and rear-end collisions are significantly reduced by controlling the occupant's seat system via sliding surface control.

Keywords: Human Safety, Vehicle Crash, Active Safety, Active Control, Sliding Mode Control

1. Introduction

In modern vehicle design, the three-point seat belt represents the primary defense of occupant protection upon front-end collisions. As a second occupant protection defense system, other supplementary restraint systems, mainly including airbags and, in some vehicle models, head seat rest active safety, come into action [1]. Injuries differ from accident to accident and from occupant to occupant, therefore severity of injuries can be reduced if the restraint system responds according to the crash condition and passenger characteristics. Smart or adaptive restraint systems react according to the crash and occupant's condition, using real time control with feedback sensors [1].

Recently, number of research studies considered adaptive restraint system, where the system responds in real time according to the crash and passengers' condition. The main objective of this system is to increase the effectiveness of the restraint system and to reduce possible occupant injury level, especially when occupant and crash uncertainties exist. Some elements of adaptive restraint systems have been implemented commercially and some are still being under investigation. Dual stage restraint systems have been designed and implemented on the road. Airbag volume and seat belt load limiter respond according to crash severity and occupant condition. Several research studies discussed the best design for restraint system elements in order to achieve enhanced protection. As an example of the current safety technology, BMW introduced Impact Depending (ID) airbags in their vehicles in order to increase the efficiency of occupant protection. Before airbag inflation, the system differentiates between severe and simple crashes. If the crash is severe the system responds with its maximum capacity to ensure occupant protection. In addition, it detects whether or not the seat is occupied using Seat Occupancy Detector and checks whether the occupant is out of the normal seating position (is he/she too close to the air bag?) [2]. However, dual-stage restraint systems show limited protection to occupants since it does not respond continuously during a crash. In the last decade, several researchers considered the control of seat belt force. Using control algorithms, control restraint force is applied to enhance occupant protection. The control restraint force depends on occupant and crash characteristics. Optimal seat belt force is designed to increase the restraint system effectiveness [3]. Seat belt force is proposed to be controlled continuously based on chest injury criteria. The proposed controller is applied on passenger thorax clinical model [4], and the current applied force is fed back to the system. $H\infty$ controller is also designed for robust control of seat belt limiting force. Chest deflection is considered as the reference control signal[5]. The controller was designed based on a simplified linear model, and it was applied on MADYMO occupant model. Extended model predictive controller is designed based on low-order occupant model [6]. Biomechanical responses such as chest acceleration and chest deflection are estimated via state observer and are fed back to the controller [7]. Only thoracic response is considered in this work. Some researchers have considered controlling more than one element in restraint systems. In [8], both the seat belt force and airbag pressure are controlled to reduce injury level during frontal crashes. The command reference signals are taken to be the tolerant values (injury criteria) for chest and head accelerations, aiming to keep the injury level as low as possible.

Bio-medically, adaptive seat belt shows an increasing level of occupant protection during different impact scenarios[9]. The applied force on the occupant's chest has to be limited (between 3-8 KN) in order to avoid the risk of irreversible thoracic injuries. Thus, force limiter, which has been implemented for about two decades, is used to ensure a limited amount of seat belt human tolerant force. However, during severe crashes, the limited seat belt force might not be sufficient to fully protect the passengers. Therefore, the idea of supplementary force, which is applied on the seat frame, was introduced in [10]. The applied force works simultaneously with the seat belt to ensure a maximum level of protection with a minimum seat belt force. Furthermore, the introduced method aims to decrease occupant injury level of the chest and head. In [11], active control of supplementary seat force is designed and tested with limited seat belt force. Closed loop controller is designed based on three degrees of freedom occupant model and a quadratic optimal feedback control. Results show the validity of this concept to reduce occupant injuries' criteria during frontal and rear crashes. However, Habib [12] has not taken into consideration the uncertainty and errors in the occupant modeling parameters as well as disturbances such as passengers of different sizes and positions in various vehicle crash situations. Therefore, a robust control method is presented in [13] to control the occupant during 60 KPH frontal crash test.

In this paper, a sliding surface controller is developed to actively control the seat force during frontal and rear 30MPH crashes. The controller is designed based on three-degrees of freedom nonlinear occupant model [13]. Simulation results of the proposed algorithm are compared with conventional limited and unlimited seat belt force. The comparisons illustrate the efficiency of the present approach in significantly reducing chest and head accelerations in both crash scenarios frontal and rear.

2. Mathematical Model

A mathematical model is derived to describe the main occupant characteristics. The developed model has to be less complex for control purposes. In literature, advanced models are available to fully describe the occupant biomechanical response and its interaction with vehicle interiors. These models are too complex for control [12]. There are attempts to develop simplified occupant models to be used in developing control algorithms [6]. The derived model in [5] contains 14 degrees of freedom which makes it difficult to be used in nonlinear controller design. In [13], a simplified occupant model is derived to describe the main biomedical characteristics: chest and head responses. The derived model considers the nonlinearities with three degrees of freedom. Figure 1 shows the three degrees of freedom occupant model: the lower body, the upper body and the head. The lower body consists of the pelvis and lower limbs. The lower body is assumed to be attached with the seat as one body via lap belt. Their total mass is m_1. The upper body represents the chest response and it contains thorax, abdomen and upper limbs. It has total mass of m_2 and moment of inertia I_1. The upper body makes angle θ_1 with the vertical axis. θ_2 represents the angle between the head and vertical axis. The head has total mass of m_3 and moment of inertia I_2. The lower body is connected with the upper body via lumbar vertebra modeled as torsional spring-damper joint (k_2, b_2).

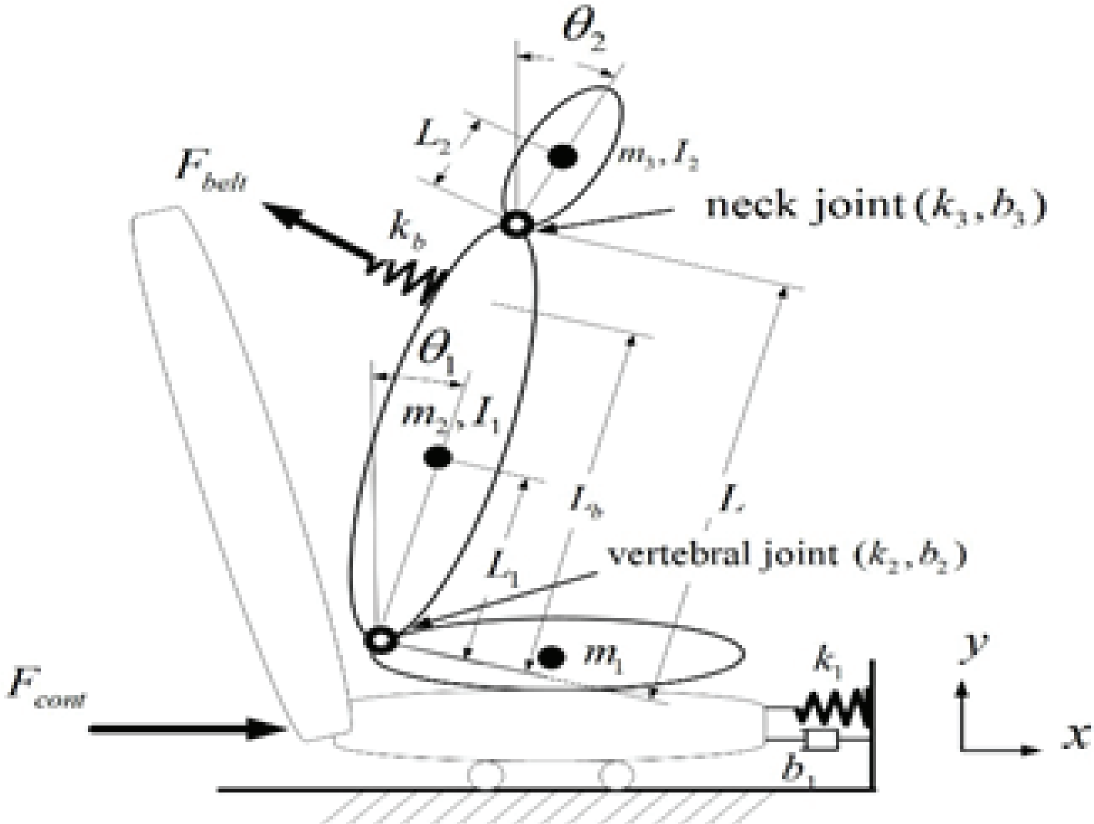

Figure 1: Occupant Model Parameters.

The upper body is connected with the head via the neck modeled as torsional spring-damper joint (k_3, b_3). L_1 represent the distance between vertebral joint and the center of mass m_2. L represents the total distance between vertebral joint and the neck. L_2 is the distance from the neck joint to the head center of mass. The belt force F_{belt} is represented as spring-like force with stiffness K_b, and it is applied at (L_b) which is measured from the vertebral joint. F_{cont} is the applied control force on the seat frame. Once the impact takes place, the seat frame will be attached with the vehicle structure via spring k_1 and damper b_1[9, 10]. The occupant nonlinear model is derived considering the three degrees of freedom: seat and lower body linear position x, upper body angular position θ_1 and head angular position θ_2. The detailed model derivation could be found in [13]. Using Lagrange's equation, the occupant model is described using three second order differential equations which could be resented in the following matrix form

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \tau \tag{1}$$

Where q, $\dot{q}$ and $\ddot{q}$ are the state position, velocity and acceleration vectors, respectively. $q = \begin{bmatrix} \theta_2 & \theta_2 & x \end{bmatrix}^T$, $\dot{q} = \begin{bmatrix} \dot{\theta}_2 & \dot{\theta}_1 & \dot{x} \end{bmatrix}^T$, and $\ddot{q} = \begin{bmatrix} \ddot{\theta}_2 & \ddot{\theta}_1 & \ddot{x} \end{bmatrix}^T$ and the input vector τ is

$$\tau = \begin{bmatrix} 0 & 0 & F_{cont} \end{bmatrix}^T$$

The system coefficient matrices are given by

$$M = \begin{bmatrix} m_3 L_2 \, cos_2 & m_3 L L_2 \, cos_{(1-2)} & I_3 + m_3 {L_2}^2 \\ \left(m_2 L_1 + m_3 L\right) \, cos_1 & m_2 {L_1}^2 + m_3 {L_2}^2 + I_2 & m_3 L L_2 cos_{(1-2)} \\ m_1 + m_2 + m_3 & \left(m_2 L_1 + m_3 L\right) \, cos_1 & m_3 L_3 \, cos_2 \end{bmatrix}$$

$$C = \begin{bmatrix} 0 & -m_3 L L_2 \, sin_{(1-2)} \, \dot{\theta}_1 & b_3 \\ 0 & b_2 & -m_3 L L_2 \, sin_{(1-2)} \, \dot{\theta}_2 \\ b_1 & -\left(m_2 L_1 + m_3 L\right) \, sin_1 \dot{\theta}_1 & -m_3 L_3 \, sin_2 \, \dot{\theta}_2 \end{bmatrix}$$

$$G = \begin{bmatrix} -m_3 g L_2 sin_2 + k_3 \theta_2 \\ -\left(m_2 L_1 + m_3 L\right) g L \, sin_1 + k_2 \theta_1 + F_b cos_1 L_b \\ k_1 x \end{bmatrix}$$

The overall system will be divided into two main equations in terms of q_u and q_a, where q_u represents the under-actuated states θ_1 and θ_2 (Thorax and head) and q_a represents the actuated state x (lower body).

The first equation represents the underacted states (θ_1 and θ_2) which can be represented by

$$M_{11}(q)\ \ddot{q}_u + M_{12}(q)\ \ddot{q}_a + C_{11}(q,\dot{q})\,\dot{q}_u + C_{12}(q,\dot{q})\,\dot{q}_a + G_u(q) = 0 \tag{2}$$

Where,

$$\ddot{q}_u = \begin{bmatrix} \ddot{\theta}_2 & \ddot{\theta}_1 \end{bmatrix}^T,\ \ddot{q}_a = \ddot{x},\ \dot{q}_u = \begin{bmatrix} \dot{\theta}_2 & \dot{\theta}_1 \end{bmatrix}^T,\ \dot{q}_a = \dot{x},$$

$$M_{11} = \begin{bmatrix} m_3L_2\ cos_2 & m_3LL_2\ cos_{(1-2)} \\ \left(m_2L_1 + m_3L\right)\ cos_1 & m_2{L_1}^2 + m_3{L_2}^2 + I_2 \end{bmatrix},\quad M_{12} = \begin{bmatrix} I_3 + m_3{L_2}^2 \\ m_3LL_2cos_{(1-2)} \end{bmatrix},$$

$$C_{11} = \begin{bmatrix} 0 & -m_3LL_2\ sin_{(1-2)}\ \dot{\theta}_1 \\ 0 & b_2 \end{bmatrix},\ C_{12} = \begin{bmatrix} b_3 \\ -m_3LL_2\ sin_{(1-2)}\ \dot{\theta}_2 \end{bmatrix} \text{and}$$

$$G_u = \begin{bmatrix} -m_3gL_2sin_2 + k_3\theta_2 \\ -\left(m_2L_1 + m_3L\right) gL\ sin_1 + k_2\theta_1 + F_bcos_1L_b \end{bmatrix}$$

The second equation represents the actuated state (x)

$$M_{21}(q)\ \ddot{q}_u + M_{22}(q)\ \ddot{q}_a + C_{21}(q,\dot{q})\,\dot{q}_u + C_{22}(q,\dot{q})\,\dot{q}_a + G_a(q) = \tau_a \tag{3}$$

where

$$M_{21} = \begin{bmatrix} m_1 + m_2 + m_3 & \left(m_2L_1 + m_3L\right)\ cos_1 \end{bmatrix},\ M_{22} = \left[m_3L_3\ cos_2\right],$$

$$C_{21} = \begin{bmatrix} b_1 & -\left(m_2L_1 + m_3L\right)\ sin_1\dot{\theta}_1 \end{bmatrix},\ C_{22} = \left[-m_3L_3\ sin_2\ \dot{\theta}_2\right],\ G_a = k_1x \text{ and } \tau_a = F_{cont}$$

The applied control force F_{cont} on the seat has to be designed in order to reduce the occupant injury criteria during the impact.

3. Sliding Mode Controller Design

In the formulation of the vehicle-occupant control problem for crash purposes, there is always a discrepancy between the actual plant and its mathematical model given by equations (2 and 3) which will be used for the controller design. These discrepancies (or mismatches) arise from unknown external disturbances, plant parameters, and non-modeled dynamics. Designing control law that provides the desired vehicle-occupant performance of the closed-loop system in the presence of these disturbances/uncertainties is a very challenging task for active safety engineers. This has led to intense interest in employing the development of the so-called robust control methods which are supposed to solve this problem. One particular approach to robust controller design is the so-called Sliding Mode Control (SMC) technique. SMC is considered as a robust nonlinear control method is insensitive to parameter variations, capable to reject disturbances and accounts for unmodeled dynamics. Therefore, it is applied widely in automotive engineering field [14].

The main control objective is assumed to keep the occupant chest at the reference position θ_{1d}, in the presence of seat belt force. This will minimize the thorax injury criteria and decrease the applied belt force on the chest. For control purposes, the thorax equation of motion will be rearranged in the following form:

$$\ddot{\theta}_1 = \alpha(q, \dot{q}) + F_{cont}\,\beta(q, \dot{q}) + d(t) \tag{4}$$

Where α and β are nonlinear functions of the system states. d(t) represents the external disturbance and it is assumed to be bounded as $|d(t)| \leq D(t)$, where $D(t)$ is a positive real number that represents the highest crash deceleration.

Since the chest angular position is considered as the main control variable, the sliding manifold *S* is defined as

$$S = \lambda\left(\theta_{1d} - \theta_1\right) + \left(\dot{\theta}_{1d} - \dot{\theta}_1\right) \tag{5}$$

λ is a positive value which represents the sliding surface coefficient. θ_{1d} and $\dot{\theta}_{1d}$ the desired chest angular position and angular speed, respectively. The choice of the positive parameter λ is almost arbitrary, and defines the unique pole of the resulting "reduced dynamics" of the system when in sliding mode. From a geometrical point of view, the equation *S = 0* defines a surface in the error space, that is called "sliding surface". The trajectories of the controlled system are forced onto the sliding surface, along with the system behavior to meet the design specifications. The next step is to determine a control action that steers the system trajectories onto the sliding manifold, that is, in other words, the control is able to steer the *S* variable to zero in a finite time. To do this a Lyapunov-like function candidate $v$is defined as

$$v = \frac{1}{2}S^2 \tag{6}$$

In sliding mode control, the nonlinear system is stable if v is monotone decreasing function where its time derivative is negative definite for all $t \geq 0$. It is represented mathematically as

$$\dot{v} = S\dot{S} \leq -\eta\,|S| \tag{7}$$

$$\dot{v} = \dot{S}\ sgn(S) \leq -\eta$$

Where η is a positive coefficient. The control law is derived based on the last condition to guarantee the system stability. The time derivative of S is substituted into (7) to obtain the condition

$$\left[\lambda\ \left(\dot{\theta}_{1d} - \dot{\theta}_1\right) + \left(\ddot{\theta}_{1d} - \ddot{\theta}_1\right)\right] sgn(S) \leq -\eta \tag{8}$$

In this approach the desired value of the chest angular speed $\dot{\theta}_{1d}$ is zero. By substituting from equation (4) with value of $\ddot{\theta}_1$ into equation (8) we get

$$\left[\lambda\ \left(\dot{\theta}_{1d} - \dot{\theta}_1\right) + \left(\alpha + F_{cont}\ \beta + d(t)\right)\right] sgn(S) \leq -\eta \tag{9}$$

The control force F_{cont} is derived based on the above condition to be

$$F_{cont} = \frac{\lambda\,\dot{\theta}_{1d} - \lambda\,\dot{\theta}_1 - \alpha}{\beta} - Ksgn(S\beta), K = \frac{D\ sgn\,(S) - \eta}{|\beta|} \tag{10}$$

K is the controller gain. Its value has to be large enough to guarantee system stability and disturbance rejection. In order to avoid chattering problem, high frequencies in the control signal, the sign function is replaced with saturation function which eliminates such frequencies[15]. The final control law is defined as

$$F_{cont} = \frac{\lambda\,\dot{\theta}_{1d} - \lambda\,\dot{\theta}_1 - \alpha}{\beta} - Ksat\left(\frac{S\beta}{\varphi}\right) \tag{11}$$

Where $K \geq \frac{D\ sgn(S)-\eta}{|\beta|}\ and\ \varphi > 0$

The control input force in (11) accounts for nonlinearities in the occupant model, external disturbances and variation in the system parameters. Three main control parameters have to be adjusted carefully to achieve satisfactory response: λ which describes the slope of the sliding surface, K which represents the control gain and the chattering elimination function saturation gain φ. It is important to note that common feature of all sliding mode based techniques is that no precise information about the original system dynamics is requested, the controlled system being treated as a completely uncertain "black box" object. Note that control force F_{cont} works for both front and rear collision.

4. Results and Discussion

A default trapezoidal impact pulse of 30 MPH crash test has been applied to investigate the effectiveness of the proposed controller. Two different scenarios are considered: front and rear crashes. All simulation parameters for the occupant model and the SMC are listed in table 1. Before the impact, the occupants' chest is assumed to rest at the backseat where the thorax angular position $\theta_1 = \theta_{1d}$, and the head angular position $\theta_2 = 0$. Once the crash takes place, the control force F_{cont} will be applied on the set frame to reduce the crash impact on the occupants' chest and head. The belt force is assumed to work passively; based on the occupant's thorax position.

Table 1: Model and control parameters.

parameter	value	parameter	value
m1	27.3 kg	*L1*	0.35 m
m2	51.1 kg	*L2*	0.2 m
m3	8 kg	*Lb*	0.5 m
k1	2e3 N/m	*L*	0.6 m
k2	2e2 Nm/rad	*Kb*	1.24e5 N/m
k3	1.6e3 Nm/rad	*G*	9.81 m/s^2
b1	100 Ns/m	*K*(front crash)	7.34e6
b2	80 Nms/rad	*K* (rear crash)	7.08e6
b3	10 Nms/rad	λ	100
I1	1.46 kg.m^2	φ	8
I2	0.03 kg.m^2	*θ*1d	-25 degrees

4.1. Front crash

Chest and neck injury criteria are highly depending on the exerted acceleration on the occupants' thorax and head [16]. Figure 2-a shows the thorax angular acceleration for the proposed controller. It has been compared with the conventional restraint system with and without load limiter, in figures 2-b and 2-c, respectively. The results show a significant decreasing on the chest acceleration where the maximum noticed value is around 5 rad/s which could be neglected in comparison to the conventional systems. The chest angular position didn't show any significant response which was almost around the initial value during the entire crash time. The head angular acceleration responses are illustrated in Figure 3 where the proposed design is compared with the conventional system. The results prove the ability of the proposed design to reduce the acceleration effects on the occupant's head.

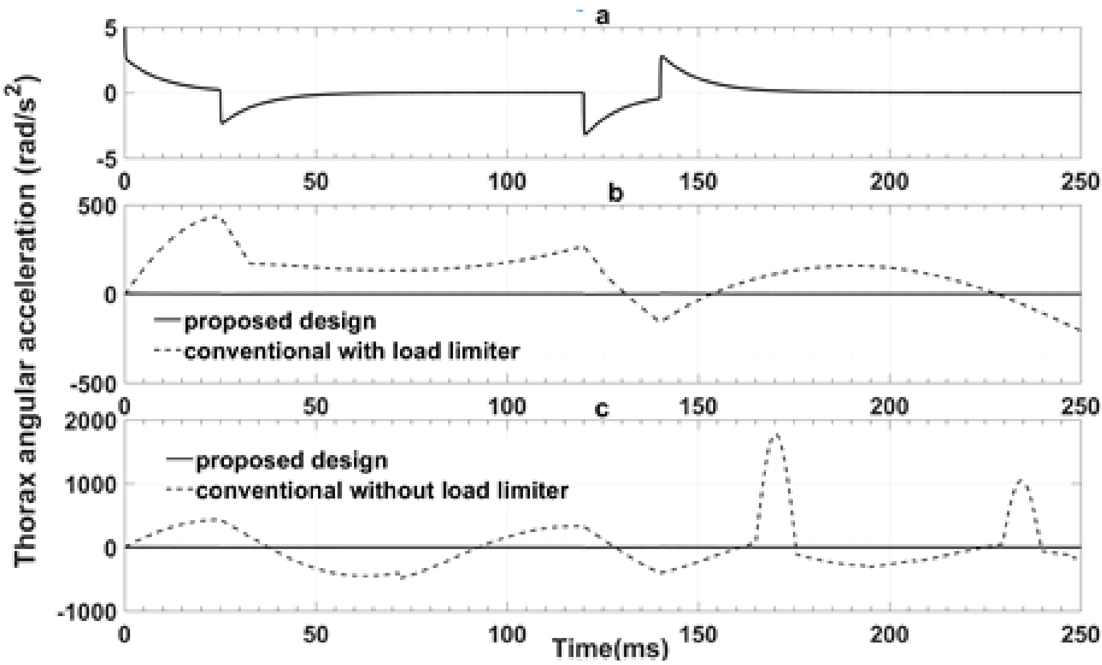

Figure 2: Thorax angular acceleration for 30MPH frontal crash.

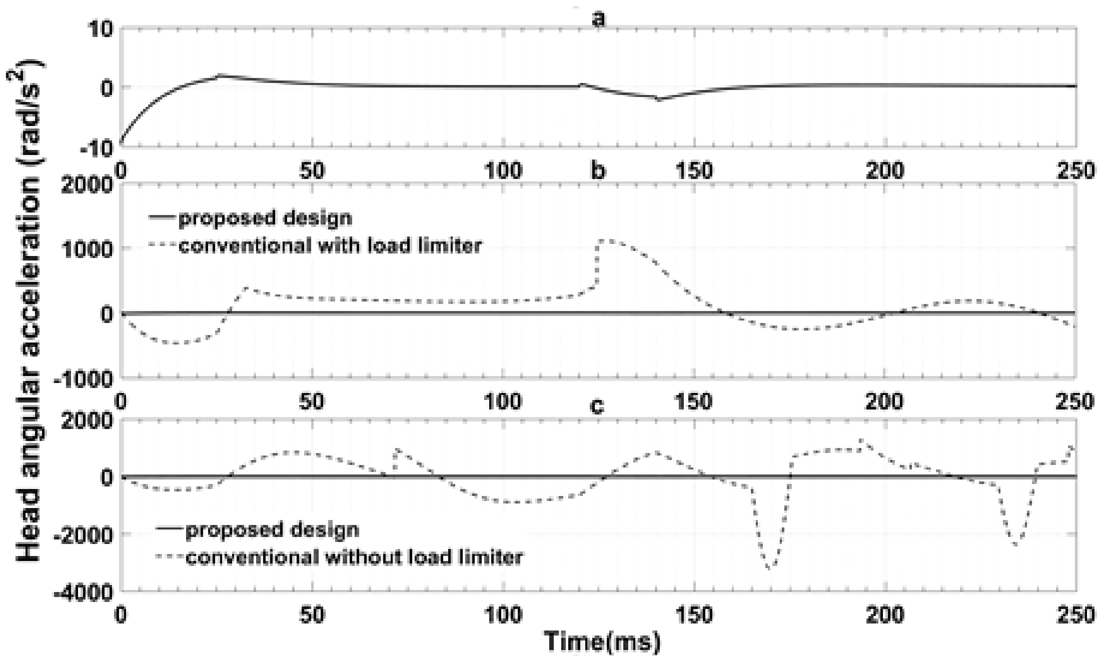

Figure 3: Head angular acceleration for 30MPH frontal crash.

More significant improvement is noticed in figure4 where the seatbelt force is presented. The results showed that the proposed system is able to decrease the applied forces on the occupant's chest to minimum level compared with the conventional designs. The needed control force on the seat frame is showed in Figure 5 which represents the needed force to maintain occupant's safety. It is noticed that the applied control force is an image of the crash pulse signal.

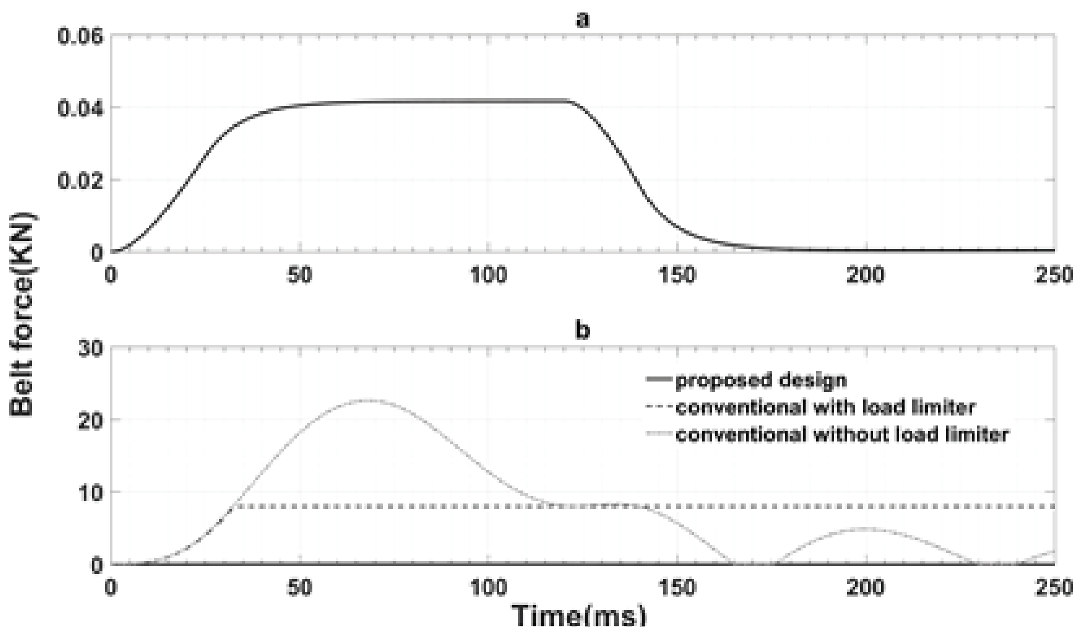

Figure 4: Seat belt force for 30MPH frontal crash.

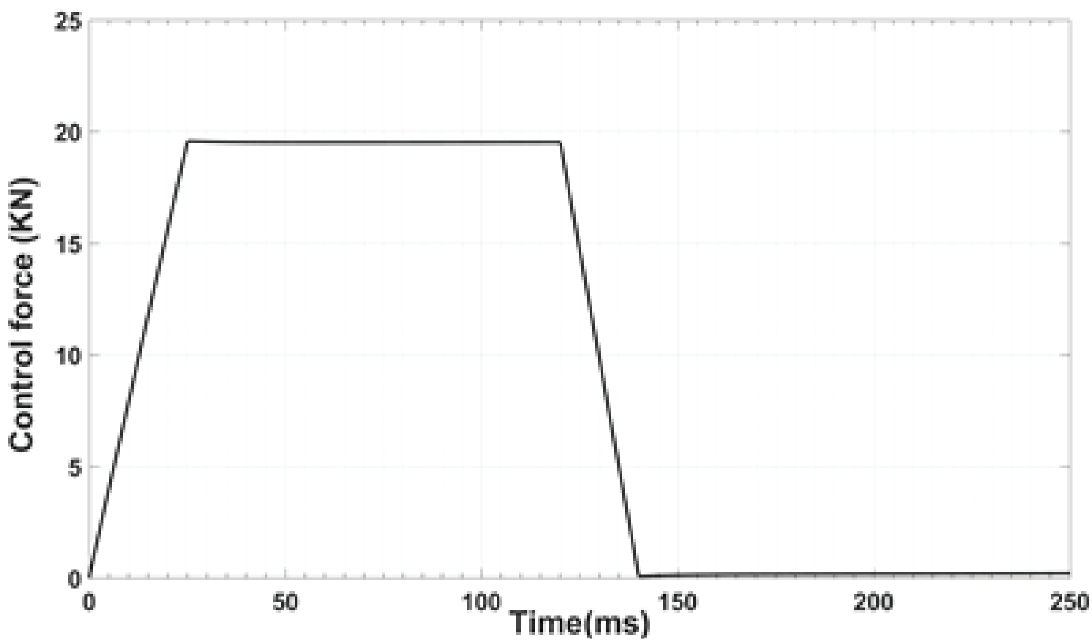

Figure 5: Applied control force for 30MPH frontal crash.

4.2. Rear crash

For the rear crash test, the applied crash pulse is reversed to simulate a rear end collision. The thorax acceleration of the proposed design is presented in Figure 6-a. It is noticed that the acceleration level is considerably below the conventional design in figures 6-b and 6-c. Oscillations which appeared in the conventional system response are mostly caused due to contact between the occupant and the seatback during the rear crash, which was prevented using the proposed design. The head angular acceleration is presented in Figure 7 which shows the superiority of the proposed controller to decrease head acceleration level compared with the conventional system. The applied control force is presented in Figure 8 which showed a reversed image of the crash signal. The seatbelt force is neglected since the occupant will be in contact with the seat back during rear crashes.

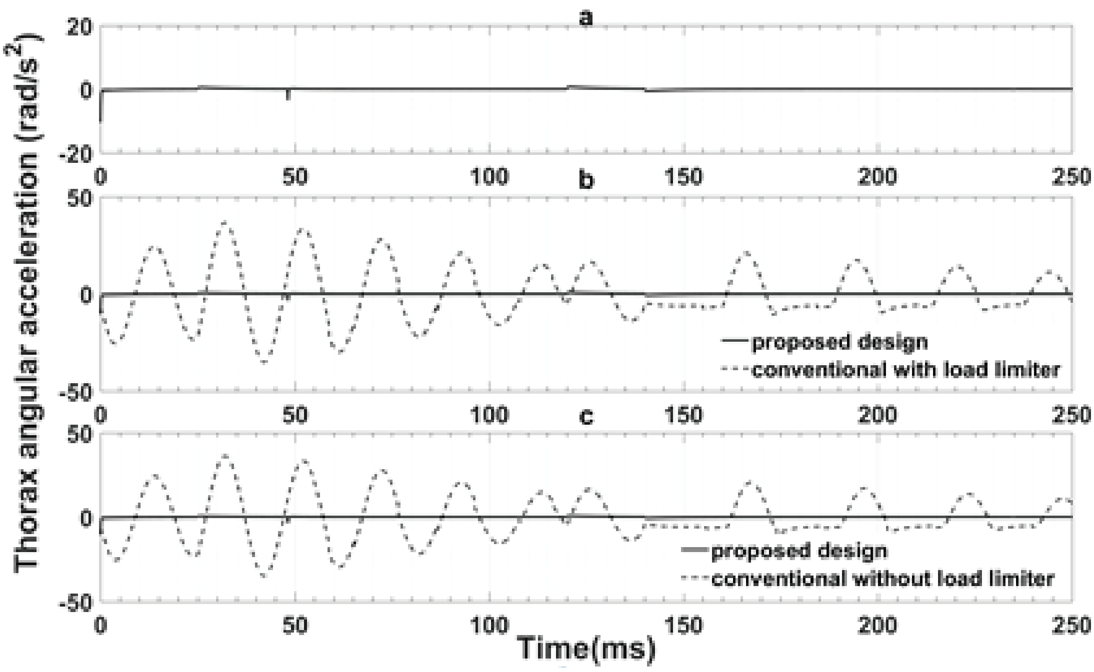

Figure 6: Thorax angular acceleration for 30MPH rear crash.

5. Conclusion

In this work, an active restraint system is proposed to enhance the occupant safety during different crash scenarios. An active supplementary force was applied on the seat during the crash to control the occupant chest and head. Three degrees of freedom mathematical model was derived to describe the occupant's main characteristics. A

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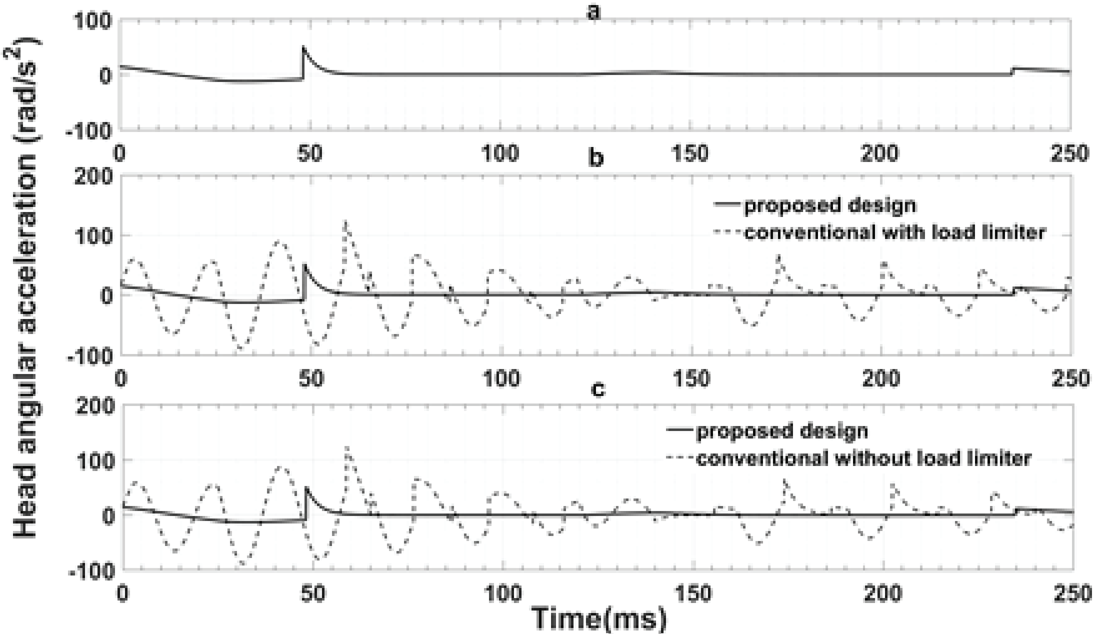

Figure 7: Head angular acceleration for 30MPH rear crash.

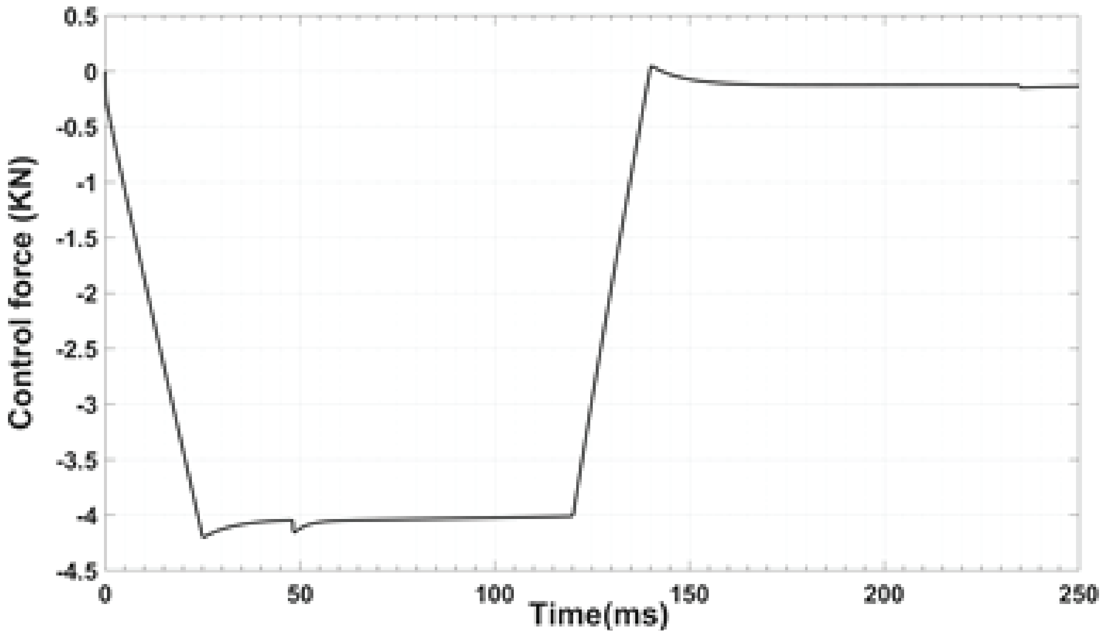

Figure 8: Applied control force for 30MPH rear crash.

sliding mode controller was designed based on the generated model to control the seat supplementary force. The system was tested in both front and rear end collisions. The results showed significant improvement in the exerted accelerations on the chest and head acceleration which lead to minimized thorax and neck injury criteria. Also, the seat force was considerably decreased during the front crash to avoid any irreversible cheat ribs deformations. It is recommended that the proposed control design is to be considered as part of future restraint system. At present, real time implementation of sliding mode control system relies on the availability of feedback sensors with higher bandwidth and faster acting actuators.

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