Study & Improvement of Occupant Out-of-position Injuries Under Pre-crash Braking Condition

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Abstract. Although the impact strength can be reduced by AEB and other active safety technologies, the occupants may move forward under braking condition and reduce the protection space of the restraint system. The out-of-position displacement and injuries of occupants under braking conditions are studied by sled tests. The injury characteristics of the out-of-position occupant are obtained. By orthogonal tests, the influence of out-of-position on the injury of different body regions are analysed. MADYMO active human body simulation model is established, and the characteristics of the occupant forward displacement under different braking waveforms are studied by single variable method. By using the active seatbelt, the occupant's forward displacement is restrained. With the use of Central Composite Design (CCD) method, the response surface model of the occupant's neck displacement relative to the pretension force and pretension time of the active seatbelt is established. The effects of pretension force and pretension time on out-of-position displacement are studied, and the optimal design is carried out to obtain the parameter combination.

1. Introduction

With the development of automobile safety technology, the concept of preventing and avoiding crash is becoming more and more important. Automatic emergency braking system (AEB) is an important technology to improve safety in the pre-crash stage. When a potential danger in front of the vehicle is detected, it will send a warning to the driver through sound or image to remind the driver to take measures to avoid crash. If the driver does not respond to the warning signal in time and the crash risk is high, the system will avoid the crash or reduce the crash strength by automatic braking [1]. Although the impact strength can be reduced by AEB and other active safety technologies, however, the occupants may move forward under braking condition and reduce the protection space of the restraint system. Especially when the initial sitting posture of the occupant is out-of-position, AEB braking will increase the forward displacement. Therefore, the occupant out-of-position displacement and injuries under braking conditions are studied. The characteristics of occupant forward displacement under different braking waveform are analyzed. With the use of active safety belt, the influence of pretension time and pretension force on the out-of-position displacement is obtained. By the response surface method, the occupant out-of-position displacement is improved.

2. Study of occupant out-of-position injuries

In order to study the occupant displacement under braking conditions, Prof. Dr. Rodolfo schoeneburg, Karl Heinz Baumann and etc. from Daimler AG collected the occupant displacement by vehicle braking test [2]. In the tests, an automated braking device is used to accurately control the vehicle braking. Mark points are placed at the neck and chest of volunteers, and the displacement analysis is carried out by
using camera. The displacement of human body under vehicle braking is shown in Figure 1. The median value of neck displacement is 134mm and the median value of chest displacement is 82mm.

![Figure 1. Out-of-position displacement of human body under braking condition](image)

In order to further study the injury characteristics of out-of-position occupants, the sled test is used to compare and analyse the injuries before and after out-of-position, with the use of displacement values above. Place the Hybrid III 50th dummy in the compartment of sled test. The frontal impact acceleration waveform with an initial speed of 50km/h is set up, as shown in Figure 2. The seat position of the dummy is adjusted according to the requirements of C-NCAP frontal impact test (2018 version), as shown in Table 1 [3]. The fire time of airbag and seatbelt pretensioner are set to 25ms and 19ms respectively, and the load limit of seatbelt is 3kN. The maximum neck displacement in the vehicle braking test is about 160mm, thus the occupant position with the dummy neck forward 160mm is selected as the research object to evaluate the maximum risk. Therefore, two occupant postures are set before the test, which are normal test postures and another posture in which the neck moves forward by 160mm.

![Figure 2. Sled test acceleration curve](image)

![Figure 3. Occupant postures before the tests](image)

| Adjustment       | Requirement                        |
|------------------|------------------------------------|
| Seat Fore/Aft    | Middle position of seat travel     |
| Seat Base Tilt   | Middle position                    |
| Seat Height      | Lowest                              |
| Seat Back Angle  | 25° to vertical                    |
| Head Restraint Height | Highest                |
| Head Restraint Tilt | Middle position            |
| Seatbelt anchorage | Middle position              |

The comparison of the sled tests is shown in Figure 4. The position of the out-of-position dummy is relatively forward. During the test, the more forward inclination angle of the dummy's body, the earlier contact with the air bag that has not been fully deployed. The load state between the head, neck and the air bag is changed. Based on the C-NCAP high performance limit, the dummy injury value is normalized. The comparison of dummy injuries in normal position and out-of-position is shown in Figure 5. Except for neck tension force Fz and chest Viscous Criterion (VC), other criteria values of head, neck and chest of out-of-position dummy show an increasing trend. Especially, the shear force Fx and extension moment My of the neck increase greatly. Therefore, it can be concluded that the forward tilting of the
An occupant under braking condition reduces the action space of the restraint system, leading to the decline of the protection efficiency of the restraint system. There is an increased risk of injuries to the head, neck and chest, among which the increase of neck injuries caused by out-of-position is more serious.

![Sled test process](image1)

**Figure 4. Sled test process**

In order to compare the influence of out-of-position and restraint system parameters on occupant injuries, a three factor and two-level orthogonal test table L4 ($2^3$) is designed for test analysis. The three factors are airbag fire time, seatbelt pretensioner fire time and occupant initial postures. The two levels of airbag fire time are 25ms and 20ms respectively, and the two levels of seatbelt pretensioner fire time are 19ms and 14ms respectively. The initial postures of the occupant are normal posture and posture of neck forward by 160mm respectively. Details of orthogonal tests are shown in Table 2. Based on the C-NCAP high performance limit, the injuries of the four orthogonal tests are normalized, as shown in Figure 6.

![Dummy injuries comparison](image2)

**Figure 5. Dummy injuries comparison**

| No. | Fire time of airbag | Fire time of seatbelt | Sitting posture |
|-----|---------------------|----------------------|----------------|
| Test 1 | 25ms | 19ms | Normal position |
| Test 2 | 25ms | 14ms | Neck forward by 160mm |
| Test 3 | 20ms | 19ms | Neck forward by 160mm |
| Test 4 | 20ms | 14ms | Normal position |

The range analysis method of orthogonal test can reflect the influence of factors on test criteria. The formula is as follows:

$$R_i = \max(K_{i1}, K_{i2}, \ldots K_{ij}) - \min(K_{i1}, K_{i2}, \ldots K_{ij})$$

(1)

$K_{ij}$ is the sum of test criterion value corresponding to j level in column i. $K_{ij}^\bar{}$ is the average value of $K_{ij}$. $R_i$ is the range of column i, the difference between the maximum value and the minimum value of the average criterion value at each level in column i. It reflects the change range of the test criteria values when the levels in column i changes. The greater $R_i$, the greater the influence of this factor on the test criteria values. According to $R_i$, the influence of factors are obtained.

Therefore, the range analysis method is used to analyse the sensitivity of criteria values under different influencing factors. The sensitivities of airbag parameters, seatbelt parameters and out-of-position can be obtained, as shown in Figure 7. Compared with the airbag fire time and seatbelt pretensioner fire time, the out-of-position factor has a greater influence on the head resultant Acc 3msec exceedance, neck shear force Fx and neck tension force Fz. There is relatively smaller influence on the head HIC36, chest compression and chest VC. The neck shear force There is the most obvious effect of out-of-position on neck shear force Fx. Due to the initial displacement of the occupant, the torso leans forward during the crash, and the contact position of the occupant relative to the airbag changes. The forward movement of the torso and the deployment of the airbag make the neck subject to greater backward force, resulting in the increase of neck injuries. Based on the above analysis, it can be
concluded that compared with head and chest injuries, neck injuries are more sensitive to the initial posture, which should be prior to protection.

3. Analysis on Factors of occupant out-of-position

From the above analysis, it can be deduced that the risk of injuries in crash test increase due to out-of-position under braking conditions. Therefore, the simulation model is established to analyse the influencing factors of occupant out-of-position. The active human model (AHM) can be used to simulate the motion of occupants under pre-crash braking by adjusting the tension of muscles [4]. With seat, seatbelt, steering column, floor and instrument panel, the simulation model under braking condition is established in MADYMO software. The vehicle braking test waveforms from reference paper [2] is used in the simulation model [2]. By adjusting the muscle tension of neck, spine, and hip, the AHM model can simulate the motion of real human body. After simulation analysis, the occupant forward displacement under braking condition is shown in Figures 8 and 9. The maximum displacements of occupant neck and chest are 133mm, 83mm respectively, which are consistent with the median displacement of neck (134mm) and chest (82mm) in real vehicle test. It verifies that the simulation model is effective.
the maximum forward displacement of occupant will not change after the peak duration exceeds 0.6s. It shows that the maximum forward displacement of occupant is related to the braking deceleration peak. When the initial braking speed exceeds a certain value, the maximum forward displacement of occupant is certain, which is uncorrelated with the gradient of reaching the peak.

4. Improvement of occupant out-of-position displacement
It can be deduced from section 3 that when the initial speed exceeds a certain value, the maximum displacement of human body is certain under the action of maximum braking deceleration. Therefore,
to effectively reduce the maximum displacement of human body, external restraints need to be introduced. The active seatbelt is gradually assembled in the vehicle to deal with the out-of-position inclination caused by braking such as AEB. It can effectively keep the occupant in a normal posture by removing the slack of the seatbelt and reducing the out-of-position displacement. In order to study the influence of different active seatbelt parameters on occupant displacement, an active seatbelt model is established in MADYMO simulation model. Jóna M. Ólafsdóttir, Jonas K. H. Östh, and etc have conducted vehicle braking tests to collect the human body displacement with the active seatbelt [5]. The pretension force of the active seatbelt is set to 170N, and the action time is 200ms before braking. The upper limit, lower limit, and average value are deduced from the displacements of the human body under the action of braking and active seatbelt. The real vehicle test parameters and braking waveform are set in the simulation model, and the parameters of seatbelt are adjusted to match the real test values. Through the simulation calculation, the simulation displacement under the action of the active seatbelt is obtained. The simulation process is shown in Figure 16. The comparison between the chest X-direction displacements of simulation data and the real vehicle test data is shown in Figure 17. The simulation value is between the upper and lower limits and close to the average value. It indicates that there is good effectiveness of the active seatbelt simulation model.

The main design parameters of active seatbelt are pretension force and pretension time. To minimize the occupant displacement, these two parameters need to be optimized. In order to effectively restrain the forward inclination of occupants, the general design range of pretension force is 100N to 400N. Considering the acceptance of occupants, the pretension time is generally the moment before or after braking, which is set in the range of 200ms before braking to 100ms after braking. In the simulation model to be optimized, the waveform with the peak value of 1.0g in Figure 10 is used, which acting at 200ms. The optimization is carried out with the minimum displacement of the neck as the goal and the pretension force and pretension time as variables.

For multi variables, the central composite design (CCD) response surface optimization method is an effective. Through the regression fitting and response surface drawing of the process, the predicted optimal value and corresponding conditions can be found [6]. The CCD design table is composed of two-level factorial design plus extreme points and center points, with the characteristics of order and coherence. After determining the parameter range, the CCD method is adopted for sampling. A total of 13 groups of simulation test data are required to input the neck displacement to the corresponding position. The results are shown in Table 3. Based on these data, the CCD response surface model is established, as shown in Figure 18. The determination coefficient $R^2$ is 0.9905, indicating that the response surface model is highly accurate. The single factor variable curve is extracted from the response surface model, and the relationship between neck displacement and pretension force, pretension time can be obtained, as shown in figures 19 and 20.
Table 3. Simulation matrix of CCD method

| Run | Pretension time (ms) | Pretension force (N) | Neck displacement (mm) |
|-----|----------------------|----------------------|------------------------|
| 1   | 362.13               | 250                  | 113.68                 |
| 2   | 150                  | 250                  | 87.95                  |
| 3   | 150                  | 462.13               | 76.41                  |
| 4   | 0                    | 100                  | 96.57                  |
| 5   | 150                  | 250                  | 87.95                  |
| 6   | 150                  | 250                  | 87.95                  |
| 7   | 0                    | 400                  | 76.25                  |
| 8   | 300                  | 400                  | 87.77                  |
| 9   | 300                  | 100                  | 124.32                 |
| 10  | 150                  | 250                  | 87.95                  |
| 11  | -62.13               | 250                  | 84.63                  |
| 12  | 150                  | 250                  | 87.95                  |
| 13  | 150                  | 37.87                | 122.67                 |

Figure 18. Response surface model of the neck displacement

Figure 19. Relationship of neck displacement and pretension force

Figure 20. Relationship of neck displacement and pretension time

As can be seen from figure 19 and figure 20, when the pretension time is constant, the greater the pretension force, the smaller the neck forward displacement, which is in a negative correlation relationship. With the delay of the pretension time, the gradient of the curve between neck displacement
and pretension force gradually increases. When the pretension force is constant, there is little change of
the neck displacement when the pretension time is within the first 100ms. After more than 100ms, the
more pretension time is delayed, the greater the neck forward displacement, which is positively
correlated. With the decrease of the pretension force, the gradient of the curve between neck
displacement and pretension time gradually increases.

Considering the influence of the two factors, through the optimization design of the response surface
model and 6 iterations, it can be deduced that the neck forward displacement is minimum when the
pretension time is 57.43ms and the pretension force is 400N. The value is calculated to be 75.43mm
through simulation, with the 39.3% decrease compared with the maximum neck displacement.
(124.32mm, when the pretension time is 0ms and the pretension force is 100N).

5. Summary

The following conclusions can be drawn through the study of out-of-position injuries, out-of-position
influencing factors and improvement of out-of-position displacement under braking condition.

(1) Combined with the out-of-position data under braking and sled tests, it is concluded that the
forward tilting of the occupant under braking condition reduces the action space of the restraint system,
leading to the decline of the protection efficiency of the restraint system. There is increased risk of
injuries of the head, neck and chest. Especially, the increase of neck injuries caused by out-of-position
are more serious. Through the orthogonal test analysis, it can be deduced that compared with the head
and chest injuries, the neck injuries are more sensitive to out-of-position, which should be prior to
protection.

(2) Through the active human body simulation model, the influence of braking deceleration peak,
braking waveform gradient and peak duration on occupant displacement are analysed by univariate
method. It is concluded that the maximum occupant forward displacement is related to the braking
deceleration peak. When the initial speed exceeds a certain value, the maximum occupant forward
displacement is certain, which is uncorrelated with the gradient of reaching the peak.

(3) By the simulation model of active seatbelt and the central composite design (CCD) method, the
response surface model of occupant neck displacement relative to pretension force and pretension time
is established. When the pretension time is fixed, the greater pretension force, the smaller the neck
forward displacement, which is negatively correlated. When the pretension force is constant, there is
little change of the neck displacement when the pretension time is within the first 100ms. After more
than 100ms, the more pretension time is delayed, the greater the neck forward displacement, which is
positively correlated. Through response surface analysis, the optimal parameters of active seatbelt are
obtained.

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