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Effect of rotation of passenger compartment on occupant behavior in car impacts

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Abstract: In vehicle collisions, vehicle accelerates and rotates during impacts, though three-dimensional rotation is generally not reflected in simulation analyses. The objective of this study is to understand the effects of car rotation on occupant kinematic behavior in vehicle impact with rotation. The method to provide the boundary condition for the occupants under car acceleration and rotation was formulated. The kinematics of occupant FE model was calculated under vehicle rotation conditions. Two crash cases with vehicle rotation were examined: small overlap frontal crash (yawing) and full-width crash tests (pitching). In the small overlap frontal test simulation, the head lateral displacement of occupant was almost the same in the conditions with and without vehicle yawing angle. The results of full frontal car simulation with pitching showed that the occupant acceleration was mitigated since the seatbelt anchor moved forward together with the occupant. Rotation angles of car influence the occupant kinematics, and it is necessary to include the car rotation to simulate the occupant kinematics in vehicle collisions.

Keywords: Occupant protection, Vehicle rotation, Finite element method

1 Introduction

In addition to translational acceleration, rotational motion can occur frequently during collisions. Especially stiff small cars have a relative large rotation angle in crash tests. In addition to vehicle linear acceleration, the occupant kinematics can be influenced by vehicle rotation. There are not many research studies that investigated the influence of vehicle rotation on occupant kinematics. Woitsch and Sinz (2013) showed the influence of yawing motion and pitching motion of vehicles on the injury measures of dummy with finite elements simulations. However, the systematic analysis were not conducted to understand the mechanisms of occupant kinematics with vehicle rotation. In this study, the condition to reproduce occupant kinematics under environment of passenger compartment rotation was formulated. The occupant kinematics under yaw and pitch rotation was compared to that without vehicle rotational behavior (only compartment deceleration was applied).

2 Theory of reproduction

The equations of motion in rotating coordinate system is derived with matrix. Stationary coordinate system O-xyz fixed at the inertial space and rotating coordinate system O-$x'y'z'$ share the origin point O. The components of column vector of the point P in O-xyz and O-$x'y'z'$ is expressed as $\{r\}=(x,y,z)^T$ and $\{r'\}=(x',y',z')^T$, respectively (Figure 1). Time derivative of the column vector is $\{\dot{r}'\}=(\dot{x}',\dot{y}',\dot{z}')^T$ and $\{\ddot{r}'\}=(\ddot{x}',\ddot{y}',\ddot{z}')^T$.

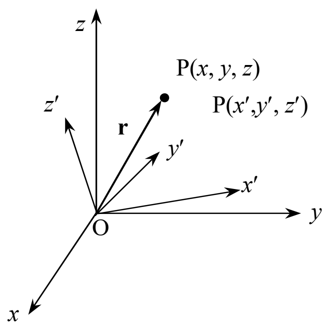


Figure 1. Coordinate system

By using the coordinate transformation matrix of rotation $[R]$, the relationship between two vectors can be transferred as

$$\{r\} = [R]\{r'\} \ . \tag{1}$$

Since $[R]$ is an orthogonal matrix, the following equations hold:

$$[R][R]^T = [R]^T[R] = [I] \tag{2}$$

$$[R]^{-1} = [R]^T \tag{3}$$

$$\{r'\} = [R]^T\{r\} \ . \tag{4}$$

By substituting Eq. (4) into the first derivative of $\{r\}$ with respect to time $\{\dot{r}\} = [\dot{R}]\{r'\} + [R]\{\dot{r}'\}$, we can obtain

$$\{\dot{r}\} = [\dot{R}]([R]^T\{r\}) + [R]\{\dot{r}'\} \ . \tag{5}$$

Then, the matrix $[R]^T$ was multiplied to Eq. (5) from the left side to express in the component of the motion coordinate system, we obtain

$$[R]^T\{\dot{r}\} = [R]^T[\dot{R}]([R]^T\{r\}) + \{\dot{r}'\} \tag{6}$$

$$[R]^T\{\dot{r}\} = [\Omega]([R]^T\{r\}) + \{\dot{r}'\} \tag{7}$$

where $[R]^T[\dot{R}] = [\Omega]$ is an angular velocity matrix. This equation is a matrix expression of velocity vector, $\dot{\mathbf{r}} = \mathbf{v}' + \boldsymbol{\omega}\times\mathbf{r}'$ in the moving coordinate system.

The acceleration of the point P can be calculated from the time derivative of (5).

$$\{\ddot{r}\} = [\ddot{R}][R]^T\{r\} + [\dot{R}][\dot{R}]^T\{r\} + [\dot{R}][R]^T\{\dot{r}\} + [\dot{R}]\{\dot{r}'\} + [R]\{\ddot{r}'\} \tag{8}$$

We substitute (5) to (8), and then in order to express the components in O–$x'y'z'$, we multiply $[R]^T$ to equation from the left.

$$\begin{aligned}[R]^T\{\ddot{r}\} = ([R]^T[\ddot{R}][R]^T + [R]^T[\dot{R}][\dot{R}]^T)\{r\} \\ + [\Omega]^2[R]^T\{r\} + 2[\Omega]\{\dot{r}'\} + \{\ddot{r}'\}\end{aligned} \tag{9}$$

Since $[\Omega] = [R]^T[\dot{R}]$, we can obtain

$$[\dot{\Omega}] = [\dot{R}]^T[\dot{R}] + [R]^T[\ddot{R}] \tag{10}$$

$$[R]^T[\ddot{R}][R]^T + [\dot{R}]^T[\dot{R}][R]^T = [\dot{\Omega}][R]^T \tag{11}$$

Eq. (9) can be rewritten as:

$$\begin{aligned}[R]^T\{\ddot{r}\} &= [\dot{\Omega}]([R]^T\{r\}) + [\Omega]^2([R]^T\{r\}) \\ &\quad + 2[\Omega]\{\dot{r}'\} + \{\ddot{r}'\} \\ &= [\dot{\Omega}]\{r'\} + [\Omega]^2\{r'\} + 2[\Omega]\{\dot{r}'\} + \{\ddot{r}'\}\end{aligned} \tag{12}$$

The equation above means the vector expression:

$$\ddot{\mathbf{r}} = \mathbf{a}' + 2\boldsymbol{\omega}\times\mathbf{v}' + \boldsymbol{\omega}\times(\boldsymbol{\omega}\times\mathbf{r}') + \dot{\boldsymbol{\omega}}\times\mathbf{r}' \tag{13}$$

If we multiply $[R]^T$ from the left, the vector is projected in O– $x'y'z'$ system.

Let us consider the case that the origin point O′ is moving with translational acceleration, and O′- $x'y'z'$ is rotating with respect to the O-xyz system. The components of column vector of point P in O- xyz is $\{r\} = (x, y, z)^T$. In O- $x'y'z'$, it can be expressed as $\{r'\} = (x', y', z')^T$ (Figure 2). The position of point P in O′– $x'y'z'$ can be expressed as the superposition of the translational motion of O′ and the rotational motion of O-$x'y'z'$ system.

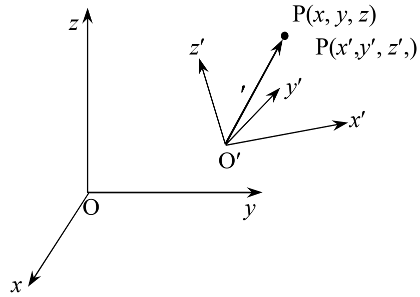


Figure 2. Coordinate system (origin moves)

$$\{r\} = \{r_{O'}\} + [R]\{r'\} \tag{14}$$

The position, velocity and acceleration of the point P in moving coordinate system can be expressed as:

$$[R]^T\{r\} = [R]^T\{r_{O'}\} + \{r'\} \tag{15}$$

$$[R]^T\{\dot{r}\} = [R]^T\{\dot{r}_{O'}\} + [\Omega]\{r'\} + \{\dot{r}'\} \tag{16}$$

$$\begin{aligned}[R]^T\{\ddot{r}\} = [R]^T\{\ddot{r}_{O'}\} + [\dot{\Omega}]\{r'\} \\ + [\Omega]^2\{r'\} + 2[\Omega]\{\dot{r}'\} + \{\ddot{r}'\}\end{aligned} \tag{17}$$

Force acting on the mass point can be expressed as

$$\{f'\} = [R]^T\{f\} \tag{18}$$

The gravity vector $\{g\} = (0\ \ 0 - g)^T$ acts vertically downward. Therefore, the equations of motion in stationary coordinate system can be written as

$$m\{\ddot{r}\} = \{f\} + \{g\} \tag{19}$$

The component of equations of motion in moving coordinate system can be expressed in the moving coordinate system.

$$m([R]^T\{\ddot{r}\}) = \{f'\} + [R]^T\{g\} \tag{20}$$

Substitute Eq. (16) (17) to (19), we can get

$$\begin{aligned}m\{\ddot{r}'\} = \{f'\} + [R]^T\{g\} - m[R]^T\{\ddot{r}_{O'}\} \\ - m[\dot{\Omega}]\{r'\} - m[\Omega]^2\{r'\} - 2m[\Omega]\{\dot{r}'\}\end{aligned} \tag{21}$$

To reproduce the equations of motion of O′– $x'y'z'$ in another system, such as sled, components of the external force acting on the mass point must be equal. Furthermore, considering that the direction of gravity is always acting vertically downward, it is necessary to reproduce the angle of O′–$x'y'z'$ w.r.t. the stationary coordinate system. Also, the acceleration of the origin O′ should be equal.

From the above discussion, we can conclude that in order to reproduce the motion of passengers in a sled test when the passenger compartment has a rotational motion, three conditions shown below should be satisfied:

1. The environment of the force applied to the dummy in passenger compartment (restraint system, seat, instrument panel, floor, etc.) should be identical with those of real test.
2. Acceleration at one arbitrary point in the passenger compartment should be identical with the acceleration at the same point in the passenger compartment in a crash test.

3. The time history of posture angle of the passenger compartment should be identical w.r.t. the stationary coordinate system.

3 Yawing Effect

3.1 The effect of yawing rotation on the compartment acceleration

The accelerations are different depending on the points at the passenger compartment when the vehicle rotates. At first step, the distributions of acceleration in the passenger compartment due to yawing were examined. As a crash with large yawing angle, a small overlap test was selected. A small overlap barrier crash test was conducted at 64.4 km/h and 25 percent overlap by IIHS (Insurance Institute for Highway Safety). The test car was Mazda 3. A Hybrid III dummy was seated in the driver seat on the impact side. Figure 3 shows the crash configuration. One vehicle accelerometer was fixed inside the vehicle (floor) and marked with photographic targets applied to the appropriate top surfaces of the vehicle.

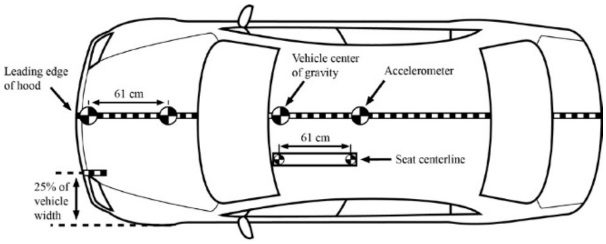


Figure 3. Crash configuration of Small overlap test

Figure 4 shows the translational accelerations of x' (longitudinal) and y' (lateral) directions. The time history of yaw angle was obtained by image analysis software from the movie of crash test (Figure 5).

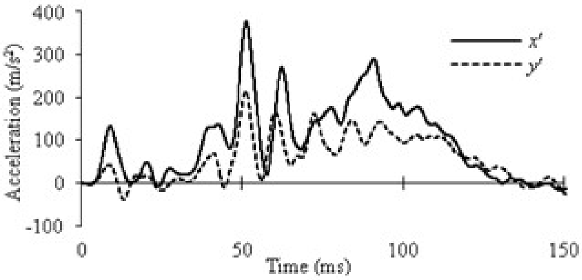


Figure 4. Acceleration of accelerometer (test result, car coordinate system)

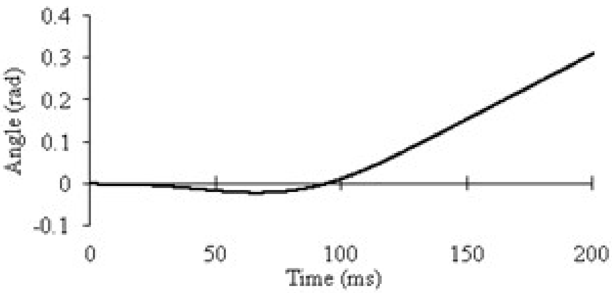


Figure 5. Yaw rotation of target car

Based on the test results, three types of acceleration field were exerted on the passenger compartment finite element (FE) model: only translational acceleration, only rotational acceleration and combination of translational and rotational accelerations were applied on the point of accelerometer attached point, and the effect of yawing rotation on the vehicle acceleration was examined. Accelerations of several points on the compartment model were measured. Figure 6 shows the locations of acceleration measured (A1 to A13).

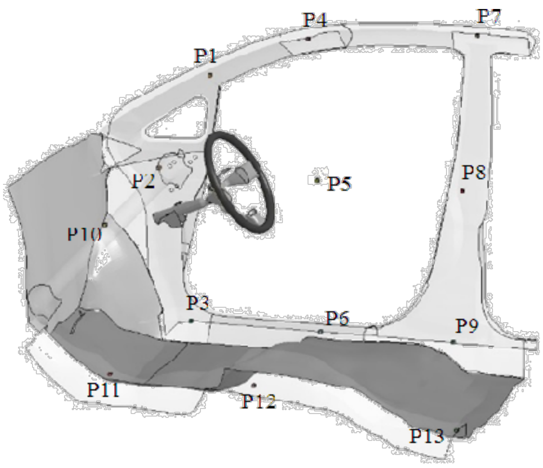
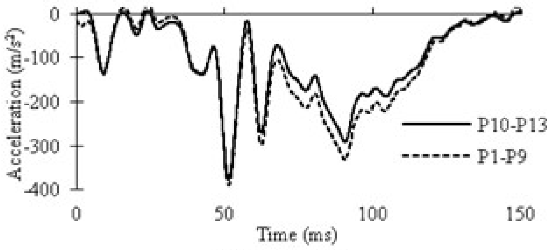


Figure 6. Locations of acceleration measured

When only translational acceleration was given, all points on the car have identical acceleration. In the case that only yawing angle with time was given, the result showed that the tendency of the vehicle acceleration curve was consistent with the curve of the yawing angular acceleration.

When both of the translational accelerations and angular acceleration were given, the accelerations of x-axis and y-axis divided into groups, respectively. The *x* accelerations of all the points on car separates into two groups. The points at tunnel side (P10, P11, P12, P13: same y' coordinate) have almost the same x' acceleration. And the points at door side (P1 to P9: same y' coordinate) also have almost same x' acceleration. Similarly, the y' accelerations of all the points on car divided into three groups (P1, P2, P3, P10, P11; P4, P5, P6, P12; P7, P8, P9, P13: same x' coordinate). Figure 7 shows the average acceleration curves of each location group. The results indicate that yawing angular acceleration can cause different acceleration of each point on the compartment according to its location.



(a) *x* acceleration

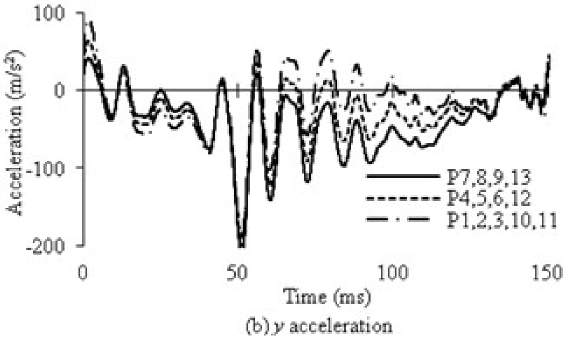


Figure 7. Accelerations of points in the compartment

The acceleration of the point in the compartment can be obtained when substituting $\boldsymbol{v}'$=0 into eq. (13)

$$\ddot{\mathbf{r}} = \ddot{\mathbf{r}}_{O'} + \boldsymbol{\omega} \times (\boldsymbol{\omega} \times \mathbf{r}') + \dot{\boldsymbol{\omega}} \times \mathbf{r}' . \tag{22}$$

The above equation is also described by x and y component expression:

$$\begin{aligned} a_{x'} &= a_{Ox'} - \dot{\omega} y' - \omega^2 x' \\ a_{y'} &= a_{Oy'} + \dot{\omega} x' - \omega^2 y' \end{aligned} \tag{23}$$

Although both of x' and y' appears in the above equation, ω^2 is too small to affect the acceleration $a_{x'}$, $a_{y'}$. As a result, the x' component of the acceleration of the point relates with its y' coordinate and y' component relates with its x' coordinate.

3.2 Reproduction of small overlap crash test

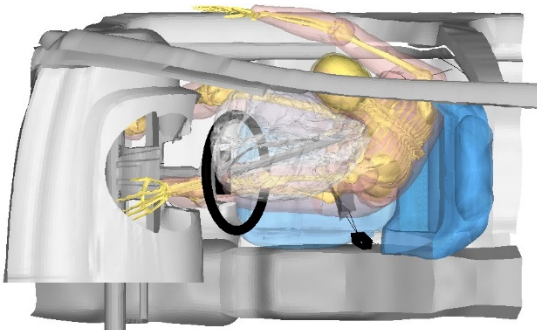
In order to understand the kinematic behavior of frontal passenger affected by yawing rotation, a small over-lap crash test was reproduced by FE simulations. The crash test in section 3.1 was chosen as a basic case and the parameters of this test condition was used in the simulations.

A simplified FE model of passenger compartment was adopted in this simulation. The model consisted of passenger compartment which includes a front seat, steering, seatbelt and airbag. A Thums FE model was seated in the driver seat. According to the theory in section 1, we gave the x' and y' acceleration to the identical point on the accelerometer location of the tested car. At the same time, we gave a yawing angle with time around this point so that the motion occurred in crash test can be reproduced.

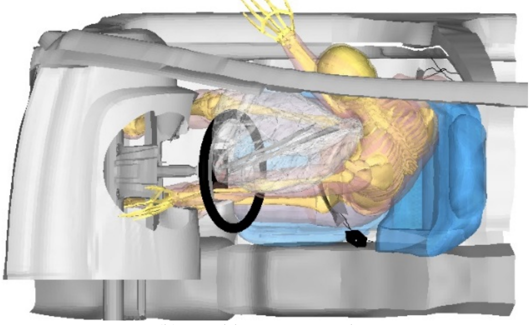
3.2.1 Relationship between head displacement of occupants and yawing motion

In order to make it clear that how yaw motion affects the kinematic behavior of occupant, we compared the yawing rotation case and no yawing rotation case by FE model simulations. The kinematic behavior of Thums is shown in Figure 8. The lateral displacement of the occupant head considering yawing motion was slightly smaller than that without yawing angle.

To understand the reason that the yaw motion has a little influence on the kinematic behavior of occupant, tension force of shoulder belt was analyzed (Figure 9). The shoulder belt outer and inner force $T_{\text{shoulder belt outter}}$, $T_{\text{shoulder belt inner}}$ were reflected in y direction (global coordinate system): $T_{y\,\text{outer}}$ and $T_{y\,\text{inner}}$. The results are shown as Figure 10. The components $T_{y\,\text{inner}}$ of both cases was almost equal while the $T_{y\,\text{outer}}$ of no yaw case was larger than that of yaw case. The difference, $T_{y\,\text{inner}}$ -$T_{y\,\text{outer}}$ (the force that prevented Thums torso from moving toward the door) was larger for the yaw case. In yawing case, it was observed the shoulder belt anchor moved clockwise because of the yawing motion of vehicle, which made $T_{y\,\text{outer}}$ (with yaw) smaller than $T_{y\,\text{outer}}$ (without yaw). As a result, the lateral head displacement of Thums model was smaller in the yaw case.



(a) With yaw rotation



(b) Without yaw rotation

Figure 8. Maximal head lateral displacement of Thums model

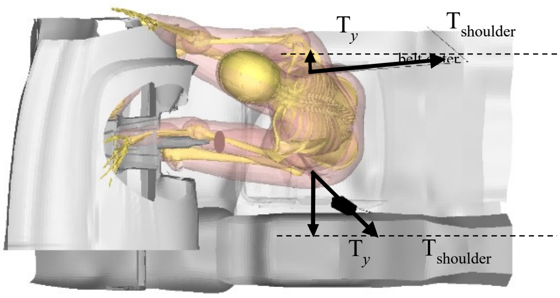


Figure 9. Shoulder belt force components

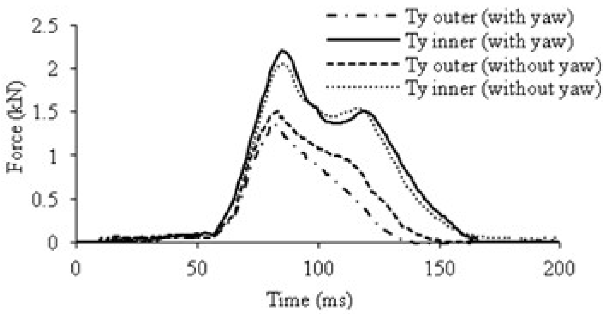


Figure 10. Shoulder belt tension in *y* direction

In addition, it was observed that the position of the seat belt anchor moved because of the yawing motion with respect to the human body, which changed the direction of resultant force applied on Thums body (Figure 11). Even though the seat belt anchor rotated, the seatbelt force was applied in the opposite direction of the Thums moving direction. As a result, it is likely that there was not a so large difference of the Thums torso motion. Another reason is that in the small overlap crash test, during the period that shoulder belt applied force on the body of Thums seated, the angle of car rotation was still small (the car yaw angle was 8 degree at 150 ms). The anchor did not move a lot to change the lateral displacement of passenger. Therefore, the influence of yaw angle was not so large for occupant motion.

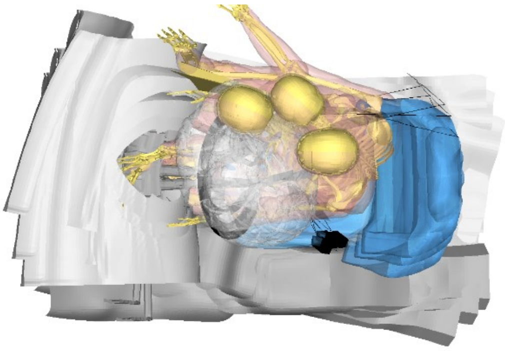


Figure 11. Track of belt anchor

4 Pitching Effect

4.1 Full frontal crash test

A full frontal crash test of a car with relatively large pitching motion was chosen to study the influence of pitching motion on occupants. The test car was minicar and impact speed was 55.6 km/h. The Hybrid III AM50th dummy was seated in the rear seat on the left hand. Several accelerometers were installed on the vehicle as shown as Figure 12.

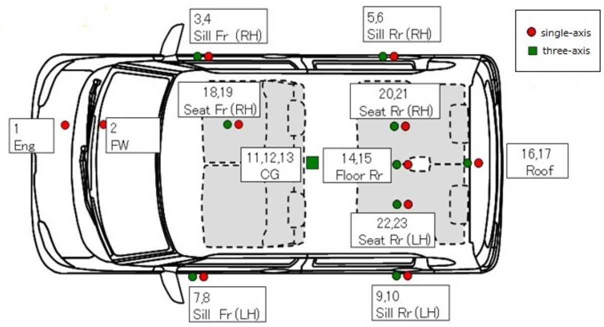


Figure 12. Location of accelerometers

4.2 Reproduction of Full Frontal crash test

The full frontal crash test was reproduced by FE simulations. We built a simplified rear seat FE model which only consisted of a rear seat and floor. The Hybrid III AM50th FE dummy model (Humanetics ver. 8.0) was seated in the seat with 3-point seatbelt. We chose the acceleration of rear side sill on the left hand to calculate the compartment rotational behavior in the crash test (Figure 13). The maximal value of longitudinal (x') acceleration reached 700 m/s^2. The pitching angle of the car was 0.175 rad at 150 ms (Figure 14).

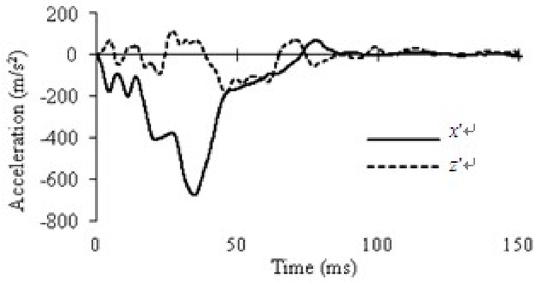


Figure 13. Acceleration of rear Side-sill on left-hand

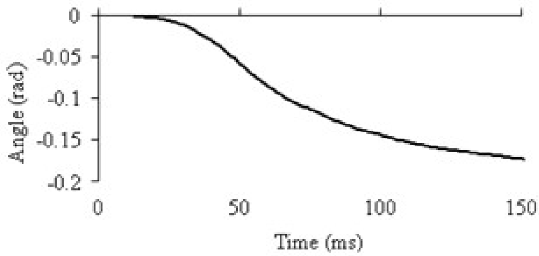
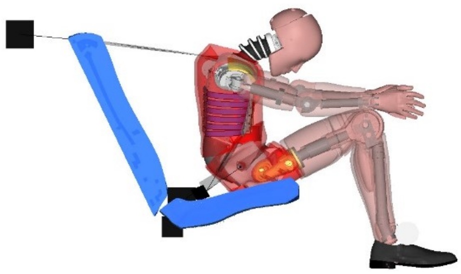


Figure 14. Pitch rotation of target car

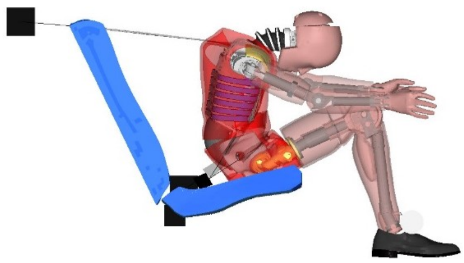
4.2.1 The effect of pitch motion on the passengers

In order to examine the effect of pitching motion on rear seat occupant, two simulations were carried out. One was the case of full pitching angle given and the other was the case of no pitching angle given. Two cases were compared to understand how pitching rotational motion acts on the kinematic behavior of occupants.

The kinematic behavior of the dummy model was compared (Figure 15). When the vehicle pitch motion was reproduced, the forward displacement of the dummy with vehicle pitching was obviously smaller than that without vehicle pitching.



(a) With vehicle pitching rotation



(b) Without vehicle pitching rotation

Figure 15. Kinematic behavior of dummy model with and without vehicle pitching

Shoulder belt tension force was compared. The results were shown as Figure 16. The maximal value of shoulder belt force showed up at about 60ms. When full pitch angle was given, the maximum of shoulder belt tension force was 12.8 kN. When no pitching angle given, the result showed that the maximum of shoulder belt tension force was 13.8 kN, which was 1 kN larger than the case of full pitching one. Similarly, the chest acceleration was also compared (Figure 17). When the pitching angle was given, the maximal value of chest acceleration became smaller. Therefore, according to the vehicle pitching behavior, the shoulder belt force was smaller and the occupant injury risk was lower.

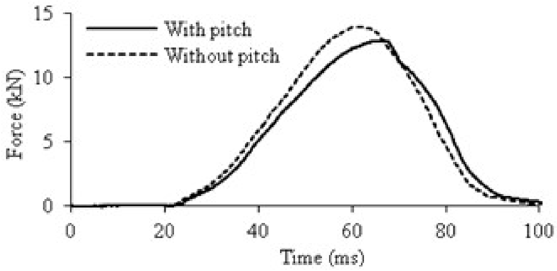


Figure 16. Shoulder belt tension force with and without vehicle pitching

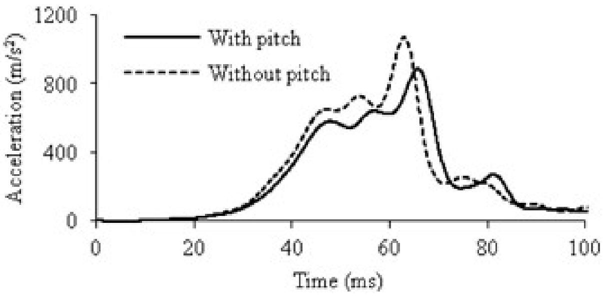


Figure 17. Chest acceleration with and without vehicle pitching

The reason for the reduction of shoulder belt tension force and chest acceleration in full pitching case can be explained from the movement of seat belt anchor. Figure 18 shows that the position of shoulder belt anchor moved forward due to the pitching motion. When the anchor moved forward, belt became longer, which resulted in the reduction of belt tension force.

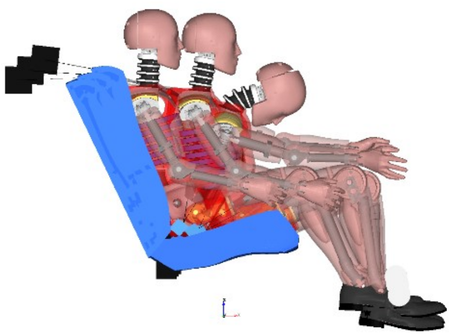


Figure 18. The seatbelt anchor movement during vehicle pitching motion

In summary, the pitching motion can reduce the force applied on chest by shoulder belts. Controlling vehicle pitch properly can protect passengers from injury of chest. However, the part that pitching motion stops and the passenger compartment falls against ground was not researched in the paper. Large angle of pitching motion may result in a severe vertical deceleration to passenger when the rear part of the vehicle falls down to the ground. Therefore, it should be examined in the future study.

5 Conclusions

The effect of vehicle rotation on the occupant kinematics was examined by FE analysis. The results are summarized as follows:

1. The theory of providing boundary conditions to reproduce the occupant kinematics in vehicle rotation was formulated: giving the acceleration at one point in the passenger compartment and the rotation with time around this point.
2. The vehicle yawing motion in a small overlap test had a relatively small effect on the occupant kinematics.
3. The vehicle pitching motion was proved to have large effect on reducing loadings on passengers.

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References

[1] Gernot Woitsch and Wolfgang Sinz, Influence of pitching and yawing during frontal passenger vehicle crash tests on driver occupant's kinematics and injury. International Journal of Crashworthiness 2013. **18**(4): p.356–370.