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Trajectory Calculation for Dummy Part Trajectory in Vehicle Collision Tests

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Abstract: Car crash tests are universally acknowledged for their critical role in assessing the passive safety performance of vehicles, given their straightforward and compelling evidence. Despite their effectiveness, traditional physical crash tests are notorious for their lengthy setup times and high costs. The evolution of Finite Element Analysis (FEA) technology, complemented by the improved precision of FEA dummies, has paved the way for evaluating passive safety through computational simulations. In the domain of virtual testing, benchmarking is essential for validating the accuracy of simulation outcomes. Among the pivotal benchmarking metrics, the congruence of dummy limb and head trajectories emerges as a dependable measure of the FEA model's accuracy. This alignment is especially significant, as the head is recognized as one of the most vulnerable areas during a crash.

Keywords: Car Crash Test; Trajectory Calculation; Simulation Benchmarking.

1. Introduction

Car crash tests serve as a fundamental tool in the automotive industry for evaluating the passive safety performance of vehicles. The direct and convincing nature of these tests provides invaluable insights into how well a vehicle can protect its occupants in the event of a collision. Despite their significance, traditional physical crash tests have long been associated with challenges such as time-consuming setup procedures and high costs, making them less feasible for frequent and extensive testing purposes.

The emergence and evolution of Finite Element Analysis (FEA) technology have revolutionized the way passive safety performance is assessed in the automotive sector. By leveraging computational simulations and sophisticated FEA models, researchers and engineers can now conduct virtual crash tests that offer a cost-effective and efficient alternative to traditional physical tests. The accuracy and reliability of these virtual simulations have been significantly enhanced by the continuous improvement of FEA dummies, which are designed to closely mimic the biomechanical responses of human occupants during a crash.

In the realm of virtual testing, benchmarking serves as a critical quality assurance process to validate the accuracy and credibility of simulation results. Benchmarking involves comparing the outputs of virtual crash simulations with real-world data obtained from physical crash tests to ensure that the virtual models accurately capture the dynamics of a crash scenario. Among the various benchmarking criteria, the alignment of the trajectory of dummy limbs and head is widely recognized as a key indicator of the precision and fidelity of the FEA model.

The trajectory of dummy limbs and head is particularly crucial in crash simulations due to the vulnerability of these body parts in real-world collisions. [1]The head, in particular, is considered one of the most critical areas of concern in terms of injury risk during a crash. Therefore, ensuring that the virtual simulation accurately replicates the movement and behavior of the dummy head and limbs is essential for evaluating the effectiveness of a vehicle's safety features and structural design in protecting occupants from harm.

By focusing on benchmarking criteria such as the trajectory alignment of dummy limbs and head, researchers and engineers can gain valuable insights into the performance of a vehicle's passive safety systems without the need for extensive physical testing. [2] This approach not only reduces the time and cost associated with traditional crash tests but also allows for faster iteration and optimization of vehicle designs to enhance overall safety performance. As the automotive industry continues to embrace virtual testing technologies, the role of benchmarking in validating simulation results will remain paramount in ensuring the safety and well-being of vehicle occupants in the face of potential collisions. In this paper, a dynamic calculation method for the dummy part trajectory is illustrated and a simulation validation case is showed.

2. Theory and Method

2.1. The Dynamics of Dummy Head Movement

In the realm of three-dimensional space, the rotation of a rigid body around a fixed point introduces three degrees of freedom. However, the representation of rotation angles is not straightforward due to the non-uniqueness stemming from the order of rotations. The method of defining rotations heavily depends on the sequence of rotations around the coordinate axes, leading to multiple ways of interpreting rotation angles.

To elaborate further, the process of defining rotations involves a systematic approach that considers the order of rotations around different axes. Initially, rotating about any one of the three coordinate axes presents three possibilities for the first rotation. Subsequently, rotating about an axis other than the one previously rotated yield two additional possibilities for the second rotation. Finally, rotating about an axis different from the two prior rotations introduces another two options for the third rotation. The combination of these possibilities results in a total of 3 x 2 x 2 = 12 distinct ways of defining rotations in three-dimensional space.[3]

Given the complexity and variability inherent in defining rotation parameters, it becomes essential to establish a clear and standardized method for specifying rotation angles. In the context of calculating head offset, two critical aspects need to be addressed. Firstly, the rotation sequence of head rotation angles during collision tests must be explicitly defined to ensure consistency and accuracy in the analysis. Secondly, the transformation matrix for the head in collision tests, specifically whether it follows a forward b2n (body-to-neck) sequence or a reverse n2b (neck-to-body) sequence, must be clearly articulated to avoid ambiguity and errors in the calculations.

By establishing a calculation coordinate system and determining the rotational coordinate system for the rotation angle, researchers can effectively navigate the complexities of defining rotation angles in three-dimensional space. [4]The systematic clarification of the rotation sequence and transformation matrix coordinate system provides a structured framework for conducting accurate and reliable calculations in scenarios involving the rotation of rigid bodies.

In the context of collision tests and head offset calculations, the precision and consistency of defining rotation angles play a crucial role in ensuring the validity of the results obtained. By combining theoretical principles with experimental data, researchers can refine their understanding of rotation parameters and enhance the accuracy of their analyses.[5] Accurately defining rotation angles and establishing a comprehensive framework for interpreting rotations in three-dimensional space are essential steps in advancing research and innovation in fields that rely on rotational dynamics and rigid body motion analysis.[6]

In this paper, the meticulous consideration of rotation sequences, transformation matrices, and rotation angle definitions is paramount in conducting rigorous and reliable calculations involving the rotation of rigid bodies. By adhering to standardized methods and clear protocols for defining rotations, researchers can streamline their analytical processes, minimize errors, and enhance the accuracy of their findings. This systematic approach not only facilitates the interpretation of rotational dynamics but also paves the way for advancements in various fields that rely on precise rotational calculations and analyses.

2.2. Procedures

2.2.1. Determine the Coordinate System and Rotation Angle Rotation Order

Define the global reference coordinate system, take the ground as the reference plane, including the X/Y/Z axis, define the XYZ axis direction by referring to the figure below, and determine the red coordinate system in the figure as the vehicle base coordinate system. Suppose the head move from vector A position to vector B position.

With reference to the figure below (left), the local coordinate system of the head is defined, and the rotation order is taken as an example according to the right of the figure below. The center of mass of the head is the origin O of the local coordinate system, and the Ox0y0z0 coordinate system is established according to the right-Angle reference coordinate system. The rotation order of the rotation Angle is defined as:

(z, y, x), that is, Ox1y1z1 is obtained after the positive rotation ψ Angle of Ox0y0z0 system around the Oz0 axis (Z first), and then Ox2y2z2 is obtained after the positive rotation θ Angle of Ox1y1z1 system around the Oy1 axis (Y again).

Finally, Ox2y2z2 system rotates φ forward around the Ox2 axis to get Ox3y3z3(last revolution X), where forward is defined as the direction of clockwise rotation according to the right hand rule, where the angle of rotation according to the x, y, z axis is defined as (φ, θ, ψ).(Figure1. Angle of rotation)

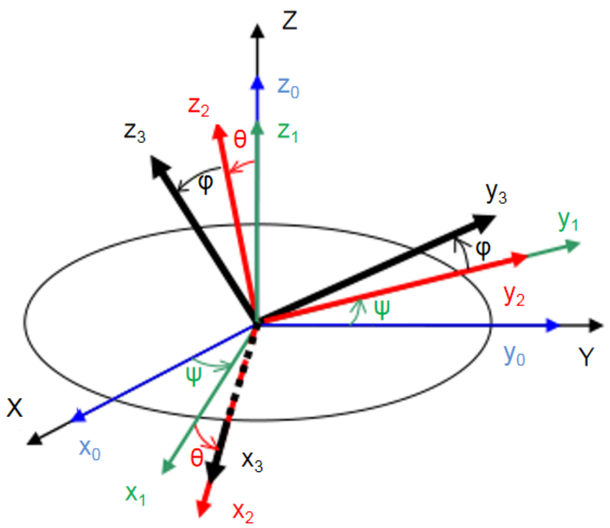

Figure 1. Angle of rotation

2.2.2. Calculation of Rotation Angle and Angular Velocity

According to the definition of coordinate system and rotation order, the rotation transformation matrix R can be obtained, and its calculation matrix is as follows:

The transformation matrix of the object rotating about the z axis:

$$[R_{z,\psi}] = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The transformation matrix of the object rotating about the y axis:

$$[R_{y,\theta}] = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix}$$

The transformation matrix of the object rotating about the x axis:

$$[R_{y,\varphi}] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\varphi & -\sin\varphi \\ 0 & \sin\varphi & \cos\varphi \end{bmatrix}$$

Through combining the three matrix we get:

$$[R] = \begin{bmatrix} \cos\psi\cos\theta & -\sin\psi\cos\theta + \cos\psi\sin\theta\sin\varphi & -\sin\psi\sin\varphi + \cos\psi\sin\theta\cos\varphi \\ \sin\psi\cos\theta & \cos\psi\cos\varphi + \sin\psi\sin\theta\sin\varphi & -\sin\varphi\cos\psi + \sin\psi\sin\theta\cos\varphi \\ -\sin\theta & \cos\theta\sin\varphi & \cos\theta\cos\varphi \end{bmatrix}$$

Based on the transformation matrix R, the analytical calculation formula of Angle φ, θ, ψ can be obtained:

$$\varphi = \arctan(R(3,2)/\cos\theta, R(3,3)/\cos\theta)$$
$$\theta = \arctan(-R(3,1), \sqrt{R(3,2)^2 + R(3,3)^2})$$
$$\psi = \arctan(R(2,1)/\cos\theta, R(1,1)/\cos\theta)$$

Based on the above formula, the rotation angles φ, θ, ψ can be obtained. Then we use the following equations for calculating the angular velocity:

$$\dot{\psi} = \sin(\varphi)\cos(\theta)w_1 + \cos(\varphi)\cos(\theta)w_2$$
$$\dot{\theta} = \cos(\varphi)w_1 - \sin(\varphi)w_2$$
$$\dot{\varphi} = -\sin(\varphi)\cos(\theta)w_1 - \cos(\varphi)\cos(\theta)w_2 + w_3$$

2.2.3. Calculate the Trajectory

The constitutive equation for calculating the dummy head centroid acceleration is $a_i = a \bullet u$. Where a_i is acceleration component expression in the three direction, u is the angular velocity vector: $u = (\varphi, \theta, \psi)^T$,through integration twice, the head centroid trajectory is illustrated as:

$$D_i(t) = D_i(t_0) + \int_{t_0}^{t} [V_i(t_0) + \int_{t_0}^{t} a_i(u)du]dt$$

Where $D_i(t_0)$ is the initial distance of the head centroid under global coordinate, $V_i(t_0)$ is the initial velocity under global coordinate. For most situations the two physical quantities equal to zero, because collision tests are implemented under stable state. Besides, $a_i(u)$ is the acceleration under global coordinate.

Therefore, through expanding the equations above, it is clear to know the physical quantity needed from the collision test: the acceleration collected from the B-column a_{cy}, the dummy head centroid acceleration in X, Y, Z direction a_{hx}, a_{hy}, a_{hz}, and the angular velocity of head centroid in X, Y, Z direction, w_{hx}, w_{hy}, w_{hz}. Then, it is easy to calculate the displacement of the test vehicle and head centroid $D_{cy}, D_{hx}, D_{hy}, D_{hz}$ through integrating the acceleration twice. Furthermore, it is easy to get the angular displacement through the equations below:

$$\psi' = f(\psi) = \dot{\psi} * dt$$
$$\theta' = f(\theta) = \dot{\theta} * dt$$
$$\varphi' = f(\varphi) = \dot{\varphi} * dt$$

Recall the trajectory adjusting equation introduced in the previous section, it is convenient to obtain the equation through plugging the physical quantities in to the adjusting equation:

$$\begin{bmatrix} DX \\ DY \\ DZ \end{bmatrix} = \begin{bmatrix} \cos\psi'\cos\theta' & -\sin\psi'\cos\theta' + \cos\psi'\sin\theta'\sin\phi' & -\sin\psi'\sin\phi' + \cos\psi'\sin\theta'\cos\phi' \\ \sin\psi'\cos\theta' & \cos\psi'\cos\phi' + \sin\psi'\sin\theta'\sin\phi' & -\sin\phi\cos\psi + \sin\psi\sin\theta\cos\phi \\ -\sin\theta & \cos\theta\sin\phi & \cos\theta\cos\phi \end{bmatrix} * \begin{bmatrix} Dx \\ Dy \\ Dz \end{bmatrix}$$

Where Dx, Dy, Dz is the head centroid displacement under vehicle coordinate, and they can be calculated through the equations below:

$$Dx = D_{hx} - D_{cx}, Dy = D_{hy} - D_{cy}, Dz = D_{hz} - D_{cz}$$

Suppose that under some circumstances, head centroid does not have displacement in X direction, therefore $Dx = 0, \theta' = 0, \psi' = 0$, and only the acceleration of head and vehicle in three direction and one angular displacement needs to be considered. Therefore, the rotational transformation equation is simplified as:

$$\begin{bmatrix} DY \\ DZ \end{bmatrix} = \begin{bmatrix} \cos\phi' & -\sin\phi \\ \sin\phi & \cos\phi \end{bmatrix} * \begin{bmatrix} Dy \\ Dz \end{bmatrix}$$

3. Validation

3.1. FEA Model Setup

To substantiate the dynamics theory we previously discussed, we have meticulously constructed a Finite Element Analysis (FEA) model. This model serves as a critical tool in our research, allowing us to simulate and analyze the complex dynamics at play. In alignment with the CNCAP far-side impact protocol, we have selected case1 as the benchmark for validating our theoretical framework. This case is particularly relevant as it provides a comprehensive scenario that closely mirrors real-world conditions, thereby ensuring the practical applicability of our findings.

Table 1. Model Setup

	Boundary Condition	Driver	Passenger
Case1	32km/h 75°passenger side pole test	World SID 50th	None

The positioning of the dummies in our study is calculated based on the R-point of the seat, which serves as a critical reference for ensuring accurate placement during simulations. Additionally, the posture of the dummies is set to the default gesture, ensuring consistency across the tests. The coordinates for the dummy's head, shoulder, and H-point for case1 is listed below (Table 2).

The input pulse data for FEA model has been collected from corresponding pole impact vehicle crash test, providing a robust foundation for our analysis. This data is essential for understanding the dynamics of the impact and the subsequent behavior of the dummy.

The layout of the sled test Finite Element Analysis (FEA) model is illustrated in the figure below(Figure 2). This model is designed to replicate real-world conditions as closely as possible, allowing us to validate our theoretical framework effectively. By integrating the dummy positioning and input pulse data into the FEA model, we aim to achieve a comprehensive understanding of occupant dynamics during a crash scenario.

Table 2. Three Scheme comparing

	X	Y	Z
H-point	1324	-390	230
Head Centroid	1501	-390	897
Shoulder	1528	-628	638

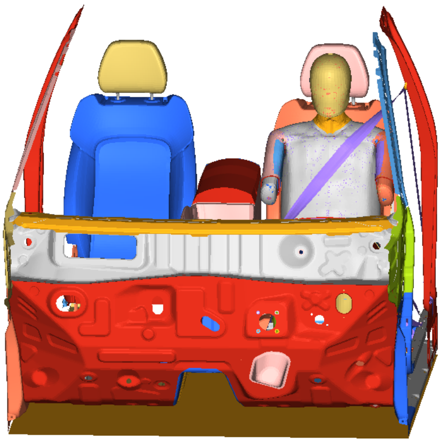

Figure 2. Model Layout

As depicted in the aforementioned figure, the Finite Element Analysis (FEA) model has been established. In this model, the boundary conditions are configured in accordance with the 2024 CNCAP protocol. By multiplying the pole impact pulse with sine functions of 15° and 75°, we have successfully decomposed the pole impact pulse into its respective X and Y directional components. These impact pulses are then applied to the brown platform that underlies the Body-In-White (BIW).

Regarding the structural configuration, the BIW components are represented by rigid shell elements, with nodes at the periphery of each BIW part being fixed to the platform. This arrangement allows the BIW to move in response to the input pulse while remaining undeformed. The passenger seat, driver seat, and console are designed as deformable components, each of which is anchored to the seat beam on the floor using the LS-DYNA keyword 'constrained extra nodes'.

The dynamic and static friction factors for the remaining assemblies are detailed in the table provided below (Table 3).

Table 3. Friction Coefficient

	Static friction ratio	Dynamic friction ration
Dummy to console	0.2	0.2
Dummy to seat	0.25	0.25
Dummy torso to seat belt	0.2	0.2
Dummy arm to seat belt	0.5	0.5

4. Result and Discussion

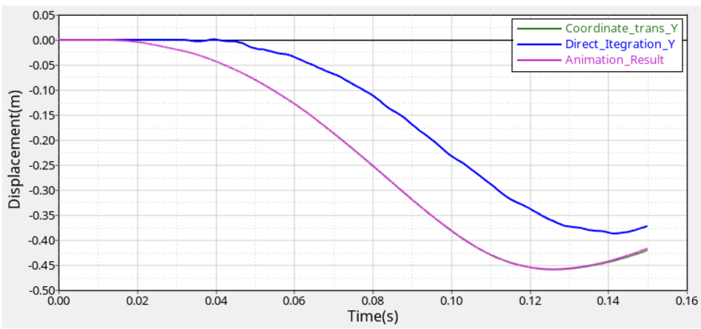

Figure 3. Head trajectory in Y direction

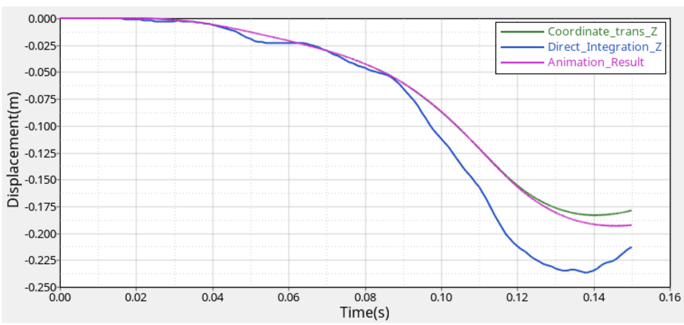

Figure 4. Head trajectory in Z direction

The data for this analysis was obtained from two graphs that plot head displacement against time. The first graph (Figure 3) represents displacement in the Y-axis, while the second graph (Figure 4) represents displacement in the Z-axis. Each graph contains three curves, each corresponding to a different method: Coordinate Transformation (green), Direct Integration (blue), and Animation Result (purple).

In figure 2, the Coordinate Transformation method (green) shows a relatively flat curve, indicating minimal displacement in the Y-axis. The Direct Integration method (blue) exhibits a more pronounced curve, with a significant decrease in displacement over time, reaching its lowest point around 0.12 seconds before slightly increasing again. The Animation Result (purple) follows a similar trend to the Direct Integration method but with a less steep decline and a more gradual increase after the minimum point. In Z-Axis Displacement (Figure 3), the Coordinate Transformation method (green) again shows a relatively stable curve, with a slight decrease in displacement over time. The Direct Integration method (blue) displays a sharp decline in displacement, reaching its lowest point around 0.12 seconds, similar to the Y-axis curve. The Animation Result (purple) closely follows the Direct Integration curve, with a slight delay in reaching the minimum point and a more gradual recovery. The differences in the curves obtained by the three methods can be attributed to the underlying principles and assumptions of each method.

The coordinate Transformation method likely uses a predefined set of transformations to calculate head displacement. The relatively flat curves suggest that this method may not account for dynamic changes in head movement as effectively as the other methods.

The Direct Integration method involves integrating the acceleration over time to obtain velocity and then integrating velocity to obtain displacement. The sharp decline in the curves indicates a high initial acceleration followed by a deceleration, which is more representative of natural head movement.

Therefore, the analysis of the head displacement curves reveals that the Direct Integration method provides a more dynamic and realistic representation of head movement compared to the Coordinate Transformation method. The Animation Result method closely follows the Direct Integration method, suggesting that it incorporates similar principles but may include additional complexities. This study highlights the importance of selecting the appropriate method for head movement analysis based on the desired level of realism and the specific requirements of the application.

Furthermore, The ISO curve correlation result is shown below:

Table 4. ISO18571 curve correlation result

Direction	Trajectory Calculation Method	Total Correlation Rating	Corridor Rating	Phase Rating	Magnitude Rating	Slope Rating
Y-Direction	Coordinate Transformed	0.9993	1	0.9966	0.9998	0.9999
	Direct Integration	0.5195	0.3893	0	0.9012	0.9177
Z-Direction	Coordinate Transformed	0.9913	1	0.9663	0.9986	0.9916
	Direct Integration	0.8241	0.8013	0.8795	0.8644	0.7736

Coordinate Transformed method consistently shows very high to perfect ratings across all categories for both Y-Direction and Z-Direction. It demonstrates a strong correlation and high performance in trajectory calculations, indicating that it is a reliable and accurate method for trajectory analysis. However, Direct Integration method shows mixed results. For the Y-Direction, the ratings are significantly lower, particularly in the Corridor and Phase ratings, suggesting that this method may not be as effective in this direction. However, for the Z-Direction, the ratings are higher, indicating better performance. The Direct Integration method still shows moderate to high correlations, but it is outperformed by the Coordinate Transformed method in all categories.

The Coordinate Transformed method appears to be superior in terms of correlation and performance across both directions, while the Direct Integration method shows variability in its effectiveness depending on the direction.

References

[1] Craig, J. J. (2005). Introduction to Robotics: Mechanics and Control (3rd ed.). Pearson Education.

[2] Jay B, Ethan S .Biomechanics of an Accessory Clavicular Head to the Sternocleidomastoid Muscle: Cadaveric Case and 3D Modeling[J].The FASEB Journal,2021,35(S1):

[3] Tsai, R. Y. (1985). Euler Angles, Rotation Matrices, and Transformations. IEEE Transactions on Robotics and Automation, 3(4), 474-478.

[4] Shoemake, K. (1992). A New Approach to 3D Rotations. In D. Kirk (Ed.), Graphics Gems III (pp. 124-132). Academic Press.Information on: www.ISSSconf.org.

[5] Bourke, P. (n.d.). 3D Rotations: Theory and Implementations. Retrieved September 27, 2024, from http://paulbourke. net/ geometry/rotate/.

[6] Peach R, Friedrich M, Fronemann L, et al.. Head movement dynamics in dystonia: a multi-centre retrospective study using visual perceptive deep learning[J]. npj Parkinson's Disease, 2024, 9: 1-12. DOI: 10.1038/s41746-024-01140-6.