3D STROKE CALCULATION AND APPLICATION USING 6-DEGREE-OF-FREEDOM SENSORS

Suk Jae (Steve) Ham, Ben Meyers
Toyota Motor Engineering & Manufacturing North America
United States of America

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ABSTRACT

Time history of movement (stroke) is crucial information for crash test analysis. The stroke is often calculated from double integration of linear acceleration data when direct measurement by a potentiometer is impossible. But this method may not be accurate for the cases with large rotations. Newer crash tests like IIHS small overlap and NHTSA oblique involve large rotation, creating 3-dimensional (3D) occupant motions compared to front rigid barrier tests which are primarily 2D events. To help overcome some of the challenges posed by newer crash tests, the authors developed a method to calculate accurate 3D motion with 6-DOF (Degree-of-Freedom) instrumentation including angular rate sensors (ARS).

The calculation of accurate 3D position and orientation for a rigid body requires data collection of 6-DOF: linear acceleration (a_x, a_y, a_z) and angular velocity (ω_x, ω_y, ω_z). The mathematical calculation to account for rotation of a rigid body was done by using the screw-axis method. The quaternion was calculated using numerical integration via the 4th-order Runge-Kutta method.

A dynamic component test was designed and conducted with a linear impactor to validate the 3D stroke calculator. The test set up included a 6-DOF sensor pack mounted on a polyethylene stick with an offset. The stick was mounted on a base, which was pushed by a linear impactor with controlled speed. The sensor experienced 3D motion when the stick was decelerated by the base impacting a honeycomb backstop.

This method of 3D rigid body tracking has various crash testing applications. The authors compared occupant head kinematics among three different frontal offset crash modes. A finding of the study was that one test mode resulted in more driver head stroke (relative to vehicle interior) compared to the other two crash test modes. The maximum head stroke, compared to the least, was more by 64% (longitudinal) and 49% (lateral).

BACKGROUND AND PURPOSE

For crashworthiness engineers, time history of ATD (Anthropomorphic Test Devices) movement is necessary information to help analyze the performance of restraint systems. The movement, or stroke, is often calculated from double integration of linear accelerometers when direct measurement by a potentiometer is not available or too difficult. But this double integration method is may not be accurate enough for the ATD motions with large rotations. For example, a 5th%ile Hybrid III ATD in the front passenger seat experiences rotation (pitching) during rebound after loading the front passenger airbag (Figure 1) in NCAP front crash tests. As a simple solution, a 2D rotation matrix can be used for this type of crash test if pitching angular velocity was measured during the test.

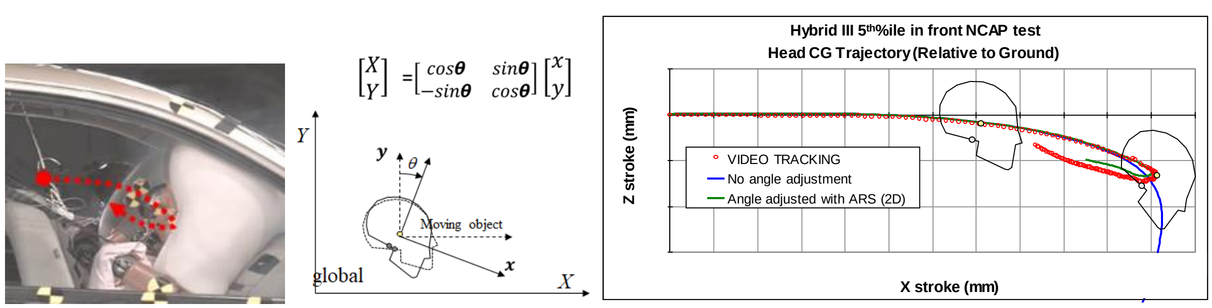


Figure 1. 5th%ile Hybrid III head stroke calculation for front impact crash test.

However, newer frontal crash tests like IIHS small overlap and NHTSA oblique tests, which have less overlap with the impact barriers, involve larger vehicle rotations than full-overlap frontal crash test. These test modes create complex 3D occupant motions compared to front rigid barrier tests. One example is the new NHTSA oblique test shown in Figure 2. In this test, the driver head experiences large rotation and no camera view is good for video tracking. Therefore, getting accurate head movement time history is very challenging. To overcome the challenge to calculate accurate 3D strokes in newer crash tests, the authors developed a calculator to get accurate motion with currently available instrumentation.

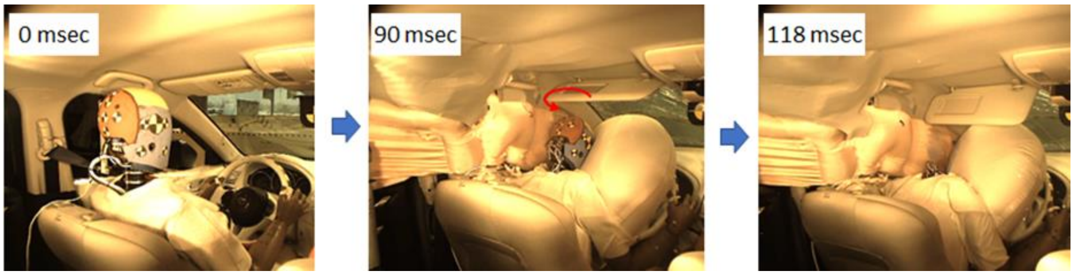


Figure 2. An example of NHTSA Oblique front impact test with large rotation of ATD head [1]

THEORY AND METHOD

To get accurate 3D position of a moving rigid body, like an ATD head in an offset crash test, all three linear accelerations need to be corrected by calculating three Euler angles by using measured angular velocities [2] before time integration or displacement (Figure 3).

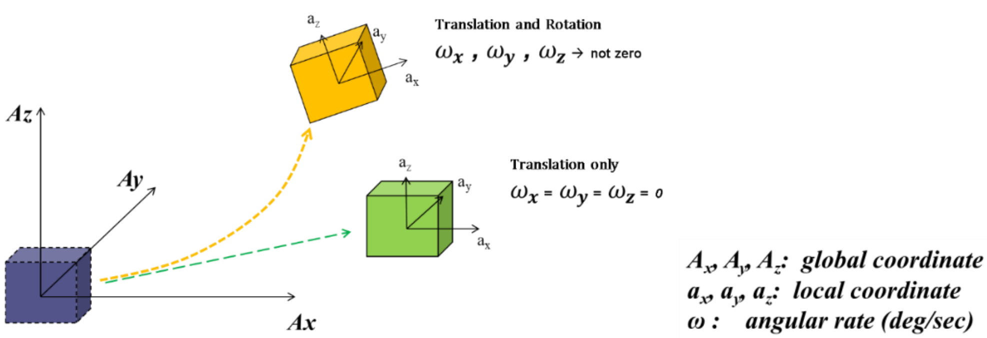


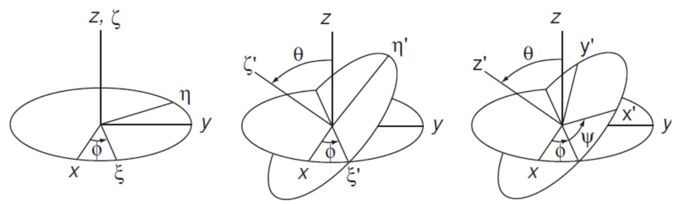
Figure 3. Consideration of angular rates for accurate 3-dimensional motions.

If all three angular velocities (ω_x, ω_y, ω_z, deg/second) are measured, along with linear accelerations, correction of linear acceleration can be done with a 3D rotation matrix **[R]** in figure 4. There are several methods to calculate the rotation matrix, but two methods, successive rotation and screw axis methods [3] were considered in this paper.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = [R] \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

Figure 4. Rotation matrix to adjust linear accelerations (X, Y, Z = corrected with angle and x, y, z = not corrected) [2].

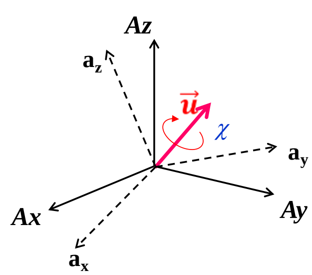
The successive rotation angle method rotates 3 axes continuously to achieve a new position in each time step using angular rate data as shown in Figure 5. It is basically a 3D version of 2D adjustment shown in Figure 1. But this method has two limitations which are Gimbal lock and complexity of calculation [2]. Gimbal lock is the case when there is more than one solution to the Euler angles calculated from angular velocities. The other challenge point is that this method requires complicated coding which could result in a higher chance of error, leading to a difficult debug process.



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

Figure 5. Successive rotation angle method: Euler angles (ϕ, θ, ψ) and associated rotational matrix equation [2], [3].

The problem of Gimbal lock can be resolved by using Euler parameters, which are unit quaternions [2]. The screw axis method uses Euler parameters to calculate the 3D rotation matrix as shown in Figure 6. The unit vector $\vec{\boldsymbol{u}}$ (Figure 6) is the axis for final rotation angle χ resulted from 3 Euler angle rotations. This study used the screw axis method for its simplicity in programming and freedom from Gimbal lock.



$$q_0 = \cos\left(\frac{\chi}{2}\right), \quad \vec{q} = [q_1, q_2, q_3] = \vec{\boldsymbol{u}}\sin\left(\frac{\chi}{2}\right), \quad q_0^2 + q_1^2 + q_2^2 + q_3^2 = 1$$

$$[\boldsymbol{R}] = \begin{pmatrix} q_0^2 + q_1^2 - q_2^2 - q_3^2 & 2(q_1q_2 - q_0q_3) & 2(q_1q_3 + q_0q_2) \\ 2(q_2q_1 + q_0q_3) & q_0^2 - q_1^2 + q_2^2 - q_3^2 & 2(q_2q_3 - q_0q_1) \\ 2(q_3q_1 - q_0q_2) & 2(q_3q_2 + q_0q_1) & q_0^2 - q_1^2 - q_2^2 + q_3^2 \end{pmatrix}$$

Figure 6. Screw axis method: Euler parameters and rotation matrix equation with quaternions [2], [3]

To get the rotational matrix **[R]**, q_0 and $\vec{q}$ need to be calculated using angular velocities measured in the physical test. Quaternions are a function of angular velocity, and they form a series of ordinary differential equations as shown in Figure 7. Angular velocities ω_x, ω_y and ω_z are measured by ARS on a rigid body.

$$\begin{Bmatrix} \dot{q}_0 \\ \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \end{Bmatrix} = \frac{1}{2}[Q]\begin{Bmatrix} 0 \\ \omega_b \end{Bmatrix}, \quad \text{Where, } \omega_b = \begin{Bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{Bmatrix} \text{ and } [Q] = \begin{bmatrix} q_0 & -q_1 & -q_2 & -q_3 \\ q_1 & q_0 & -q_3 & q_2 \\ q_2 & q_3 & q_0 & -q_1 \\ q_3 & -q_2 & q_1 & q_0 \end{bmatrix}$$

Figure 7. Time derivative of quaternions [2]

The authors calculated quaternions using numerical integration via the 4th order Runge-Kutta method [4]. Four unknown variables (quaternions) were expressed as a system of 4 ordinary differential equations, $f1$, $f2$, $f3$ and $f4$ shown below. The authors used MS Excel® to calculate quaternions, the rotational matrix **[R]** and the adjusted position of the rigid body. The inputs were 6-DOF data (3 linear accelerometers and 3 ARS) of two objects (i.e. ATD head and vehicle body) and the outputs are the corrected stroke of both objects.

$$\dot{q}_0 = \frac{-q_1\omega_x - q_2\omega_y - q_3\omega_z}{2} = f1$$

$$\dot{q}_1 = \frac{q_0\omega_x - q_3\omega_y + q_2\omega_z}{2} = f2$$

$$\dot{q}_2 = \frac{q_3\omega_x + q_0\omega_y - q_1\omega_z}{2} = f3$$

$$\dot{q}_3 = \frac{-q_2\omega_x + q_1\omega_y + q_0\omega_z}{2} = f4$$

VALIDATION

To validate the calculation method, a component test was devised to create a complex motion path of a known point. The component test setup allowed for accurate video analysis at multiple angles (top & side) of this point, as seen in Figures 8 and 9. At this known point, a 6-DOF sensor pack was installed. The purpose of the test was to calculate the path of the point using the 3D calculator with the 6-DOF sensor pack, and then compare the calculation result to the known motion of that point based on accurate video tracking.

The component test was comprised of a platform that could slide on tracks toward a rigid wall which would stop the platform's motion. A section of honeycomb was fixed to the wall to reduce the peak g experienced by the platform. A 5/8" diameter flexible plastic (polyethylene terephthalate) shaft approximately 2 feet in length, extending vertically, was attached to the platform. At the top of the shaft was a plate where the 6-DOF pack was mounted. The sensor pack was aligned to the platform so that the platform's sliding motion would be the X-axis, vertical from gravity would be the Z-axis, and the remaining orthogonal axis would be the Y-axis. A cantilever mass was attached to the shaft, offset in the Y-axis at a height of 18" from the base. The purpose of the mass was to introduce a twisting motion of the shaft when the platform was stopped by the rigid wall.

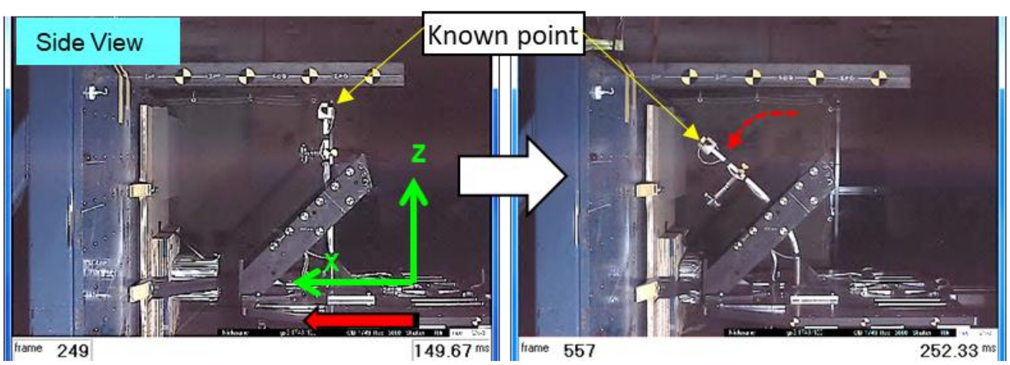


Figure 8. Side view of component test before impact with the rigid wall (left) and when the shaft is at peak forward rotation (right).

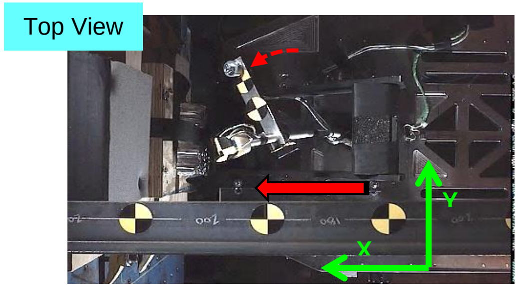


Figure 9. Top view of component test showing axial rotation of the shaft.

The result of the component test matched the calculation result explained in this paper as shown in Figure 10. Red color is the calculated stroke and blue is by video analysis. The calculated stroke data showed close correlation to video analysis. For comparison, the calculation result without 3D angular correction is also shown (green).

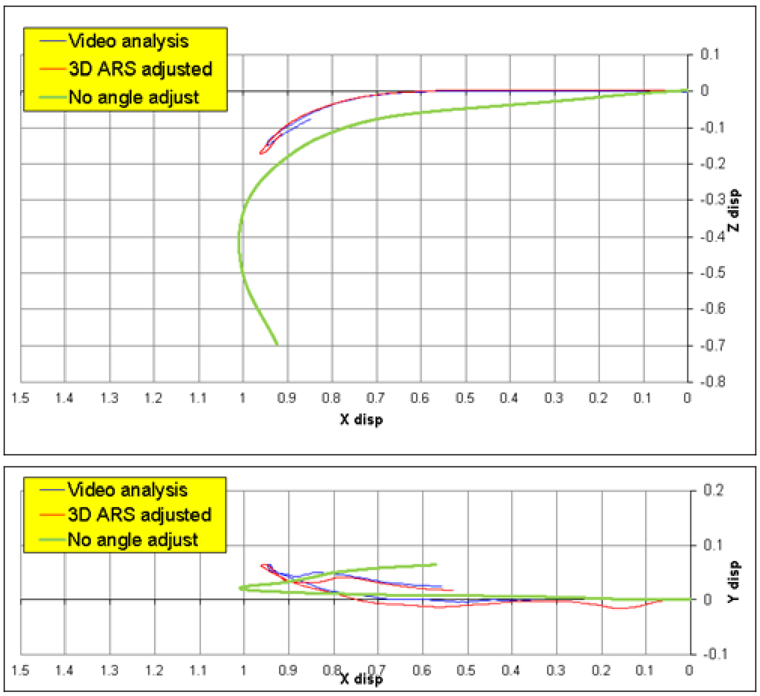


Figure 10. Comparison of results observed by video analysis vs 3D angular rate (ARS) correction calculation method vs original calculation method without angle adjust.

APPLICATION EXAMPLES AND DISCUSSIONS

The authors applied the 3D calculation method to two crash tests. The first application was a comparison of the front passenger head trajectory in an NCAP frontal impact sled test. In most cases, off-board video tracking can provide accurate head stroke information but, in some cases, the video target on the head C.G. becomes invisible due to the passenger airbag or the side curtain airbag blocking the camera view. In either case, 3D stroke calculation can be an alternative to video tracking. Figure 11 shows an example of this application to a front NCAP case study. As shown in Figure 11, maximum head stroke in the longitudinal and vertical axis are distinguishable from test to test, even though the head target was not visible.

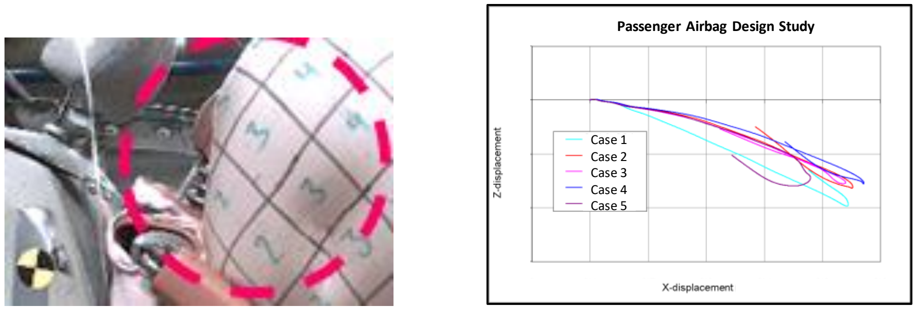


Figure 11. Example of head stroke analysis (Hybrid III 5th%ile head stroke in front NCAP sled test).

Another example was to compare a driver ATD head motion in three different frontal offset crash modes (TESTS A, B and C). The goal was to compare the maximum head stroke (relative to vehicle) in three (x, y and z) directions. The three test modes had different impact speeds, barrier types and amounts of overlap. Two of the tests used Hybrid III 50th%ile and the other used a THOR 50th%ile. All three tests were done with the same vehicle model for direct comparison. Data from 6-DOF sensors were measured for both the ATD head and the vehicle floor to calculate relative stroke. Head stroke results in side and top views are shown in Figure 12. In the case of TEST A, it had the largest stroke observed in all three directions. Compared to test B, maximum stroke was greater by 64% in the longitudinal direction and 49% in the lateral direction. Also, the head moved up (relative to vehicle interior) in early timing due to vehicle pitching.

The application is not limited to the examples shown in this paper. Crash tests with large vehicle rotation can get benefit from this 3D calculator as long as 6-DOF data were measured properly.

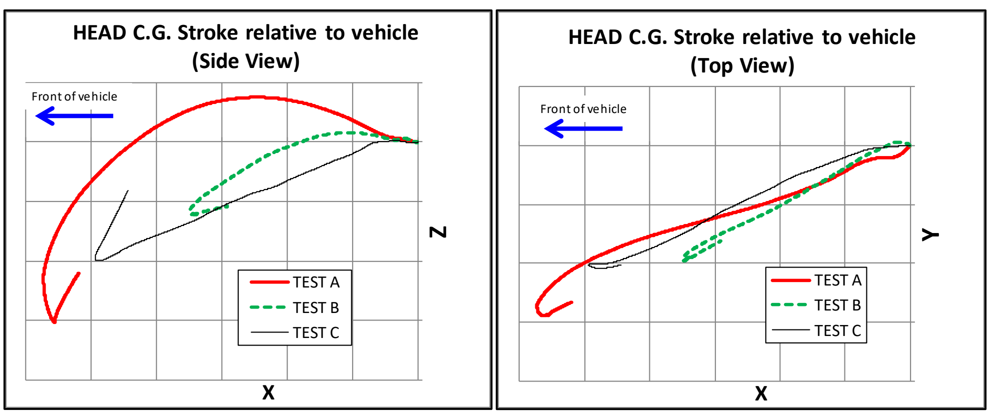


Figure 12. Example of head stroke calculation method – Comparison ATD head CG stroke relative to vehicle for three different frontal offset crash modes.

CONCLUSION

The 3D stroke calculator was developed using the screw-axis method and 4th-order Runge Kutta integration in this study. The calculator was validated by component testing, which demonstrated more accuracy than double-integration methods without angular correction. Example studies using the 3D calculator provided accurate stroke of an ATD head relative to the vehicle which could be valuable data for occupant restraint strategy and performance analysis. Furthermore, this 3D calculator could be used on any two rigid-body system with 3D rotational kinematics as long as 6-DOF sensor data and initial condition are measured.

LIMITATIONS

Theoretically, the method looks promising but there are limitations in actual application. The first limitation is that accurate initial conditions (position and angle relative to the ground) are necessary because this method is a typical initial value problem with explicit time integration. Also, the authors observed that the ARS could give invalid data if the ARS did not include shock-resistance feature or if the sensor mount location on the vehicle was involved in local deformation. The authors recommend the use of shock-resistant ARS mounted in an area with no deformation on the vehicle.

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