NHTSA OBLIQUE TEST DATA ANALYSIS METHOD BY LS-DYNA MODELING

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ABSTRACT

The National Highway Traffic Safety Administration (NHTSA) as an update to New Car Assessment Program (NCAP) for the model year 2020 vehicles will be introducing Oblique Impact Test procedure with a Research Moving Deformable Barrier (RMDB) and Test device for Human Occupant Restraints (THOR) as new Anthropomorphic Test Device (ATD) in both driver and passenger seat. During the oblique impact test, the vehicle translates and rotates in XY plane and as a result dummy moves in oblique direction inside the vehicle making a partial contact with the deployed airbag restraints. The NCAP update will also introduce the new head injury criterion for brain rotation measurement called Brain Injury Criterion (BrIC). Given the dynamics of oblique impact test, partial dummy interaction with restraints, and new head injury criterion BrIC it has become very critical to understand the vehicle and dummy motion in the three dimensional space during the test for the development of restraints system.

The objective of this study to generate 3-D translational and rotational motion of vehicle and dummy using “Rigid Body Prescribed Motion” numerical scheme of LS-DYNA solver by processing sets of test data output from accelerometers and Angular Rate Sensors (ARS) in vehicle and ATD.

A numerical model consisting of finite element vehicle model and finite element head model of Test device for Human Occupant Restraints (THOR) was developed. The LS-DYNA numerical model generates a global reference frame data format by transforming output from accelerometer and ARS in vehicle and ATD. The acceleration and rotational output data from the numerical model was co-related with acceleration and rotational from the NHTSA vehicle test RC5370 and used for model validation purpose. The results from video film analysis of vehicle motion in NHTSA test compared with generated translational and rotational motion from the numerical model as a final confirmation.

The oblique motion angle of dummy in vehicle during the oblique impact test is critical in determination of setup for the oblique sled testing. The output from the numerical model can be useful to determine the appropriate angle for the oblique sled testing. This numerical model can also be useful for the development of optimal restraints necessary in various crash impact modes.

INTRODUCTION

As full frontal vehicle impact tests with fixed rigid barrier are required in the FMVSS208 Occupant Protection and Regulation, the occupant's kinematics and injury mechanism understanding are important in automotive restraints suppliers and vehicle manufacturers. To better understand occupant kinematics and injury mechanisms, the video film analysis has been used to analyze ATD (Anthropomorphic Test Device)'s motion and trajectory.

Recently NHTSA announced their plan to update the New Car Assessment Program (NCAP) for model year 2020 vehicles. The major changes on 2020 NCAP includes, (1) Oblique Impact Test Procedure with Research Moving Deformable Barrier (RMDB), (2) the introduction of THOR (Test device for Human Occupant Restraint), and (3) The introduction of BrIC (Brain Injury Criteria) for NCAP rating matrix. NHTSA Oblique Impact Test specifies RMBD to impact into the test target vehicle at 15 degrees of oblique angle with 35% of impact area overlap (Figure 1). The oblique loading to target vehicle by RMDB creates a translational and rotational motion of target vehicle in XY plane. The oblique impact of RMDB caused the test target vehicle to experience the pitching and rolling motions as well as the yawing motion at the beginning of NHTSA Oblique Impact Test event.

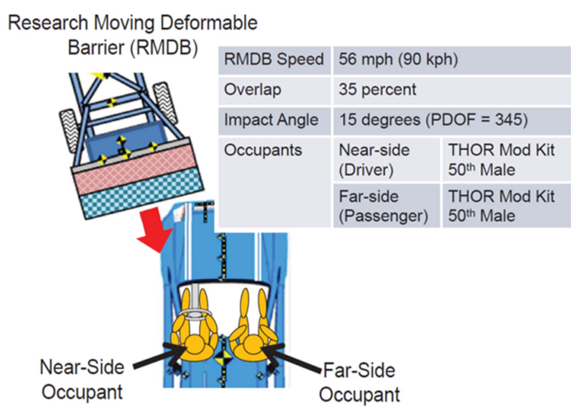

Figure 1. Test setup and descriptions of NHTSA Oblique Impact Test with RMDB [1].

The new Oblique Impact Test with THOR induces significant oblique direction translational and rotational motion of dummy in vehicle during the impact. A significant portion of THOR's head and chest hidden by the adjacent surrounded airbags, i.e. driver airbag, passenger airbag, curtain side airbag from the video camera view. The tracking marks on the dummy's head are often invisible from the video camera (Figure 2), and the video film analysis approach widely used in automotive industries is difficult to use for the occupant kinematics analysis of Oblique Impact Test.

Figure 2.THOR dummy interaction with restraint in NHTSA Oblique Impact Test.

Due to the interference from airbag restraint and interior environment, the rigid-body dynamics approach [2] and the multi-body numerical analysis procedure [3] of rigid-body dynamics approach can be an alternative solution of ATD's 3-D motion and trajectory calculation. The numerical implement-tation of the rigid-body mathematical equations requires iterative equations solving by using the Runge-Kutta Method. Recently, dummy's 3-D motion and trajectory calculated with multi-body occupant safety simulation software [4] or FE occupant safety simulation software [5]. Achieving ATD's 3-D motion and trajectory data using occupant simulation software requires an occupant safety simulation FE model, which necessitates significant resources and efforts in collecting and processing of engineering data, vehicle body structure, interior CAD data, occupant injury data, etc.

THOR HEAD CG 3-D MOTION CALCULATION PROCEDURE FOR THE NHTSA OBLIQUE IMPACT TEST

A new approach for THOR head's 3-D motion and trajectory calculation is proposed by utilizing a LS-DYNA FE model of vehicle along with LS-DYNA FE model of THOR head as a data processing tool of the vehicle and THOR test data. Rigid body modeling assumption is applied to the Head Model and Vehicle Model. Combining the Head Model with the

Vehicle Model becomes the new LS-DYNA numerical model as a data processing tool to achieve the THOR head's and vehicle's CG 3-D translational and rotational motion in the global reference frame. The important function of the data processing tool is to convert the acceleration and angular rate data in the local reference frame of THOR head to the 3-D motion and trajectory data of THOR head in the global reference frame. Multiple sets of the acceleration data measured from several locations over the vehicle body structure are also processed into the vehicle's 3-D translational and rotational motion in the global reference frame as well.

The displacements of THOR head in relative to the interior environments of the test target vehicle is calculated from the Head FE Model's displacements in the global reference frame subtracted from the Vehicle FE Model's displacements in the global reference frame. The calculation procedure of THOR head's 3-D translational and rotational motion is explained in the flow chart in Figure 3.

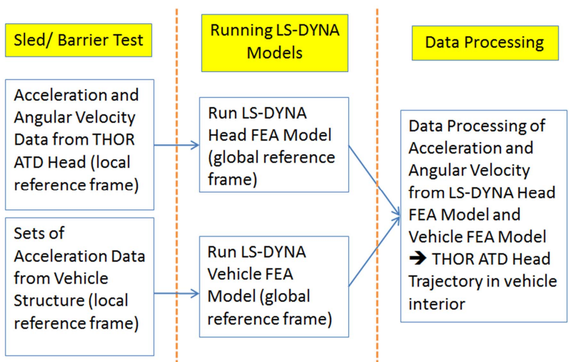

Figure 3. Numerical calculation procedure for THOR head 3-D motion under NHTSA Oblique Impact Test.

It is important to clarify the reference frame used for acceleration and angular velocity data in FE model and vehicle test (Figure 4). A local reference frame (x, y, and z) for the three accelerometers and three angular rate sensors defined at the CG location of THOR head. In the similar manner, a local reference frame (x, y, and z) defined at the vehicle's CG location of test target vehicle and its equivalent FE vehicle model. The global reference frame used in this study is fixed to the ground, and is the same as the FE model reference fixed frame

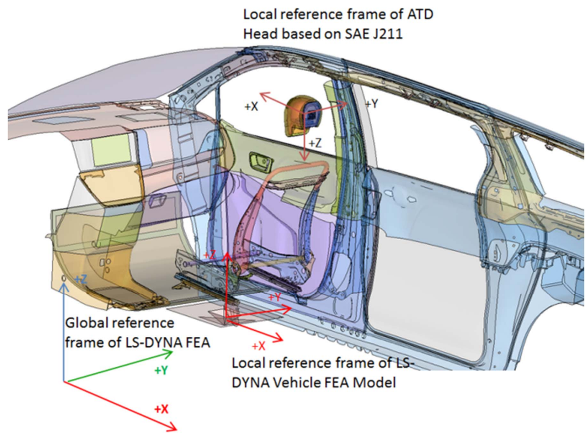

Figure 4. Local reference frame and global reference frame defined in LS-DYNA Head and Vehicle FE Models.

THOR HEAD CG 3-D MOTION CALCULATION IN GLOBAL REFERENCE FRAME FROM THE NHTSA OBLIQUE IMPACT TEST

In Oblique Impact Test with THOR, the video film analysis is challenging due to both the significant head oblique direction trajectory and the head rotational motion (Figure 5).

Figure 5.THOR head tracking marks hidden by passenger side airbag (NHTSA Test RC5370).

In this study the THOR head 3-D translational and rotational motion (6 Degrees Of Freedom) in the global reference frame calculated by performing LS-DYNA model analysis of the accelerations and angular rate data obtained from the Passenger Side THOR Head of NHTSA Oblique Impact Test (NHTSA Test RC5370). A LS-DYNA Head FE model (Figure 6) developed to process the accelerations and angular rate data obtained from the CG of THOR head during NHTSA Oblique Impact Test. The head FE model moves and rotates with respect to the CG of Head FE Model per "Prescribed Motion" as dictated by the acceleration and angular rate input data obtained from the NHTSA Oblique Impact Test.

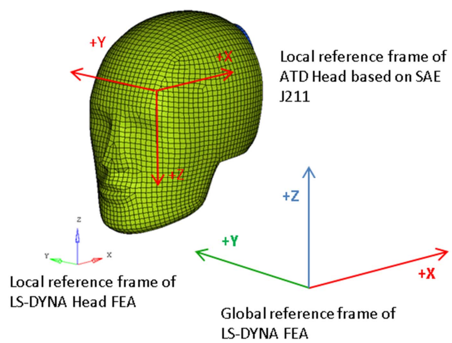

Figure 6. LS-DYNA Head FE Model for THOR head in local reference frame with local reference frame of SAE J211 Convention.

THOR head has three linear accelerometers and three angular rate sensors (ARS) located at the CG of THOR head. A set of three acceleration and three angular rate data recorded during the vehicle impact test event. This data is recorded in every time step with respect to the local reference frame (Figure 4) fixed at the CG of THOR head. It is important to remember that the local reference frame of Accelerometers and angular rate sensors is moving and rotating simultaneously with THOR head. Therefore, the acceleration and angular rate data of THOR Head's CG for each time step in local reference frame should be transformed to the acceleration and angular rate data in the global reference frame. The flow chart for the data processing procedure for the 3-D translational and rotational motion calculation of THOR head is shown below in Figure 7.

The validation of LS-DYNA Head FE Model can be achieved by showing that the angular rate and linear acceleration output data from LS-DYNA Head FE Model matches well with the angular rate and linear acceleration data measured from the THOR head from vehicle tests.

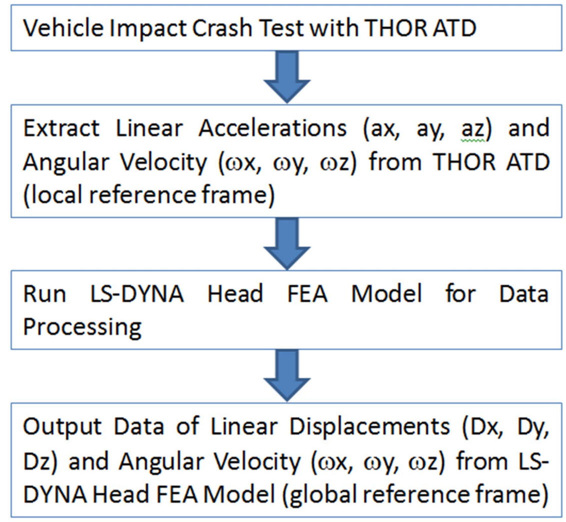

Figure 7. Flow chart of LS-DYNA numerical procedure for THOR head 3-D motion calculation in global reference frame.

Validation of LS-DYNA Head FE Model as a Data Processing Numerical Tool

The NHTSA Test RC5370 examined for the validation of this data processing approach based on LS-DYNA Head FE Model. Figure 8 shows that the acceleration and angular rate data results from Head FE Model are precisely overlaid with the test data of NHTSA Test RC5370. It confirmed that the LS-DYNA Head FE Model could serve well for the processing of accelerations and angular velocities of THOR Head.

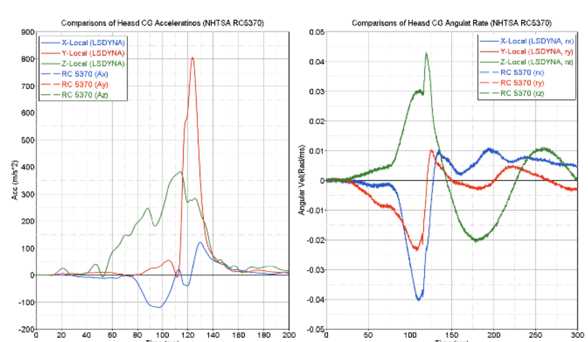

Figure 8. Comparison of output data from LS-DYNA Head FE Model with THOR Head test data from NHTSA Test RC5370.

THOR Head's Trajectory Calculation Using LS-DYNA Head FE Model for NHTSA Test RC5370

The left side plot of Figure 9 shows the acceleration data recorded in the local reference frame from the LS-DYNA Head FE Model overlaid with the acceleration data calculated from the LS-DYNA Head FE Model in global reference frame. The sharp peak of the y component acceleration of head CG (local reference frame) tells that the left side of the THOR head hit instrument panel surface. The THOR head rotation was induced by the THOR's face interaction with the passenger airbag cushion and the oblique directional motion of THOR during the NHTSA Oblique Impact Test. It is evident that the direction of THOR head contact with the instrument panel is z direction of the global reference frame from Figure 6.

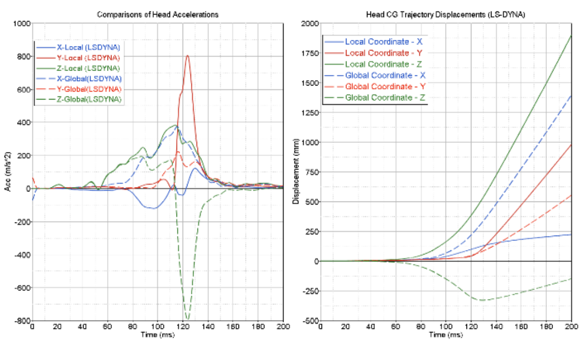

Figure 9. Comparison of accelerations and displacements of LS-DYNA Head FE Model in the local reference frame with the accelerations and displacements of LS-DYNA Head FE Model in the global reference frame (NHTSA Test RC5370).

The right side plot of Figure 9 shows that the head CG's x, y, z displacements in the local reference frame is compared with the results processed in global reference frame. An important point to mention is that THOR head's displacement in the x direction of local reference frame is 240mm at 200ms, but the head's displacement in the x direction of global reference frame is 1400mm at 200ms. Also, THOR head's y component displacement in the global reference frame is 550mm over 960mm of y component displacement in the local reference frame calculated from the accelerations of head CG at 200ms. Another point is that THOR head moves lower in the global z direction during most of the event duration, and this head motion is not intuitively comparable to 1900mm of z displacement in the local reference frame of THOR head. The data interpretation of displacement and rotation of LS-DYNA Head FE Model provides an understanding on the rotational behavior and oblique direction trajectory of the THOR head in the NHTSA Oblique Impact Test.

Figure 10 shows the overlaid pictures of Head FE Model's 3-D motion (0ms, 50ms, 100ms, 150ms) from the side view of the global reference frame. The Head FE Model turns 90 degrees to the left at 150 ms with respect to the x-axis of global reference frame, and the direction of y-axis of local reference frame of the Head FE Model becomes the direction of z-axis of global reference frame.

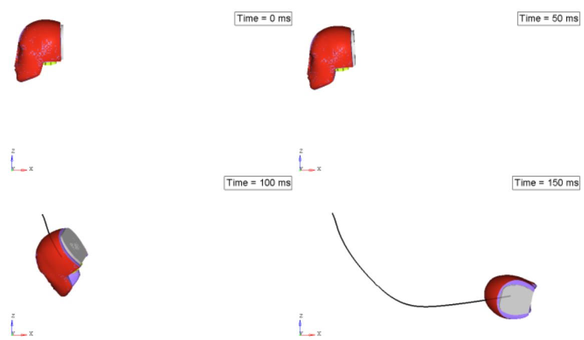

Figure 10. Head's translational and rotational motion processed from the LS-DYNA Head FE Model in the global reference frame (Events at 0ms, 50ms, 100ms, and 150ms of NHTSA Test RC5370).

3-D MOTION CALCULATION OF TEST TARGET VEHICLE IN GLOBAL REFERENCE FRAME FOR NHTSA OBLIQUE IMPACT TEST

Compared to traditional full frontal vehicle crash tests, the NHTSA Oblique Impact Test causes the impacted test target vehicle to be pushed away in the oblique direction with pitching, rolling, and significant yawing motions. Inevitably, the test target vehicle under NHTSA Oblique Impact Test goes through 3-D translational and rotational motion. To understand the post-impact 3-D motion of test target vehicles, analytical model approaches based on mathematical formulations have been developed in academia and automotive industries [6]. Analytical model approach requires solving differential equations of a numerical model by using the Runge-Kutta numerical method. The numerical model procedure based on analytical model approach has been further extended to accident reconstruction applications to understand the complicated vehicles' collision accident events.

Recently, the FE modeling approach enables automotive engineers to investigate the vehicle post-impact 3-D translational and rotational motion in a detailed realistic level. The full-scale FE simulation of vehicle impact crashes provide an essential understanding of vehicle structural deformations and vehicle post-impact kinematics, such as vehicle 3-D translational and rotational motion. The most common FE program used for vehicle impact crash simulations is LS-DYNA nonlinear FE software [7]. The full-scale nonlinear FE vehicle crash simulation model is made up of a large number of component parts' FE models, engineering material data, component parts' connection modeling, and proper contact definitions between structural component parts, etc.

An approach proposed in this study is to calculate a vehicle's 3-D translational and rotational motion by running the LS-DYNA Vehicle FE Model with prescribed motion input data (multiple sets of x, y, z accelerations) measured from the accelerometers affixed on the body structure of the test target vehicle (Table 1). Instead of building a full-scale LS-DYNA vehicle FE model, a simplified half-vehicle FE model (Figure 11) is developed with the rigid body assumption of a vehicle body structure. Also this simplified rigid body LS-DYNA Vehicle FE Model has several FE accelerometers planted at the same locations as the test target vehicle at NHTSA Test RC5370.

Table 1. Accelerometers' axis definition and locations for NHTSA Test RC5370

No. (Axis)	Accelerometer Location	Measurements(mm)		
		X	Y	Z
#1 (X,Y)	LH Rear Sill	880	-578	1196
#2 (X,Y)	RH Rear Sill	861	583	1198
#3 (X,Y,Z)	Vehicle CG	2545	2	1312
#4 (X)	Instrument Panel	2643	11	890
#5 (X,Y,Z)	Driver Seat Track	2046	-656	1287
#6 (X,Y,Z)	Floor Pan	3296	-451	1141
#7 (X,Y,Z)	Passenger Seat Track	2061	653	1294
#8 (X,Y,Z)	Vehicle CG (Rdt)	2555	2	1312
#9 (X,Y)	LH Rear Sill	880	-578	1196

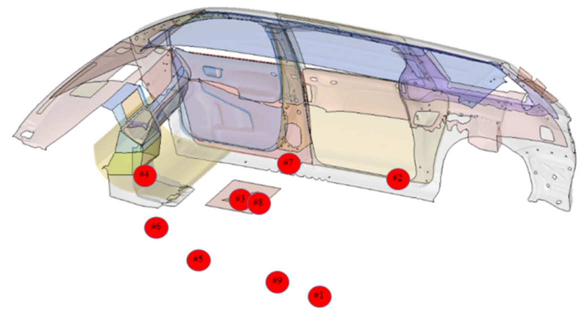

Figure 11. LS-DYNA Vehicle FE Model with FE accelerometers planted on the vehicle body structure (NHTSA Test RC5370).

The prescribed motion input data to the Vehicle FE Model consists of five selected sets of acceleration x, y, z data captured from the accelerometers of test target vehicle. This Vehicle FE Model serves as a data processing tool of the acceleration data obtained from the NHTSA Oblique Impact Tests for the calculation of the test target vehicle's 3-D translational and rotational motion in the global reference frame.

The flow chart for the 3-D translational and rotational motion calculation of the test target vehicle is shown below in the Figure 12.

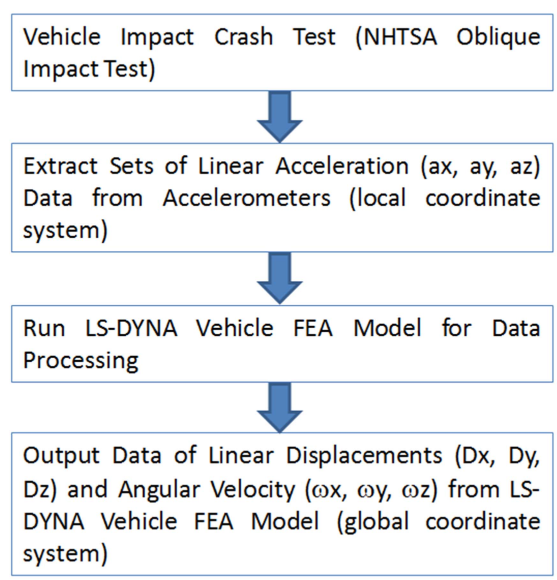

Figure 12. Flow chart for the translational and rotational motion calculation of Vehicle CG in global reference frame.

Evaluation of Acceleration Data of NHTSA Test RC5370 for the Selection of Input Data to LS-DYNA Vehicle FE Model

An important consideration for this calculation procedure is the selection of the available acceleration data for the input data to LS-DYNA Vehicle FE Model. Sometimes accelerometers are attached on a less rigid surface of the vehicle body structure, and the accelerometers' signal data include interference noises generated from structural vibrations. To evaluate the quality of captured acceleration data for the input to the LS-DYNA Vehicle FE Model, the x, y, z acceleration data obtained from the test target vehicle structure were integrated with respect to time in the local reference frame. Figure 13 shows the data evaluation results from the NHTSA test.

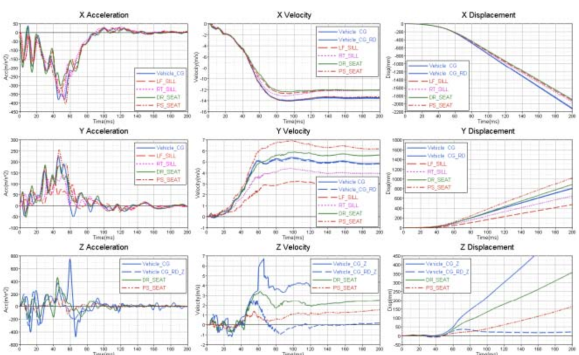

Figure 13. Velocities and displacements data from the integration of accelerometer data in the local reference frame from NHTSA Test RC5370.

After reviewing the velocities and displacements from the data evaluation in Figure 13, x and y components velocity and displacement data from the integration of the acceleration have shown consistent and reasonable displacements. The z component velocity data integrated from the Vehicle CG z component accelerometer has shown data corruption, and therefore the acceleration data measured from the Vehicle CG accelerometer can't be used. Accelerometer data from the Redundant Accelerometer at the Vehicle CG are used for this calculation process. Still the z displacements double integrated from the "driver seat track" and "passenger seat track" are 360mm and 170mm at 200ms each. 360mm of z displacement of driver seat track is less likely from NHTSA Oblique Impact Tests. Also z component accelerometers at the Left and Right Sills were not installed at the target test vehicle of NHTSA test. Three other accelerometers were installed at the instrument panel and driver side floor pan and left rear sill to capture the acceleration signals of the test target vehicle of the NHTSA test.

Along all with the difficulty encountered during the evaluation process of accelerations, five sets of accelerations from the test target vehicle were selected from the nine sets of acceleration data available from the NHTSA test. Further it is critical to pay more attention to the z component of accelerations measured at the test target vehicle structure for the proper pitching and rolling motion calculation using the LS-DYNA vehicle FE model.

Test Target Vehicle's 3-D Motion Calculation from LS-DYNA Vehicle FE Model with NHTSA Test RC5370

In Figure 14 the comparisons of LS-DYNA vehicle CG x, y trajectory, pitching and yawing animation with Test Videos from NHTSA test. The yawing motion of Vehicle FE Model at 160ms seems matched well with NHTSA test, but the pitching motion of the Vehicle FE Model looks to be more than that of the NHTSA Test.

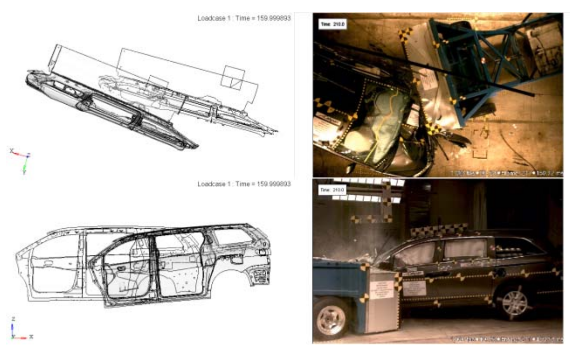

Figure 14. Comparison of vehicle kinematics of LS-DYNA Vehicle FE Model with NHTSA Test RC5370 (Event at 160ms).

The Video film analyses for NHTSA test conducted to validate the effectiveness of LS-DYNA vehicle FE model. The vehicle CG x, y displacements of the vehicle FE model compared with the results of test video film analysis evaluation of NHTSA test (Figure 15). The X displacement output from vehicle FE model compared well with x displacement of the test target vehicle from the video film analysis of the NHTSA Test. The Y displacements of LS-DYNA Vehicle FE Model shows 37 mm (Event at 60ms), 44 mm (Event at 80ms), and 27 mm (Event at 160ms) larger than y displacements of test target vehicle from the video film analysis of NHTSA Test RC5370. These differences could be explained as the signal data interference of y component acceleration data measured from the vehicle structural vibration. Another possibility is the difference from the perspective of the reference x, y-axis of video film analysis with 15 degrees oblique angle of target test vehicle used at NHTSA Test RC5370.

The yawing angle calculation of the Vehicle FE Model matches very well with the results of video film analysis of NHTSA Test RC5370 (Right side plot of Figure 15). Vehicle pitching motion from the Vehicle FE Model keeps increasing with time, but the test video film analysis reveals the early engagement of the vehicle's left front corner structure produces the nose diving pitching motion until 70ms. After the early engagement, the pitching motion keeps sustaining until the separation of RMDB from the impacted test target vehicle. This discrepancy of pitching motion result of LS-DYNA Vehicle FE Model with vehicle motion calculation using test video film analysis is mainly attributed from the z component acceleration data containing vibration noises inherited from the vehicle body structural vibration.

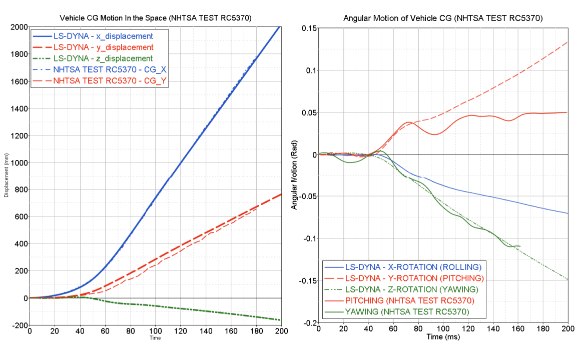

Figure 15. Comparison plots of vehicle CG X, Y, Z displacements and angular motions of LS-DYNA Vehicle FE Model with Results from Video Analyses of NHTSA Test RC5370.

It has been known that the vertical components of acceleration signals are relatively easy to be superimposed by the interference of vehicle structures' vibrations due to structural impact. Due to the vertical acceleration influenced by the structural impact induced vibrations, the pitching and rolling motions from the LS-DYNA Vehicle FE Model become more amplified than the reality of NHTSA Test RC5370.

THOR HEAD'S TRAJECTORY RELATIVE TO VEHICLE INTERIOR IN NHTSA OBLIQUE IMPACT TEST (NHTSA TEST RC5370)

The THOR head's 3-D translational and rotational motion in the target test vehicle's interior environments is calculated using an integrated LS-DYNA Head FE Model with LS-DYNA Vehicle FE Model. Figure 16 shows passenger side THOR motion of NHTSA Test RC5370 at 20ms, 60ms, 80ms, 90ms, 100ms, 110 ms.

Figure 16. Pictures of passenger side THOR motion of NHTSA Test RC5370 (Events at 20ms, 60ms, 80ms, 90ms, 100ms, 110ms from top left to bottom right).

Figure 17 shows that LS-DYNA Head FE Model's kinematics well compared with the motion of NHTSA Test RC5370 for events at 50, 90, 110, and 130ms.

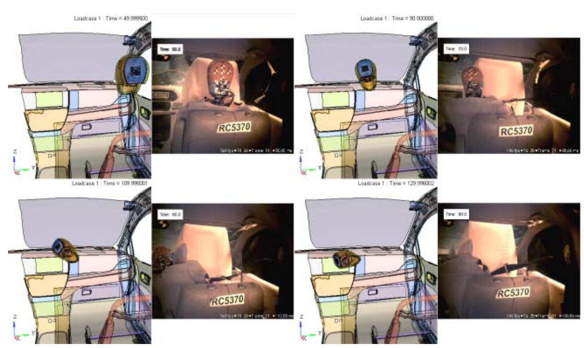

Figure 17. Comparison of head kinematics LS-DYNA Head FE Model with NHTSA Test RC5370 (Events at 50ms, 90ms, 110ms, and 130ms).

After performing video film analysis of the passenger side THOR head for NHTSA Test RC5370, y relative displacement of LS-DYNA Head FE Model to the vehicle interior matches well to the y displacement of THOR head relative to the vehicle interior (Right side plot of Figure 18). There is no available test video for the THOR head' x trajectory from the NHTSA Test, but THOR Head of the NHTSA Test collided strongly with the IP (Instrument Panel) surface. The x displacement of Head FE Model in the Vehicle FE Model are verified using the geometric penetration of the side face of the Head FE Model to the IP surface, the penetration of which is about 35 mm at 130 ms.

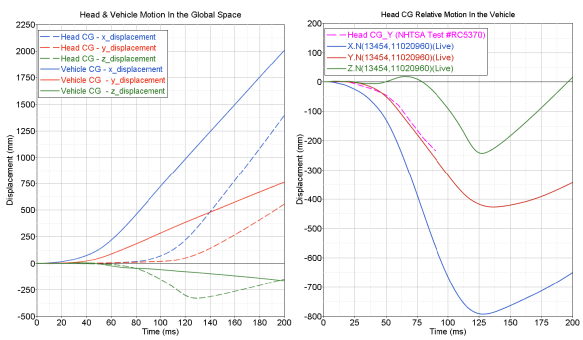

Figure 18. X, Y, and Z displacements of LS-DYNA Head FE Model and Y displacement of THOR head from video analysis of NHTSA Test RC5370.

Now x, y and x, z displacement trajectories of THOR Head relative to the vehicle interior for NHTSA Test RC5370 are shown in Figure 19. Left side of Figure 19 produces 24.9 degrees of trajectory angle of THOR Head of NHTSA Test RC5370. This head trajectory angle information is critical to designing the cushion panel contour of passenger airbag under the NHTSA Oblique Impact Test. This head trajectory angle information is also used for selecting the setup yaw angle of the sled test device which is replicate of the NHTSA Oblique Impact Test. Another finding from the right side of Figure 19 is that THOR head travels -240mm in the vertical direction until hitting the IP surface.

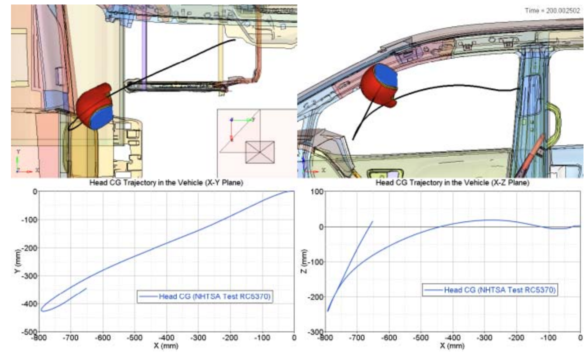

Figure 19. X,Y and X,Z trajectory plots of LS-DYNA Head FE Model based on THOR Head of NHTSA Test RC5370 (Head Trajectory Angle = 24.9 Deg.

CONCLUSIONS

This study introduced a new LS-DYNA FE Model approach for 3-D translational and rotational motion calculation of THOR head by processing sets of test data from accelerometers and Angular Rate Sensors (ARS) of vehicle and THOR by utilizing "Rigid Body Prescribed Motion" numerical scheme of LS-DYNA. An Important task for the calculation of 3-D translational and rotational motion of the test target vehicle is the selection process of the available acceleration data for the input data to the LS-DYNA vehicle FE Model.

THOR head's 3-D translational and rotational motion from numerical analyses of LS-DYNA FE Models are confirmed by the video film analyses of occupant motion in test target vehicle test of NHTSA Test RC5370. Due to the yaw motion of the test target vehicle under NHTSA Oblique Impact Test, THOR head's oblique trajectory angle information is even more critical in the determination of setup angle for the oblique sled tests. This numerical modeling approach serves to develop new safety restraints devices for various impact conditions by providing THOR head's 3-D motion information for oblique impact condition.

The next step in improving the predictability of pitching and rolling motion of LS-DYNA Vehicle FE Model will be to add extra accelerometers at the different locations over the test target vehicle's body structure. This extra acceleration information will help a better vehicle CG's 3-D calculation performed by the LS-DYNA Vehicle FE Model.

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