

A Method for Determining the Vehicle-to-Ground Contact Load during Laboratory-based Rollover Tests

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ABSTRACT

Many rollover safety researches have been conducted experimentally and analytically to investigate the underlying causes of vehicle accidents and develop rollover test procedures and test methodologies to help understand the nature of rollover crash events. In addition, electronic and/or mechanical instrumentation are used in dummy and vehicle to measure their responses that allow both vehicle kinematics study and occupant injury assessment. However, method for measurement of dynamic structural deformation needs further exploration, and means to monitor vehicle-to-ground contact load is still lacking. Thus, this paper presents a method for determining the vehicle-to-ground load during laboratory-based rollover tests using results obtained from a camera-matching photogrammetric technology as inputs to a FE SUV model using a non-linear crash analysis code. Results obtained from a FE vehicle model simulation of an SAE J2114 dolly test represent the first time a promising means with which the dynamic contact loads between the vehicle roof and ground during this rollover mode can be quantified.

INTRODUCTION

Rollover crashes are the most complicated and yet least understood one among all the vehicle crashes. Many rollover safety researches have been conducted experimentally and analytically to investigate the underlying causes of vehicle accidents and develop rollover test procedures (Summers and Hicks, 1997) and test methodologies (Chou et al. 2005) to help understand the nature of rollover crash events pertaining to both vehicle and occupant kinematics. Studies of the vehicle and/or occupant kinematics during rollover crashes, in turn, help understand occupant injury mechanisms and develop countermeasures for improved rollover occupant protection.

To investigate the vehicle crashworthiness and development of occupant protection devices during rollovers require in general several test modes to replicate different real world rollover scenarios. Chou et al. (2005) conducted an extensive literature review of rollover test methodologies, including FMVSS 208 dolly test, curb-trip

test, corkscrew test, etc. and various component test methodologies along with a summary of the pros and cons of those tests. Therefore, conducting inclusively available rollover tests to evaluate the overall rollover crashworthiness of a car and develop associated protection systems seem to be unrealistic, for such tests are very expensive, especially during the development stage of a new car line. As a result, replication of vehicle motion of various rollover crash modes is resorted to a feasible suite of existing vehicle level and/or sub-system level rollover test procedures, development of which can be accomplished by mathematical modeling and/or CAE using either rigid-body-based and/or deformable-body based approaches (see Chou et al. 1998). It should point out that both the test and modeling methodologies are developed interactively with each other. Experimental data obtained from testing can be used for developing rollover CAE models that not only replicate vehicle motion under similar test conditions, but also can provide roll or no-roll test conditions for experimental test setups. Analyses of simulated results provide valuable feedback to help enhance the test procedures. Testing with enhanced procedures can provide additional data for continued model refinements. In addition, those scenarios not investigated by experiments can be supplemented with numerical models, once they are validated.

This study serves as an exemplary of another interactive development where analysis of test data supplement numerical model to obtain needed information that cannot be achieved through measurement with electronic instrumentation. This paper describes a method using a nonlinear FE crash code capability via a provision of using prescribed vehicle motion feature for determining vehicle-to-ground load (or force), which cannot be measured at existing test laboratories where instrumentation capability may be lacking.

BACKGROUND

In practical rollover test setups as mentioned in the rollover test methodologies reviewed by Chou et al. (2005), electronic and/or mechanical instrumentation are used in dummy and vehicle to measure their responses that allow both vehicle kinematics study and occupant injury assessment. Generally speaking, channels that

are used to collect data include, but not limit to the following:

- Tri-axial linear accelerometers at vehicle CG
- Angular rate sensors for roll/pitch/yaw measurements (currently, most rollover tests monitored roll rate only, pitch and yaw rates may be obtained by using IMU (Inertia Measurement Unit) which has three linear acceleration and three angular rate measurements capacity)
- Strategic locations for mounting accelerometers at side rail, etc.
- Off-board and onboard cameras with calibration to allow film analysis
- Timing marks and clock
- Instrumented dummies
- Belt load, if dummies are restrained
- Dimensional analysis (DA) of pre- and post-test measurements
- Still photos to document pre-test set up conditions and post-test configuration.

However, James et al. (1997) reported that appropriate vehicle and dummy instrumentation has yet to be developed to measure all of the variables of interests. For example, (1) Method for measurement of dynamic structural deformation also needs to be explored, and (2) Means to monitor vehicle-to-ground contact load is still lacking. Recent progress and/or start-of-current technology pertaining to these two areas are briefly summarized below:

(1) Method for measurement of dynamic structural deformation:

Vehicle structures generally deform as a result of vehicle-to-ground contact in rollovers. Statically, structural deformation can be made using dimensional analysis (DA) of pre- and post-rollover vehicle configurations with CMM (Coordinates Measurement Machine). Such static measurements cannot provide deformation-time history, and are not necessarily indicative of maximum dynamic deformation encountered during a rollover due to "spring-back" when DA is taken. Dynamic means to monitor structural deformation has long been sought by many researchers. In 2005, McClenathan et al. used image analysis or motion tracking programs to analyze digital images of targets placed on various vehicle interior locations and dummy head when recorded using high speed digital cameras. The post-process tool for analyzing images in three-dimensional sense requires development of new and/or improvement of existing methodologies. Another approach using 3D photometry, namely a camera-matching photogrammetric technique developed by Fenton et al. (2001) for determining crash data in accident reconstruction deemed to be potentially applicable. This method was then explored by Chou et al. (2006) in re-analyzing a segment of images of rollover sequences, particularly with focus on structural deformations of a vehicle in an existing SAE J2114 dolly

test. This study found that the photogrammetric method is a useful tool to extract vehicle kinematics from test video. Since the test was previously conducted without using quality digital cameras and with lacking of appropriate calibrations, such as facility setting, markings etc., done prior to test, the accuracy of structural deformations obtained in this study was not certain. Therefore, this camera-matching photogrammetric technique was further investigated by Rose et al. (2008) with needed digital cameras and required calibrations for image analysis. Results indicated that this technique has a high potential in yielding dynamic data of vehicle structural deformation during rollovers when the method and its associated process are fully developed and implemented.

(2) Means to monitor vehicle-to-ground contact load:

Although commercial pressure mats are available for measuring contact forces, these mats cannot allow continuous monitoring of impact loads, thus unable to provide the time histories. Load cells are well known and widely adapted for measuring impact forces in crash safety testing. However, in most laboratory environments, load cells are not instrumented on the surface along the path along which the vehicle rolls during a rollover test, thus unable to monitor the vehicle-to-ground contact force. Theoretically, should one consider a vehicle as a whole in a total system, its kinematics can be described by a 6-degrees-of-motion (DOF) at its center of gravity. Treatment of a vehicle as a rigid body motion needs six known quantities to define its motion. In theory, linear accelerometers can be mounted at six different locations to measure their respective accelerations. Mathematical treatment of this approach was presented by Friedewald (1995, 1996). However, this approach has been attempted by many researchers in the '70 to determine the acceleration at the head CG using external linear acceleration measurements. Accuracy of accelerometer readings and drifts (or noise) may cumulate enough errors to cause numerical instability in solving the equations of motion (Chou et al. 1976). Disorientation of accelerometers located in the crash zone will also pose similar problems and difficulties. Although Friedewald (1995, 1996) has provided some results from his analysis, the accuracy of which remains unanswered.

It should be remarked that recent angular rate sensor technology has advanced to IMU (inertia measurement unit) package with capability of measuring three linear accelerations and three angular rates. An IMU can be mounted at the vehicle center of gravity to provide 6-DOF data for its 3D motion. Accuracy of such instrument in rollover with large structural deformation has not yet been fully proven.

Another approach to obtain 3D motion of a vehicle during a rollover crash is to use a reconstructed model from 3D photogrammetry by Rose et al. (2008) as mentioned above. For a 3D rigid body motion,

equations of motion of a rigid body under the action of external forces are:

$$M\ddot{X}_i^{cm} = F_i^x \quad (1)$$

$$J_{ij}\dot{\omega}_j + \epsilon i_{jk}\omega_j J_{kl}\omega_l = F_i^\omega \quad (2)$$

where M = diagonal mass matrix

J = inertia tensor

X^{cm} = location of the center of mass

ω = angular velocity of the body

F^x = generalized forces

F^ω = generalized torques

For given external forces, the acceleration vector $\ddot{X}$ and angular velocity vector ω can be solved. Conversely, in theory, if the motion, namely, $\ddot{X}$ and ω of a rigid body is given, then, external forces can be found by numerically solving Eqs (1) and (2) in reverse.

For a given laboratory-based rollover test, if one considers vehicle-to-ground contact force as “external forces”, which can be determined if complete vehicle motion at its center of gravity. Results from camera-matching photogrammetry technique developed by Rose et al. (2008) presented above allow realization of determining vehicle-to-ground force. However, it should be noted here that numerically solving Eqs.(1) and (2) simultaneously is not an easy task. A special feature in LS-DYNA3D is capable of tackling numerical manipulation of such problem. The methodology and associated technical approaches used in this study are presented in the following sections.

METHODOLOGY

In order to demonstrate use of the non-linear FE code, LSDYNA-3D, for developing a methodology to determine the vehicle-to-ground contact load (or force) when a vehicle hits the ground during a rollover event, an SAE J2114 laboratory-based rollover test is used. The technical approaches are described in the following:

GENERATION OF A FEA MODEL OF THE TEST VEHICLE:

The FE vehicle model used in this study was an SUV (Ford Explorer) model previously developed by Hu et al. (2007). In this model, several sub-models shown in Figure 1, including a vehicle structure sub-model, four tire sub-models from eta/VPG, two suspension sub-models were first developed and then integrated together. The full vehicle model consisted of about

100,000 elements. Piecewise linear plasticity material were used for most structural members. The power-train components were defined as rigid material. Lumped masses were added to the model to account for all non-structural components. A Mooney-Rivlin type rubber material was defined for the tire, and an airbag model was defined to simulate the tire pressure. Several validations have been conducted to each sub-model. The tire and suspension sub-models were also validated against previous experimental data by Lee et al. (1997) and Zhang et al. (1998), respectively.

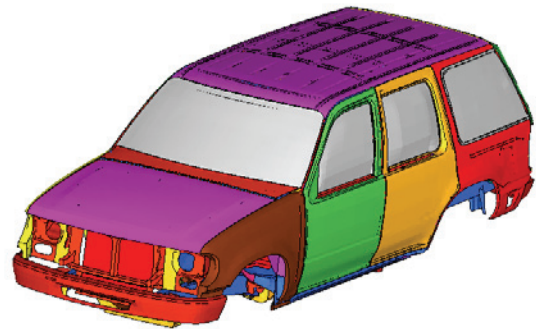


Figure 1a: Structure sub-model

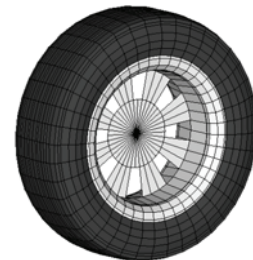


Figure 1b: FE tire sub-model

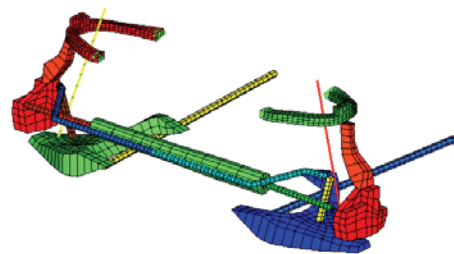


Figure 1c: Frontal suspension sub-model

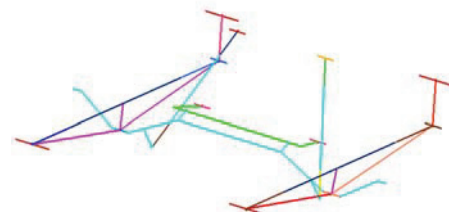


Figure 1d: Rear suspension sub-model

Figure 1: FE vehicle model consists of four sub-models