

HIC(d) and Its Relation With Headform Rotational Acceleration in Vehicle Upper Interior Head Impact Safety Assessment

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ABSTRACT

Upper interior head impact safety is an important consideration in vehicle design and is covered under FMVSS 201. This standard generally requires that HIC(d) should not exceed 1000 when a legitimate target in the upper interior of a vehicle is impacted with a featureless Hybrid III headform at a velocity of 15 mph (6.7 m/s). As HIC and therefore HIC(d) is based on translational deceleration experienced at the CG of a test headform, its applicability is often doubted in protection against injury that can be caused due to rotational acceleration of head during impact. A study is carried out here using an improved lumped parameter model (LPM) representing headform impact for cases in which moderate to significant headform rotation may be present primarily due to the geometric configuration of targets. The present LPM is an extension of an earlier work and its properties are arrived at using responses obtained from analyzing equivalent finite element models with the explicit LS-DYNA code. It is observed that compliance to FMVSS 201 requirement will generally imply low rotational acceleration although theoretically even for low HIC(d) values, the resultant contact angle can potentially cause headform peak rotational acceleration to be above a reported concussion threshold range.

INTRODUCTION

Investigation of fatalities suffered by occupants of vehicles involved in collisions points out that a significant number of those are due to severe head injury [1]. These injuries occur when an occupant's head is struck against the interior of a vehicle during a collision. In order to reduce the occurrences of head injuries with an AIS rating exceeding 2, the National Highway Traffic

Safety Administration (NHTSA) introduced a mandatory head impact safety requirement for all vehicles of gross vehicle weight rating (GVWR) up to 10000 pounds (4540 kg). This extended FMVSS 201 regulation dictates that when the upper interior of a vehicle is impacted with the forehead of a featureless free-motion Hybrid III headform at a speed of 15 mph (24 kph), HIC(d), an acronym for Head Injury Criterion (dummy), should not exceed 1000. In areas of the vehicle upper interior where deployable inflatable curtain is provided, the compliance criterion can be met for a reduced headform impact speed of 12 mph (19.2 kph).

Compliance to the safety requirement mentioned above implies that energy-absorbing countermeasures of adequate crush dimension should be designed covering areas of high stiffness within a vehicle's upper interior. Often, head impact countermeasures (such as foam or crushable plastic ribs) will be concealed by interior trim and headliner, and will not be visible to the occupants of a vehicle. However, it has been sometimes found in headform impact tests that even for relatively rigid targets not covered adequately by protective energy-absorbing countermeasures, low HIC values may result due to headform rotation actuated by target geometry or orientation of headform prior to impact. It has been shown in [5] that inclined impact on a target can cause reduction of HIC due to decrease in impact duration or peak translational deceleration depending on target rigidity. However, as HIC is based on resultant translational acceleration of headform CG, it may appear that it has no bearing on rotational acceleration which is thought to play an important role in closed head injury by researchers in biomechanics and neurology [2, 3]. An aim of the current study thus is to investigate, with the aid of simulation, the levels of rotational acceleration that can possibly be generated in vehicle upper interior headform impact scenarios. The investigation carried out here is accomplished with the help of lumped parameter

and finite element-based models. A nonlinear lumped parameter model (LPM) applicable to normal impact without headform rotation was initially presented in [4] using closed-form solutions. Later, an improved LPM with a nonlinear spring employing numerical integration and capable of representing both linear and rotational motion of headform was introduced in [5]. In the present study, the LPM of [5] has been further enhanced by incorporating piecewise linear representation of unloading [6] which leads to more realistic shape of translational deceleration in its descending phase when compared to test-based responses and consequently, better prediction of headform contact duration with an impacted target. A validated finite element model (FEM) [6] of the featureless Hybrid III headform stipulated in the FMVSS 201 standard is used for establishing confidence in angular acceleration variations obtained from the present enhanced LPM. To the authors' best knowledge, angular acceleration time histories from vehicle upper interior headform impact tests have not been reported in literature. The FEM-based simulation has been carried out with the explicit LS-DYNA solver. For two headform impact targets yielding contrasting HIC(d) values, good correlation is obtained between the results of FEM-based analysis and equivalent representations of current enhanced LPM. As the validated LPM is an extremely efficient tool for parametric studies, it is utilized here for studying the effect of headform contact angle (i.e. the angle between the vertical axis through headform CG and the line joining the CG to the location of the resultant contact force) on HIC(d) and peak rotational acceleration.

TEST PROCEDURE FOR VEHICLE UPPER INTERIOR HEAD IMPACT SAFETY

According to the FMVSS 201 standard for upper interior head impact, automotive manufacturers have to ensure that HIC(d), a parameter derived from 36 ms HIC to empirically account for neck restraint in a dummy, should not exceed 1000 when various targets on a vehicle's upper interior are impacted with a free-motion Hybrid III headform of mass 4.5 kg at a speed of 15 mph (24 kph). Typical targets inside a vehicle such as on A-pillar and front header are shown in Figs. 1 and 2 respectively. The headform needs to be oriented at each target in a manner that is likely to yield maximum HIC(d). Typically, this would occur when the headform impact velocity is nearly normal to the target surface. However, it needs to be ensured that the center of the forehead zone of the headform will strike the target first. In order to meet the latter condition, it may sometimes be necessary to rotate the headform away from the surface normal and this will usually lead to a less severe value of HIC(d). In all test conditions, a tri-axial accelerometer is placed at the CG of the test headform and the resultant translational acceleration ($\ddot{x}$) is used to compute HIC(d) according to the following relations [4]:

$$HIC(d) = 0.75446 * HIC + 166.4 \quad (1)$$

$$HIC = \left\{ \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \frac{\ddot{x}}{g} dt \right]^{2.5} (t_2 - t_1) \right\}_{\max} \quad (2)$$

In the above relation, g is the acceleration due to gravity, and $0 \leq t_1 \leq t_2 \leq t_f$. The final time t_f corresponds to the condition $\ddot{x} = 0$, i.e. when a striking headform loses contact with the target being impacted. And $(t_2 - t_1)$ should not exceed 36 ms.

The level of HIC(d) on an unprotected target will depend on target compliance and its surrounding geometry which will determine whether substantial headform rotation will take place following impact. For example, the headform striking an A-pillar in Fig. 1 rotates minimally as the face of the headform comes into contact with the target after initial impact with the forehead zone; it is likely that in this situation, the resultant contact force passes practically through the CG of the headform. On the other hand, the resultant contact force in Fig. 2 passes through a point in the forehead zone of the headform resulting in a turning moment (clockwise) about the headform CG; thus, in this latter case, a perceptible fraction of initial translational impact energy can be converted into rotational kinetic energy, thus resulting in a reduction in translational deceleration and hence HIC(d) as compared to the target in Fig. 2. With the help of an improved LPM to be presented in the next section, rotational effects on an impacting headform will be studied for targets similar to those shown in Fig. 2.

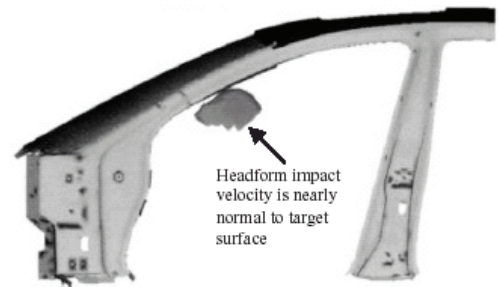


Fig. 1: Impact on an A-pillar target followed by minimal headform rotation

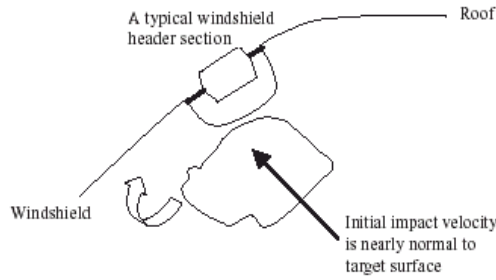


Fig. 2: Impact on a typical front header target allowing headform rotation

FORMULATION OF AN ENHANCED LPM FOR HEADFORM IMPACT SIMULATION

The LPM considered in the current study is shown in Fig. 3. A spherical rigid mass of radius R represents an equivalent headform. A numerical value of R may be obtained by equating the principal moment of inertia of the FMVSS 201 headform about its lateral axis to that of the lumped spherical headform. The angle ϕ (which will be referred to as “resultant contact angle”) in Fig. 3 will control the moment inducing rotation of the headform. As a special case, $\phi = 90^\circ$ will imply that the radial segment PC will be in line with the energy-absorbing spring representing a target with countermeasure, and no rotation of the headform will take place. In Fig. 3, the translational and rotational degrees of freedom of the headform are denoted by x and θ respectively while the linear displacement of the spring is given by x_s .

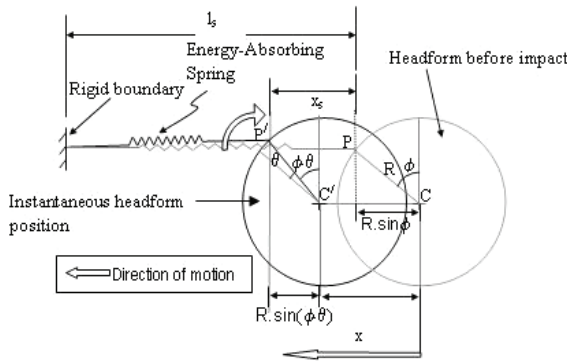


Fig. 3: Lumped parameter model for headform impact with rotation

The above LPM was first discussed in [5]. The nonlinear spring in this LPM had an unloading path parallel to the elastic line of slope K_e as shown in Fig. 4. However, as observed in [5], this customary representation of unloading behavior does not lead to good correlation with test-based responses such as deceleration in the descending phase. It has been shown in [6], for the case of an LPM with a single translational degree-of-freedom

(DOF), that this deficiency can be overcome by adopting a piecewise linear representation of an arbitrary unloading path as indicated in Fig. 4. Thus, a similar formulation for unloading is incorporated here to substantially enhance the two-DOF LPM given in [5].

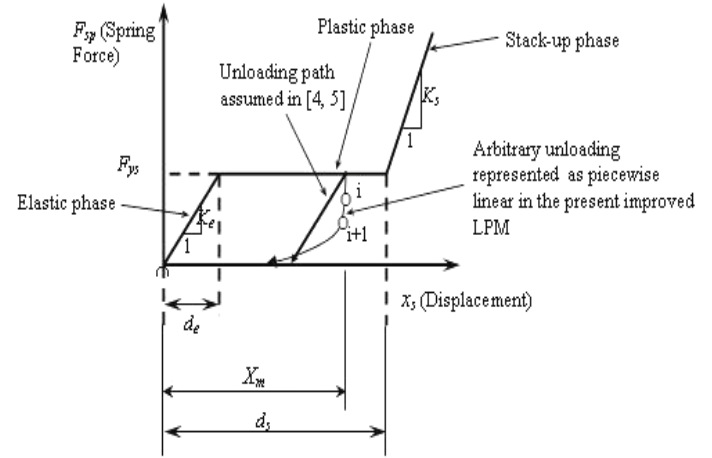


Fig. 4: Assumed behavior of nonlinear spring

The governing equations of motion [5] for the LPM defined by Figs. 3 and 4 are:

$$m\ddot{x} + F_{sp} = 0, \quad (3)$$

$$I_c\ddot{\theta} + K_r\theta - F_{sp}R\cos(\theta - \phi) = 0, \quad (4)$$

where,

m : mass of headform assumed as 4.5 kg

I_c : mass moment of inertia ($= \frac{2}{5}mR^2$) of headform

$\ddot{x}$: headform translational acceleration at time t

$\ddot{\theta}$: headform rotational acceleration at time t

F_{sp} : spring force at any instant of time t

K_r : rotational stiffness of headform to neck joint

The various quantities related to the assumed spring behavior in Fig. 4 are defined below:

d_e : maximum elastic deformation in spring

d_s : maximum elasto-plastic deformation in spring
($d_s = c_f l_s$)

c_f : compaction factor

l_s : undeformed spring length

K_e : elastic stiffness

K_{ep} : stiffness in plastic phase (shown as zero in Fig. 5)

K_s : stiffness in the stack-up phase