

Simplified MADYMO Model of the IHRA Head-form Impactor

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ABSTRACT

Interest in pedestrian head injury has prompted a need to measure the potential of head injury resulting from vehicular impacts. A variety of head impactors have been developed to fulfill this measurement need. A protocol has been developed by the International Harmonization Research Activity (IHRA) to use head impactor measurements to predict head injury. However, the effect of certain characteristics of the various head impactors on the measurement procedure is not well understood. This includes the location of the accelerometers within the head-form and testing the head-form under the variety of conditions necessary to establish its global performance. To address this problem, a simple model of the IHRA head-form has been developed. This model was created using MADYMO[®] and consists of a solid sphere with a second sphere representing the vinyl covering. Stiffness and damping characteristics of the vinyl covering were determined analytically from drop test data of an IHRA head-form. The model was validated by comparing its response to a drop test of 0.5 meters onto a steel plate. The results show that the model is an effective, simple solution to evaluating an IHRA impactor. The results also indicate that a more complete description of the vinyl covering (i.e., finite elements) would be appropriate for certain impact configurations.

INTRODUCTION

Head injury continues to be of concern in automobile impact biomechanics because the head is the most seriously injured body part in many collisions including in a pedestrian/automobile collision [6]. Head-form impactors are used to test the aggressiveness of vehicle structures such as the hood and windshield, which are leading sources of head injury. Various head impactors have been developed to measure injury potential based on the Head Injury Criteria (HIC) [5], a dimensionless

measure of averaged head acceleration, and have been validated biomechanically. Injury evaluation utilizing a physical impactor requires the hardware, instrumentation, and test surface to conduct a test. Creation of a computer model of the impactor allows application of the impactor to novel systems, permits investigation of perturbations of a system, and allows for parametric studies of the systems. Studying different situations such as varying speed and angle of impact using a computer model would be more cost effective and less time consuming. A validated computer model can also be used to reconstruct a real-world accident situation.

A number of mathematical models of the human head have been developed over the years to study head injury. Mathematical models are also available which simulate head-form impactors. A comparison of some of the mathematical head-form models is given in Table 1. In Table 1, the software and finite element approach used, the type of material modeled, the experimental method utilized to determine the material properties, and the validation performed are listed for eight different models. The first model developed using MADYMO[®] was published by Konosu [8] in 2000. Konosu [8] developed a computer simulation MADYMO[®] model of the European Enhanced Vehicle-Safety Commission (EEVC) pedestrian subsystem impactors, which included the adult and child head-forms. The model was intended to promote the development of pedestrian friendly cars by simulating head-form drop tests on cars. Though the models showed good agreement with the values obtained from subsystem tests, some improvements would be needed to apply it to simulate subsystem tests on cars. Deb [4] developed a nonlinear lumped mass model for simulating head-form impact with rotation on a stiff target containing countermeasures for HIC reduction. Results from the model were verified against an equivalent finite element based model using LS-DYNA[®].

Table 1 Comparison of various mathematical head-form models

Developed by	FE Software/approach used	Material type	Experiment/method used to determine material properties	Head-form model validation	Reference
Nakahama 1992	An explicit FE code	Rigid body	Not Applicable	Impact against plastic plates @ 2.2, 4.4 and 6.7 m/s	[9]
Sugita 1995	PAM-CRASH	Crushable foam	Static compression testing of dummy skin	Standard head drop test @ 2.68 m/s	[10]
Bilkhu 1995	LS-DYNA3D	Elastic-plastic hydrodynamic	Uni-axial quasi-static test	Head drop test @ 2.68 and 6.71 m/s	[2]
Barbat 1996	PAM-CRASH & RADIOSS	Viscoelastic	High velocity head drop tests	Head drop test @ 2.68, 4.02 and 6.71 m/s	[1 & 3]
Chou 1997	LS-DYNA3D & FCRASH	Viscoelastic	Trial & error and optimization technique through design of experiment method	Head drop test @ 2.68, 4.02 and 6.71 m/s	[3]
Konosu 2000	MADYMO	Not known	Not known	Head drop certification test and head-form to bonnet top test	[8]
Kamalakkannan 2005	MADYMO	Mooney-Rivlin	Oscillatory compressive experiments on cylindrical sample of vinyl skin	Head drop certification test	[7]
Deb 2004	LSDYNA/Lumped parameter based approach	Elasto-plastic	Assumed values for spring stiffness	Head drop @ 6.7 m/s and head-form impact tests in the upper interior of vehicle	[4]

The model could be used as a good tool for head impact safety evaluation in the preliminary design phase of vehicles. The model also gave an indication of how head-form rotation could reduce HIC. Kamalakkannan [7] developed a complex finite element model of the IHRA impactor using a hyperelastic material model for the vinyl. The model was validated using drop tests from 376 to 950 mm. The model reasonably reproduced peak accelerations and HIC within this impact range. The model was then used to calculate the effect of changes to the head-form parameters and the resulting effect of these changes on head-form response.

The IHRA proposed two head-forms (adult and child) to be used internationally to evaluate vehicle-head impact response [6]. The IHRA head-form's parameters such as mass, diameter, center of gravity location and accelerometer location, are specified with tolerances within which these parameters can be varied. Within these tolerances, the head-form is intended to respond in a prescribed range (i.e. peak acceleration should be within 225 – 275 g for the adult head-form in a certification test). No tests have been performed on the IHRA head-form to confirm this design objective. It is highly impractical to vary these parameters within the respective tolerances and hence a computer model of the head-form would better study the effect of these parameters on the response characteristics of the head-form. A computer simulated model would facilitate evaluating the head-form itself as well as the effect of placement of instrumentation. Development of such a model requires sufficient detail to replicate appropriate response and at the same time requires adequate generalization to allow for greater utility.

Kamalakkannan [7] developed a MADYMO© model of the IHRA head-form using a finite element representation of the vinyl skin. This model is reasonably complex and requires measurement of the hyperelastic properties of the vinyl. However, MADYMO© is a lumped parameter simulation program

with finite element capability. Kamalakkannan's model of the IHRA head-form did not attempt to simplify the model to see if the stiffness of the head-form vinyl can be modeled using the lumped parameter capabilities of MADYMO.

The objective of the research discussed in this paper is to develop a simple, MADYMO© based, multibody head-form model to simulate the response characteristics of the IHRA head-form impactor and to validate this model. Most previous computer simulation head-form models have used a finite element representation of the vinyl skin material. The model development will be limited to an impact speed of about 3.5 m/s, consistent with the speed used in standard head-form calibration tests [5].

The most important aspect of modeling the head-form is assigning the appropriate material model to the head-form skin and determining the appropriate material properties for this material model. Previous researchers have used crushable foam, elasto-plastic and viscoelastic material models for the head-form skin. One of the two MADYMO© models of a head-form is for the EEVC head-form and was developed by Konosu [6]. However, Konosu did not publish the material properties that he used for the head-form skin. The other MADYMO© model by Kamalakkannan [7] used a hyperelastic material model for the vinyl. This material model is reasonably complex.

In an effort to avoid the difficulty of determining detailed material properties of the head-form and to simplify the model, it was decided to attempt to group these properties into global parameters of the head-form. This is best achieved by the development of a simple, one mass model of the head-form. This would also allow development of stiffness and damping functions of the vinyl skin without the constraints imposed by a finite element material model, the tradeoff being the benefit a finite element approach offers for accommodating geometry effects. The stiffness and damping

characteristics of the IHRA head-form discussed in the current paper were derived from the acceleration response obtained from a calibration drop test and modified to allow the head-form response to better model test data.

MATERIALS AND METHODS

The physical adult head-form is shown in Figure 1 and consists of a hollow aluminum truncated sphere with an outer diameter of 151 mm. A plate is attached to the opening in the truncated sphere. This backing plate serves as an attachment point to the impactor ram used for accelerating the head-form up to the desired velocity during testing. The response of the head-form is measured by three accelerometers mounted in triaxial fashion on the inside of the backing plate such that they are located near the center of gravity of the head-form. A 12.5 mm thick vinyl skin covers the spherical surface and provides the compressible stiffness and damping characteristics of the head-form. The aluminum core by comparison is quite stiff and does not deform during impact. The mass of the adult head-form is 4.5 kg.

HEAD-FORM GEOMETRY IN MADYMO[®]

The MADYMO[®] model of the head-form includes two concentric spheres, one the same diameter as the aluminum hemisphere of the physical head-form and the second dimensionally the same as the vinyl skin. The center of mass of the head-form model is located at the center of the sphere. Forces are transferred between the head-form model and other objects by way of a force-penetration function defined for each object that contacts the head-form. For this model, only the head-form skin has a force-penetration function defined. No interaction with the aluminum sphere is considered. This is primarily due to the markedly greater stiffness of the aluminum compared to the vinyl of the physical head-form and partly due to the fact that compression of the vinyl skin accounts for almost the entirety of the force interaction with an object. At lower speed impact, this should not pose a restriction on the model since the vinyl does not compress enough to involve the aluminum sphere. At higher speed impact, any deformation of the sphere will manifest itself as vibration in the sphere that would be well above the cutoff frequency of the data acquisition. As a check to verify this assumption, penetration of the outer sphere is monitored to ensure it does not exceed the thickness of the vinyl skin.



Figure 1. IHRA adult head-form device

STIFFNESS AND DAMPING CHARACTERISTICS

The force-penetration characteristics of the head-form contacting an object include forces arising from both stiffness and damping. To determine the nature of these functions, a head-form calibration drop test was performed. This test consists of dropping the head-form from a height of 0.376 m (14.8 in) onto a rigid steel plate. The drop height of 0.376 m produces an impact speed of 2.71 m/s.

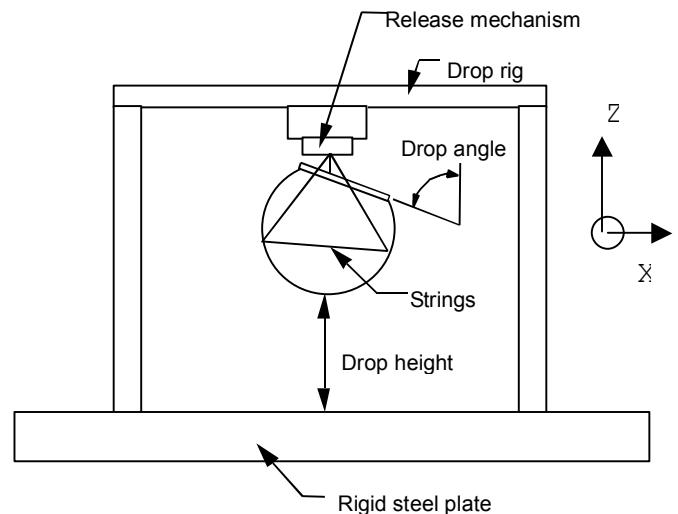


Figure 2. Test set up for head-form impactor calibration test

This drop test is performed by suspending the head-form in a string sling and cutting the string support. This procedure allows accurate measurement of drop height and eliminates any potential for rotation of the head-form during freefall. The test set up is shown in Figure 2. The tri-axial acceleration of the center of gravity of the head-form is sampled at 10 kHz with 2000 g accelerometers. The right hand coordinate system was used with Z-axis positive upward as shown in Figure 2, thus giving a positive (upward) acceleration upon impact.

The resultant acceleration of the head-form in a calibration drop test is shown in Figure 3. The head-form was dropped normal to the plate. The components of

acceleration in the x and y directions were small compared to the acceleration in the z direction. The components of acceleration in x and y directions were mainly a result of the rotation of the head-form at impact due to the center of gravity of the head-form not being at the center of the sphere. The head-form rotates because of the moment produced by this center of gravity offset, in spite of the impact being normal to the steel plate. Since this center of gravity offset was accommodated in the MADYMO[®] model as well, the resultant acceleration from both the laboratory drop and the MADYMO[®] simulation results were compared. The force applied to the head-form when it contacted the steel plate was calculated by multiplying the resultant acceleration curve by the mass of the head-form. The deformation of the vinyl skin was obtained by double integrating the acceleration. Any deformation of the steel plate is assumed to be negligible. The force applied to the head-form as a function of the deformation of the head-form skin is given in Figure 4. Figure 4 shows the loading part of the force-penetration curve; the unloading part will be discussed later.

The force-penetration curve shown in Figure 4 is divided into two sections at a penetration of about 3.4 mm, the first exhibiting an exponential rise in force and the second a quasi-linear phase. The second section is comparatively linear with an R² value of 0.9867 for a linear regression model of the second section. The two sections are divided at a point where the force-

penetration function transitions from exponential rise to a more linear rise. This break point also appears to correspond to a change in the damping function. The vinyl skin on the head-form clearly has a stiffness that accounts for some portion of the force measured during impact. However, the vinyl skin has viscoelastic characteristics as well, making the response of the vinyl both displacement and rate dependent. This force-penetration function includes the effects of both the stiffness and the damping of the vinyl skin. To develop an appropriate model of the head-form, these two characteristics must be separated.

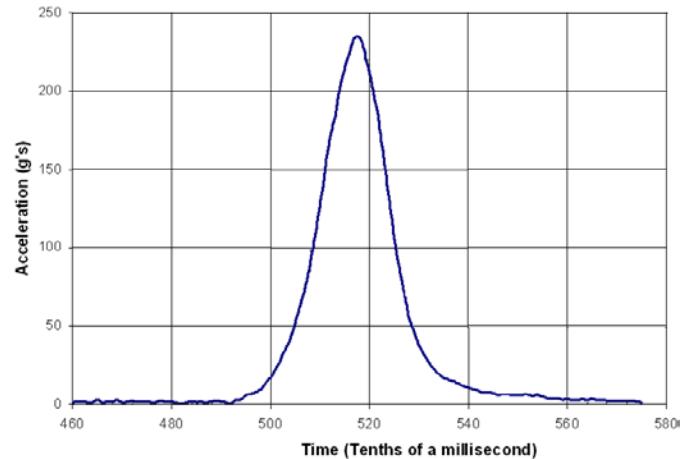


Figure 3. Resultant acceleration trace of the head-form calibration drop test

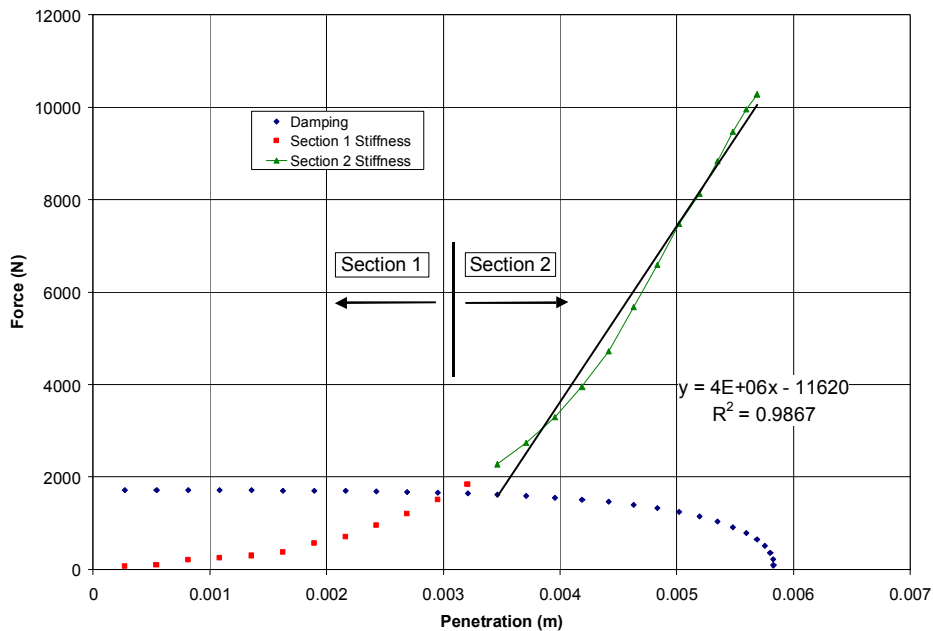


Figure 4. Force vs. displacement characteristics of the vinyl skin of the head-form

To separate stiffness characteristic from damping, the vinyl skin was assumed to behave as a Voigt model with a spring and damper positioned in parallel. This representation is mandated by the limitations of MADYMO®, which does not have a viscoelastic parameter for a simple force-penetration function. The Voigt model was used and incorporated with a complex, nonlinear, damping function to accommodate the behavior of the vinyl material.

The contributions of both damping and stiffness to the total force-penetration function shown in Figure 4 must be determined in order to determine appropriate functions for both damping and stiffness. Separation of the damping and stiffness functions is achieved by first assuming that damping can be represented by a simple damping coefficient, C_d . This coefficient can be calculated by

$$\Delta KE = \frac{1}{2} m(v_f^2 - v_i^2) = \int C_d v \, dx \quad (1)$$

Equation (1) assumes that all kinetic energy not restored upon rebound is lost through damping.

$$C_d = \frac{\Delta KE}{\int v \, dx} \quad (2)$$

$$C_d = \frac{\Delta KE}{\sum_{i=0}^n v_i \Delta x} \quad (3)$$

Where,

C_d – damping coefficient

m – mass of the head-form

v_i & v_f – initial velocity (2.71 m/s) and final velocity (1.28 m/s) of impact respectively

$\sum_{i=0}^n v_i \Delta x$ – the trapezoidal integration of the velocity with respect to the penetration.

v_i – velocity of the head-form at point i

Δx_i – change in displacement of the head-form at point i

The velocity and displacement of the head-form at all points ‘ i ’ can be calculated by integration of the measured acceleration of the head-form. Calculation of the damping coefficient gave a value of 631 N-s/m. The damping force can then be calculated.

$$F_{dt} = C_d \, v_t \quad (4)$$

Where,

F_{dt} – damping force at time t

v_t – velocity at time t

The plot of the total response along with the damping force is given in Figure 4 for the loading phase of the impact. At this point, damping during unloading is neglected.

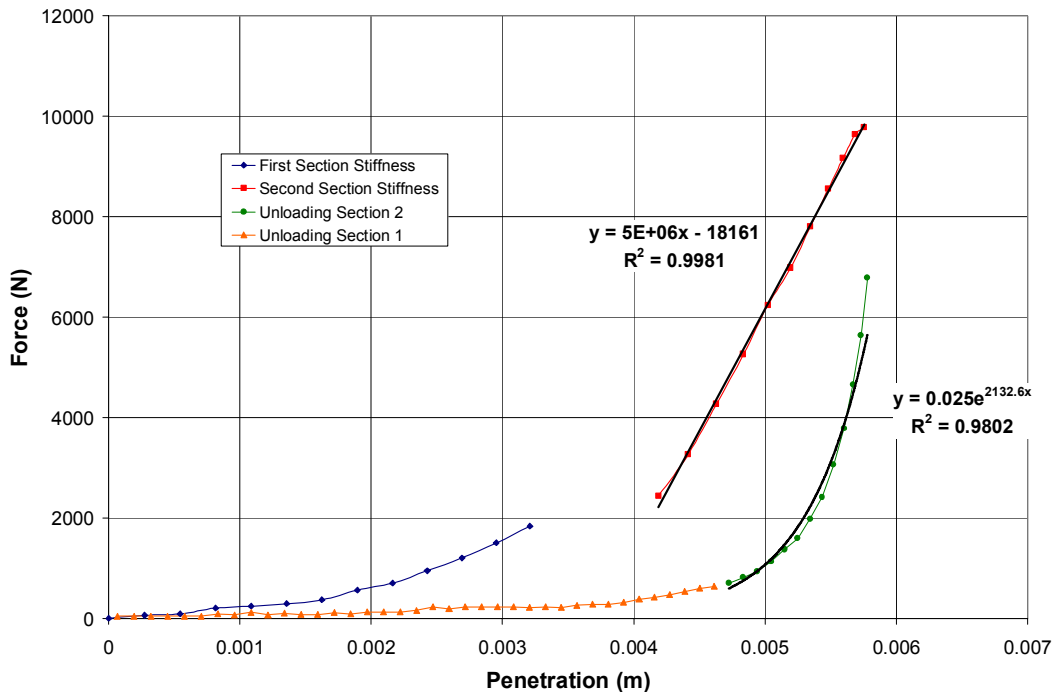


Figure 5. Loading and unloading stiffness characteristics of the vinyl skin of the head-form

Since the force applied to the head-form is comprised of the stiffness force and the damping force, subtraction of the damping force from the total force should reveal the contribution of stiffness to the total force. Reference to Figure 4 shows this would be difficult at best. For penetrations up to 3.4 mm, the calculated damping force is unrealistically greater than the total measured force. This is due to the assumption of a linear damping coefficient for the vinyl skin throughout contact. At first contact between the head impactor and the steel plate, the velocity of the impactor is high but the involvement of the vinyl skin is not yet well developed. As a result, it is unlikely that the vinyl skin is absorbing much, if any, energy during the early portion of contact. This is the elastic portion of the viscoelastic material. However, once the impact develops to significantly compress the vinyl skin, the characteristics of the loading appear to change. This is evidenced by the change in shape of the force-penetration curve from exponential ($0 < x < 3.4 \text{ mm}$) to quasi-linear ($3.4 \text{ mm} < x$). Notice that the total force, which is comprised of the damping and stiffness forces, is less than the damping force alone until approximately 3.4 mm of penetration. The change in the force-penetration curve at 3.4 mm of penetration suggests the introduction of an additional force at this point. The fact that the deceleration of the head-form is not large enough to reduce the damping force below the total force applied to the head-form implies that the damping force is, in fact, minimal during the first 3.4 mm of compression of the vinyl skin. This again is consistent with a viscoelastic material. Hence, it is reasonable to conclude that damping becomes relevant only once the vinyl skin is compressed to about 3.4 mm.

This penetration is about 25 percent of the total thickness of the vinyl skin. Thus, the stiffness accounts for the majority of the total force encountered from 0 mm to 3.4 mm. The elastic contribution of the viscoelastic damping can then be included in the stiffness function. Above 3.4 mm penetration, the damping force can be subtracted from the total force to give the stiffness force as shown in Figure 5. The stiffness of the second section loading is linear as can be seen from the linear regression model in Figure 5. A discontinuity arises in the loading stiffness function between the first and second sections. This discontinuity is due to subtraction of the damping force from the total force in the second section but not in the first. This arises because of the assumption of damping becoming significant only after 3.4 mm. The stiffness function was smoothed by assuming a continuously increasing function at the junction of these two sections.

The combined forces from stiffness and damping for unloading are shown in Figure 5. To obtain the force due to stiffness alone during unloading, the damping force must be subtracted in the same way as it was for the loading phase. Damping force in the vinyl skin arises from the resistance of the vinyl to compression above that provided by stiffness alone. However, there is no further compression of the vinyl during unloading over that occurring during loading. As a result, the vast majority of force present during unloading should be due to stiffness and not damping. With this in mind, the stiffness during loading and unloading is given in Figure 6. The unloading data are extrapolated to meet the loading data.

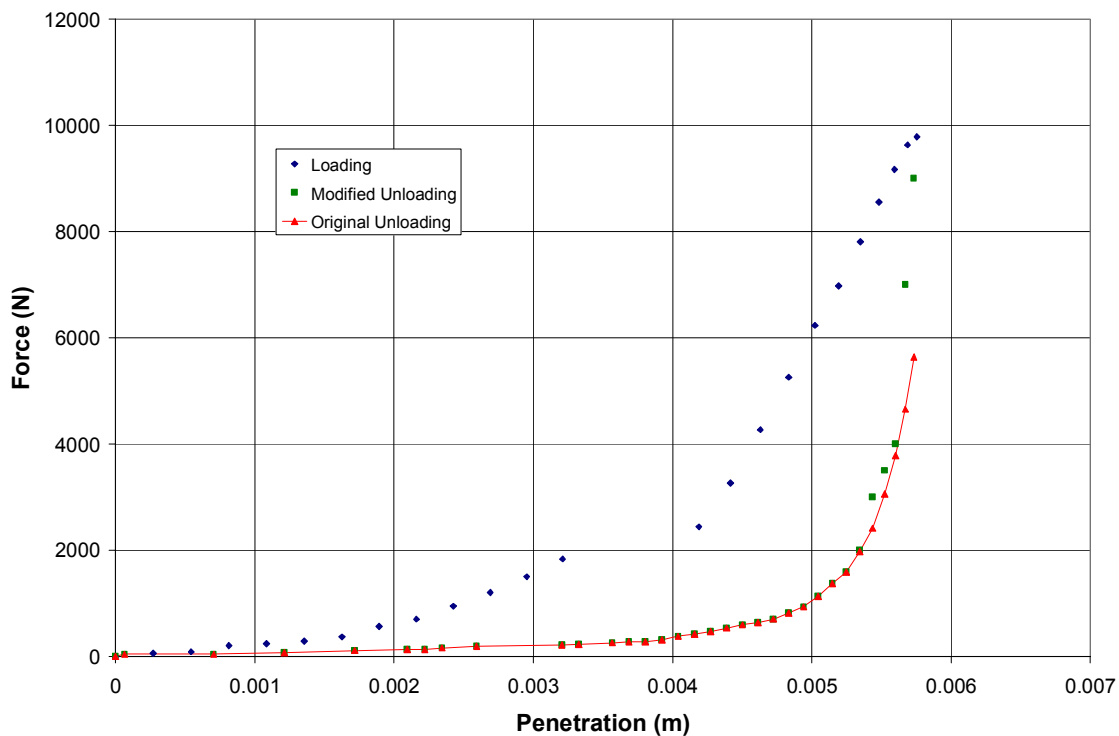


Figure 6. Extrapolated loading and unloading stiffness characteristics of the vinyl skin of the head-form

MADYMO HEAD-FORM MODEL

Given the characteristics of the vinyl skin, the model of the head-form can then be developed. The model created for the simulated head-form was comprised of two concentric multibody spheres representing the aluminum core and the rubber skin. The loading and unloading characteristics were applied to the skin, and the penetration of the aluminum was neglected. The rigid steel plate was modeled as a surface plane. Data was sampled at a frequency of 100 kHz and filtered with a CFC 1000 fourth order low-pass filter. The mass, moment of inertia, center of gravity and geometry of the head-form were obtained from the National Highway Traffic Safety Administration (NHTSA). Since the steel plate is rigid, a slave contact characteristic was used between the head-form and the steel plate. Figure 7 shows the multibody head-form and the surface plane modeled in MADYMO®.

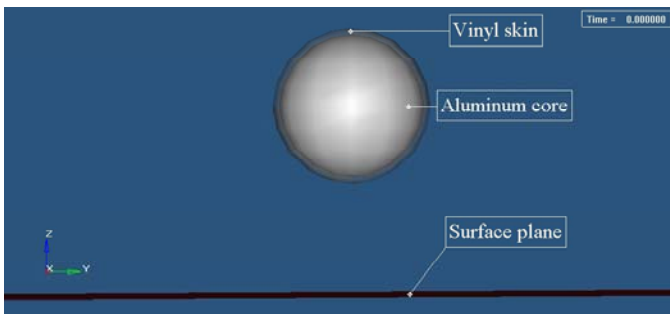


Figure 7. MADYMO® model of multibody head-form and surface plane

RESULTS AND DISCUSSION

The goal of this research is to match the response of the MADYMO® head-form model to that of the physical head-form impactor. Ideally, the match would result in the acceleration response of the model and the impactor being identical. Using the model based on the stiffness shown in Figure 6 and the damping coefficient of 631 N-s/m gave a response that generally agreed with the head-form response but was of significantly different magnitude. Relying solely on the acceleration response, one would conclude marginal agreement between the model and the head-form.

The two singular criteria often used to evaluate head injury are peak acceleration and HIC. Using these identifiers allows a second, simpler measure of performance of the model. These parameters are more easily compared when evaluating the model and are used in this study to quantify the ability of the model response to correlate with the physical head-form impactor response.

Simulation of the head-form with the stiffness and damping coefficient of 631 N-s/m produced a model

response of HIC and peak acceleration quite different from that of the head-form. The damping present during rebound was identified as being one reason for the disparity. While deriving the damping coefficient, the damping during unloading was neglected. During rebound the compressed vinyl retracts at a slower rate. Hence, the contact between the head-form and the steel plate decreases, thereby decreasing the damping during rebound. In order to decrease damping in the unloading part in the MADYMO® model, a damping velocity function was used instead of the damping coefficient. This allowed empirical adjustment of the damping to obtain a HIC and peak acceleration that more closely simulated the head-form response. It also allowed greater flexibility in adjusting damping than could be obtained using a simple damping coefficient. The shape of the input damping-velocity function is given in Figure 8.

Inspection of the damping function of Figure 8 shows that when the head-form first makes contact (maximum velocity) the damping is zero and increases linearly until the velocity of the head-form drops to about 90 percent of its initial velocity. This point corresponds to approximately 3 mm of compression of the vinyl skin. As stated earlier, there is minimum damping during this first 3 mm of compression. The damping function then drops linearly through maximum compression and reaches zero at the end of rebound. Continuing the damping function into the rebound phase permits introduction of limited damping during rebound but at a much lower level than during compression. The presence of a damping force at maximum compression (zero velocity) is reasonable given the viscoelastic nature of the vinyl.

The sign definition for a damping coefficient in MADYMO® could be best understood by this example. A damping coefficient of 100 N-s/m corresponds to a force of 200 N at the velocities of 2 m/s and -2 m/s and a force of 0 N at a velocity of 0 m/s. Hence, the force due to a linear damping coefficient is always positive. The damping function used for the vinyl skin in the MADYMO® model does not correspond to any constant damping coefficient. Instead, it is designed to accommodate the peculiarities of the vinyl skin. Again it should be noted that the complex behavior of the vinyl skin is modeled using a Voigt model. It was found that the calculated damping coefficient of 631 N-s/m was too low. Increasing the slope of the damping function to 737 N-s/m and adding a constant to produce the damping function as in Figure 8 produced reasonable results (constant not shown in Figure 9). Apart from this damping function, no other linear damping coefficient was added to the model. Comparison of acceleration responses of the model simulation and the head-form impactor response in a calibration drop test is shown in Figure 9. The HIC and peak acceleration are compared in Table 2 for the 376 mm height drop test.

Validation

The actual physical calibration test of the IHRA head-form is a free fall test as specified by the NHTSA. Hence, the validation was also performed as a free fall test but at a higher velocity. The head-form was dropped onto the steel plate from a height of 500 mm. The test set up (Figure 2) used for dropping the head-form that included the string support mechanism had a constraint that limited the maximum height of the head-form drop to 500 mm. This drop height corresponds to an impact velocity of 3.13 m/s. Since the damping function begins at zero at the beginning of impact and increases to a maximum at about 3.4 mm of compression, the damping function for the 3.13 m/s, impact required modification from that for the 2.71 m/s impact. It should be noted that this modification only related to the beginning condition of the damping function and that after 3.4 mm of compression, the damping function is the same for all cases. Likewise, the form of the

damping function for less than 3.4 mm of compression is the same for all cases. The only difference is the velocity at which the damping begins to increase, consistent with the objective of the damping function. The damping velocity function for the 3.13 m/s impact speed during the first 3.4 mm of compression and unloading is shown in Figure 10. Table 2 gives the calibration drop test and validation test results of the MADYMO© simulation and laboratory drop.

Drop height (mm)	Peak acceleration (g)			HIC		
	MADYMO	Drop	% Error	MADYMO	Drop	% Error
376	261	255	-2.3	820	875	6.3
500	293	320	8.4	1372	1406	2.4

Table 2 Calibration drop test and validation test results.

Figure 9. Comparison of acceleration traces of MADYMO simulation and laboratory calibration drop test.

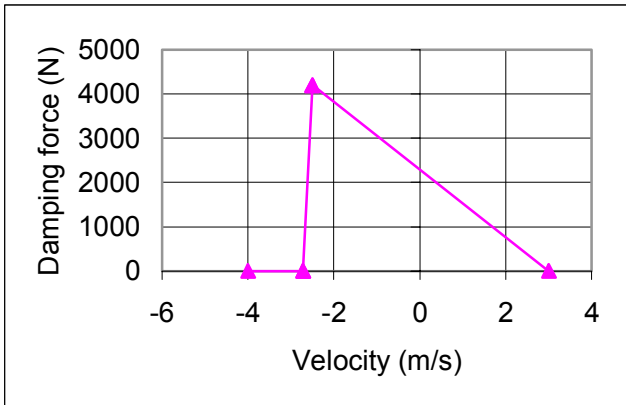


Figure 8. Damping force - velocity function for the contact between head-form and steel plate for the 376 mm drop height, zero damping below 2.71 m/s

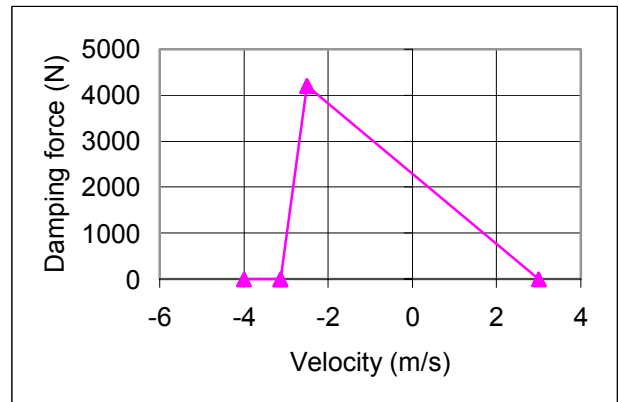
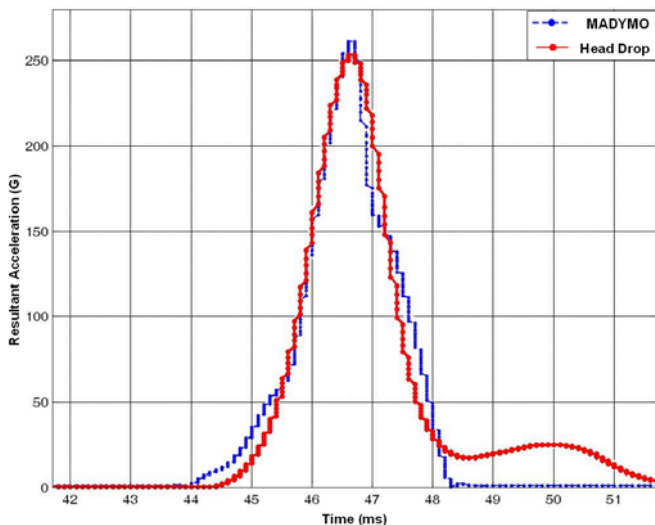


Figure 10. Damping force - velocity function for the contact between head-form and steel plate for the 500 mm drop height, zero damping below 3.13 m/s



The results of both calibration drop and validation tests of MADYMO© simulations are within 10 percent of the corresponding laboratory drop results. This suggests that the head-form model could be used in applications within the given impact speed range. The speed range within which the head-form performs reasonably well could be higher, but validation at higher velocities has not yet been performed. The head-form impactor is validated only for normal impacts and currently could not be used for angular impacts causing rotation pending validation for such impacts.

The head-form model could be effectively employed to analyze low speed impact situations such as a low speed hood or windshield impact or a rear end impact. The model could also be used to study the effects of geometric and mass constraints on the head-form response. Once the model is validated at higher impact

velocities, it could be applied to study high-speed impact situations such as sports injuries and the benefit of helmets in reducing head injury.

Measurement of damping is a problem. The damping coefficient was initially calculated assuming that damping is a constant and subsequently was modified to be a function of velocity for the vinyl skin. The calculated constant value of damping coefficient was found to not adequately characterize the damping characteristics of the vinyl skin of the head-form. A damping velocity function for the contact between the head-form and the steel plate was found to better simulate the peak acceleration and HIC values obtained from the calibration test. A finite element model for the vinyl skin would better model the material characteristics and would avoid many of the shortcomings present in a multibody model but determining the material parameters, especially damping characteristics, for a finite element model would still be difficult.

Any penetration of the aluminum core was neglected. This appears to be a valid assumption since the total penetration of the vinyl is less than 6 mm, which is less than half its thickness. The vinyl has a quite complex material behavior where it has different loading and unloading stiffness as well as non-linear damping. The input damping function used in MADYMO© is the total damping of the head-form – steel plate contact, not just the damping of the head-form. It would be more appropriate to model the head-form using finite elements wherein the vinyl material properties could be applied to the vinyl part of the finite element model of the head-form. This would also enable the simulation of head-form impact onto a non-rigid contact and would accommodate geometric effects that cannot be simulated in a simple multibody model. In addition, a finite element representation of the vinyl skin would allow a check of the assumption that the aluminum sphere does not contribute to the model response. Non-rigid contact between two multibodies could also be modeled using the 'COMBINED' contact option in MADYMO©. These features support the use of the Kamalakkannan [7] model for the IHRA head-form.

CONCLUSION

A simple model of the head-form was developed with multibody elements. The model consists of two concentric spheres one representing the aluminum core and the other representing the outer vinyl covering. The model was developed using data from a calibration drop test with an impact velocity of 2.71 m/s and was validated using another laboratory drop from a higher drop height producing an impact velocity of 3.13 m/s. The results suggest that the head-form model could be used in applications falling within the given speed range. Although this speed range includes the impact speed used for calibration of head-forms, further validation would be needed to apply the model to typical pedestrian head impacts. The results imply that a more

complete description of the vinyl covering using methods such as finite elements would be appropriate for certain impact configurations. Such finite element representations of the vinyl skin are needed to properly accommodate the complexity of the skin properties.

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