Development of translational head injury model (THIM) and translational energy criteria (TEC) of child

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The Ohio State University, 1992
DEVELOPMENT OF TRANSLATIONAL HEAD INJURY MODEL (THIM)
AND TRANSLATIONAL ENERGY CRITERIA (TEC) OF CHILD

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
School of the Ohio State University

by

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* * * * *

The Ohio State University
1992

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dedicated to my parents
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CHAPTER I

Introduction

1-1. Overview

Numerous researches about the impact head injuries have been made by the government and industry in the past thirty years because of the greater attention to prevent the head injury in the accident environment. However, all head injury researches were limited to adult. The head injury research about child was neglected due to lack of the information of child head injury and simple consideration of a child head as a scaled-down adult head.

Statistics have shown that nearly half of the accidental deaths were a consequence of motor vehicle injuries. Children under 14 year of age accounted for 6% of these deaths, with 2-3% of the occupant deaths being infants and children under 5 year of age.[1] The child head is the body area most frequently and seriously involved in automotive collisions (the head injury in children is about 77% of all child injuries). The reasons for this greater frequency of head injury in children can be demonstrated both anatomically

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The number in [ ] refers to references at the end of this text.

1
and biomechanically. The child's head is proportionately larger than in the adult. This heavier head mass and resulting higher seated center of gravity in child, coupled with weaker neck supporting structures, may be the basis for this higher frequency of head injury. Therefore, the child head injury is much important in comparison with the adult head injury.

The objective of this research is to develop a child head injury criterion for the better protection of a child head. The difficulties of this research are not available of mechanical properties and injury data of a child head. To overcome these difficulties several reasonable assumptions will be needed. The two dimensional finite element head models of adult, 6 and 2-year old child, and newborn infant will be built based on the anatomical and physical data. The adult experimental mechanical driving-point impedance curves will be used to validate the finite element model. Then, the child's head models will be simulated to find the driving-point impedance curves. Then, using the impedance curves, the conceptual characterizations (lumped parameter model : Translational Head Injury Model) of the children's head with two masses coupled by a spring and dashpots is possible. Using this lumped model, the Translational Energy Criterion(TEC) of a child head will be developed.

1-2. Significance of the Problem

Over the years, numerous head injury researches about the adult head were made and various head injury criteria developed for the purpose of a head protection, but the researches about a child head were negligent because a child head was considered simply
as a scaled-down adult head, and because the mechanical properties and injury data of child head are not available. However, the child head is quite different with the adult head in size and structure, and the properties of child head may be different with those of the adult head. So, the treatment of a child head as a scaled-down adult head is inappropriate. Also, the portion of the child head in the body is much bigger than that of the adult head. So, the child head is the body area most frequently and seriously involved in automotive collisions. Therefore, the child head injury is much important in comparison with the adult head injury.

Therefore, the child head injury criterion in consideration of these anatomical and mechanical differences is demanded for the better protection of a child head.

1-3. Scope and Objectives of the Research

The objective of this research is to develop a child head injury criterion for the better protection of a child head by using the finite element modeling technique. A broad overview of the tentative scheme to establish a child head injury criterion is as follows. A finite element model of an adult head will be developed first. Then, using experimental data on the impedance of the adult head, the parametric studies will be made to find mechanical properties of the head providing the best correlation between experimental and finite element model data. Then, finite element models of a child head (newborn infant, 2-year, 6-year old child) will be built and simulated to find the driving-point impedance curves based on the correlated mechanical properties of adult head model. Then, using the impedance data, the conceptual characterization (lumped parameter model) of the child
head with two masses coupled by a spring and dashpot will be made. (the translational head injury model) Using this model, the translation energy criterion of a child head will be developed.

1-4. Literature Survey

1-4-1. Type of Head Injury

Due to the complex structure of a head, the head injury cannot be classified as a unitary phenomenon. Many investigators have been studied to determine which types of head injury are regularly associated with neurological disability and to identify the causal mechanism associated with them. In general, the head injury can be classified as follows;

Table 1-1. Types of head injury[2]

<table>
<thead>
<tr>
<th>skull injury</th>
<th>focal injury</th>
<th>diffuse brain injury</th>
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<tbody>
<tr>
<td>vault fracture</td>
<td>epidural hematoma</td>
<td>mild concussion</td>
</tr>
<tr>
<td>linear depressed</td>
<td>subdural hematoma</td>
<td>cerebral concussion</td>
</tr>
<tr>
<td>basilar fracture</td>
<td>contusion intracranial</td>
<td>diffuse injury</td>
</tr>
<tr>
<td></td>
<td>hematoma</td>
<td>shear injury</td>
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</table>
When the structural change of the skull is occurred due to the impact, this phenomenon is known as skull fracture. Skull fracture can occur with or without the damage to the brain. Focal brain injuries occur when brain lesions are large enough to be seen by the naked eye. Because of these lesions, masses are created within the cranium and result in brain shift, herniation and brain stem compression that contributes to local brain damage. Nearly 50% of all head injuries are caused by focal brain injuries and are responsible for two-thirds of head injury mortalities. Diffuse brain injuries are not generally associated with macroscopically visible brain lesions, and they are usually associated with more widespread disruption to the brain either functionally or structurally.

Diffuse brain injuries can be classified into four different categories[2];

a) Mild Concussion: Victims will temporarily experience neurological dysfunction without loss of consciousness

b) Classical Cerebral Concussion: Temporary loss of neurological proficiency with momentary loss of consciousness (not more than 24 hours). Classical cerebral concussion is fully recoverable after victims regain their consciousness.

c) Diffuse Injury: A traumatic brain injury with more than 24 hour loss of consciousness. Usually, no sign of brainstem dysfunction is observed, however, residual neurological effects may be experienced by some patients upon recovery.
Studies have shown that diffuse brain injuries accounted for approximately 40% of head injuries, one-third of the deaths, and are the most serious cause of persistent neurological disability in the survivors.

1-4-2. **Head Injury Mechanisms**

Head injury mechanisms are characteristic of the head responses undergoing some applied physical process that can be related to head injury severity. The types of mechanical injuries to the head are usually complex and numerous. However Dr. Gennarelli [2] suggests that the basic mechanisms that produce a head injury may be classified into three broad categories.

a) **Contact Phenomena** have been implicated in scalp laceration, fracture of the cranial vault, epidural hematoma and some other forms of cortical contusions. The severity of the contact phenomenon strongly depends on the size and shape of the impacting device and the magnitude of the force upon impact.

b) **Stress Wave Propagation** results from an object striking the skull, and the effects of skull oscillations cause brain damage at a distance away from the impact site. The stress wave propagation is responsible for contrecoup contusions and other vascular disruption within the brain substance.

c) **Acceleration (or Inertial) effects** are the major cause of diffuse brain injuries when
subjected to impact or impulse loading, as opposed to the contact phenomena and stress wave propagation which are the main cause of focal injuries.

1-4-3. Development of Head Injury Model

The human head may be considered as a physical system. Given such a system, a simulation is resorted to instead of direct experimentation with the system itself. This is obviously necessary since experimentation with the human head can not exceed the tolerances of volunteers, therefore, the results of such experiments have limited values. Simulation implies conduction experiments on some model, which is a simplified representation of the real system. The human head, like any other physical system, consists of physical elements of various characteristics of properties that interact according to certain relationships or physical laws. The complexity of these characteristics and relationships, and often the lack of data describing them, necessitates that reasonable assumptions and simplifications be made prior to the conception of any representative model.

In general, there are two different approaches toward physical or mathematical modeling of a physical system.

a) Structure Modeling emphasizes duplication of the structural and physical characteristics of the human head as closely as possible, and attempts to associated the responses in reproducing the injury experienced on an actual head when subjected to similar loadings.
b) Functional Modeling pays little attention to the structural and physical similarities between the model and the actual head. It concerns itself primarily on reproducing the dynamic responses related to head injuries.

1-4-3-1. Structural Head Injury Model

Over the years, numerous head models have been developed in validating a specific hypothesis or theory of head injury. The first structural treatment of the head (modeled as a continuum) subjected to dynamic mechanical loading appeared in the literature. Anzelius[3] considered the head as a rigid spherical shell filled with an inviscid compressible fluid and that the motion of the fluid was axisymmetric and irrotational. The model was used to study the cavitation phenomena and was subjected to instantaneous change in velocity from some initial value to a zero velocity. The model was criticized as the elasticity of the skull was not taken into consideration.

Engin and Liu[4] replaced the rigid shell with an elastic shell and examined the response to a local radial impulse, expressed as a Dirac delta impulse, as well as the free vibrational response. This model was further improved by Benedict[5] who replaced the elastic shell with a membrane. The models developed in those periods did not consider the damping effects between the skull and brain materials. In addition, some of the models limited by the boundary conditions of the fluid filled shell to axisymmetric and irrotational motion.

In 1970, a model that accounted for the viscoelastic property of the brain was
developed by Lee and Advani[6]. The model was used for studying the responses of the head under a step, symmetric, torsional acceleration.

With the development of large scale computational capabilities and the progress in the finite element codes, this method of structural analysis had become practical in biomechanical applications. In 1971, Hardy[7] made the first finite element model of the head. This model was developed for the static analysis of the skull. Shugar[8] made a 2D mid-sagittal section head model that included the brain and three layered skull. In this model the skull was assumed as elastic material, and the brain was viscoelastic material. Later Shugar[9] made a 3D Rhesus monkey head model. Localized shell strains were compared with empty Rhesus skulls, and the intracranial pressure was compared against in-vivo pressure. Subsequently Ward[10] developed the three dimensional model for the brain which included the membrane and ventricles. Another finite element model that included with scalp, brain, and layered skull, was made by Khalil[11] in 1977 to study skull fracture loads and comparison with experimental cadaver data. Spherical and ovaloid shapes were assumed for the finite element representation of the brain. This idealization of the geometry despite the geometrical freedom in finite element modeling was later questioned. The skull and the scalp were assumed as elastic material, and the brain was viscoelastic material.

In 1985, Gennarelli[12] developed some simple physical models, using skull-brain structure as an experimental tool to study the relationship between the rotational and angular acceleration induced shear strain to the acute subdural hematoma and other heavy injuries. The physical models that represent the primate head have been constructed to include a skull and surrogated brain material.
The limitations of some finite element modeling efforts in head injury were questioned in the early eighties. This is because of highly idealized geometry to avoid the mathematical complexities associated with the solution of these models. Furthermore, all materials were assumed to have linear, homogeneous, and isotropic properties. Undoubtedly, the response of such idealized model will not be accurate as compared to the actual testing on the human volunteers or cadavers. Nonetheless, such studies on mathematical modeling of the human head as a physical system is necessary and important as it is economically unsound to carry out the experimental testing conducted on cadavers and human volunteers. In addition, when direct experiments are carried out on human volunteers, the tolerance level has to be observed for preventing possible injuries, making the data obtained from such experimentation of limited value.

However, recently, much effort has been carried out in modeling the human head as a more accurate continuous system, in that a more sophisticated finite element model of the human head has been developed. This model is capable of handling the non-linear aspects of geometry and material behavior.

1-4-3-2. **Functional Head Injury Model**

A functional head injury model emphasizes mainly the relationship between the mechanical input and some indication of head injury. One of the simplest functional head injury model was introduced by Stalnaker.[13] A two-degree of freedom mechanical
lumped-parameter model was made, as a head-brain model for generating a head injury
criterion called the Mean Strain Criterion (MSC). (see Figure 1-1-a) This model was
composed of two masses, one spring, and one damper. The model parameters were
generated by fitting the model's impedance response to the experimental impedance data
in the lateral direction. Output of the model corresponded to the impedance test curve at
resonance point, however, the correspondence at the antiresonance point was not
apparent.

To simulate head responses during impact motion for different directions, a new
mechanical lumped parameter head model—the Translational Head Injury Model (THIM)
was developed.[14] (see Figure 1-1-b) This THIM model was based on the study of the
human head's frequency response and head's geometrical and inertial properties. In
addition, the THIM model was designed in four directions: anterior-posterior (A-P),
posterior-anterior (P-A), left-right (L-R), and superior-inferior (S-I). This THIM model
was used to generating a Translation Energy Criterion (TEC).

Aleml[15] developed a discrete parameter head injury model. This twelve degree of
freedom mechanical system consists of spring, dashpots, and masses as shown in Figure
1-2. The classical Lagrange's method was used in formulating the equations of motion.
Due to lack of reliable experimental data, this model was used primarily in studying the
effects of the physical parameters of impact on head injury.

Low[16] developed a rotational head injury model as shown in Figure 1-3 and the
model was calibrated with the experimental data obtained by Gennarelli[12].
Figure 1-1: Mean Strain Criterion Model and Translational Head Injury Model
Figure 1-2: The 12 Degree of Freedom Head Injury Model developed by Alem
Figure 1-3: The Rotational Head Injury Model by Low
1-4-4. **Head Injury Criteria**

The head injury criteria are needed for correlating the mechanical force input to the resulting head injury level. The basic criterion for most evaluation of a head impact trauma is the Wayne state university tolerance curve (WSTC) [17]. This curve was determined from cadaver, animal, and human volunteer test data. The curve shows that very intense head acceleration is tolerable if it is very brief, but that much less is tolerable if the pulse duration exceeds 10 or 15 milliseconds. This tolerance curve has been questioned because the impact data were sparse and the determining a peak acceleration and duration is highly subjective.

In 1966, Gadd [18] suggested the severity index (GSI) by a straight line approximating the WST data as follows:

\[ GSI = \int T a(t)^{2.5} dt \]  \hspace{1cm} (1-1)

where \( a(t) \) is an acceleration magnitude of the head. A GSI value of 1000 was originally recommended as the injury threshold criterion for frontal head impact.

In 1971, Versace [19] modified the GSI and suggested a head injury criterion (HIC) as follows:

\[ HIC = \left( t_2 - t_1 \right) \left\{ \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t) dt \right\}^{2.5} \bigg|_{\text{max}} \]  \hspace{1cm} (1-2)
where $a(t)$ is a resultant acceleration magnitude at head center of gravity, and $t_1$ and $t_2$ are the two points in time during the impact that maximize HIC. An injury threshold value of 1000 is maintained for HIC and it is to be stressed that $t_1$ and $t_2$ are not simply the value of time at the onset and end of impact, but are the values, within these bounds, which maximize HIC. The definition of HIC and the veracity of its prediction have been analyzed in great deal. According to Ward[10], HIC is (i) unsuitable for acceleration lasting less than 5 ms, (ii) provides good injury estimates for those lasting 5 to 10 ms, (iii) too conservative for longer duration of acceleration. The HIC is currently recognized by the U.S. Department of Transportation's National Highway Traffic Safety Administration, and is required in the Federal Motor Vehicle Standard 208(FMVS-208).

In the accident investigation studies for documenting each injury, an Abbreviated Injury Scale(AIS) is necessary for a quantitative measure of head injury, and it described with general categories as listed in Table 1-2.[20]

The Abbreviated Injury Scale is a numerical rating system for establishing the levels of severity of all injuries. This injury level or injury severity level donates the magnitude of damage in terms of physiological changes and structural failures that occur in a living body as a consequence of mechanical violence.

In 1971, Stalnaker[13] suggested the Mean Strain Criterion(MSC) based on an experimentally determined head model. In 1987, the Translation Energy Criterion(TEC)[14] was developed based on the analysis of a three-degree of freedom semi-definite lumped parameter model called the Translational Head Injury Model(THIM) for four directions. Figure 1-4 shows the comparison of the several head injury criteria.
Table 1-2: Abbreviated Injury Scale

<table>
<thead>
<tr>
<th>AIS Code</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No injury</td>
</tr>
<tr>
<td>1</td>
<td>Minor</td>
</tr>
<tr>
<td>2</td>
<td>Moderate</td>
</tr>
<tr>
<td>3</td>
<td>Severe (not life-threatening)</td>
</tr>
<tr>
<td>4</td>
<td>Serious (life threatening, survivable)</td>
</tr>
<tr>
<td>5</td>
<td>Critical (survival uncertain)</td>
</tr>
<tr>
<td>6</td>
<td>Maximum (currently untreatable)</td>
</tr>
</tbody>
</table>

Figure 1-4: Comparison of several head injury criteria
1-5. Closure

This chapter provided the essential background information for the head injury study. The various types of head injuries, the head injury mechanisms, the head injury model, and head injury criteria were surveyed. In the next chapter, the comparison of adult and child head will be provided, and based on the those data, the finite element head models of adult, 6 and 2-year old child, and newborn infant will be developed.
CHAPTER II

Background

2-1. Overview

In this chapter the previous works about the translational head injury head model (THIM) and the translational energy criteria (TEC) will be summarized in detail.

2-2. Driving Point Impedance Characteristics of the Head

Due to the structural and material complexity of the head, and accurate head model has not yet been developed. Although several lumped parameter models were developed, these models suffered from the lack of the necessary physical response data required to evaluate the many parameters of which they were composed. The lumped model parameters (mass, spring, damper) determine the dynamic response of the model. In general, these are a function of frequency and can be evaluated by mechanical impedance techniques assuming linear system characteristics.

Several researchers conducted mechanical impedance experiments on living and/or
death primate heads, cadaver heads, and dry skulls using different types of instruments and techniques. The general trend of impedance curves were very similar for all cases. The differences were mainly on the locations of resonant and antiresonant peaks and the slope of the impedance curves. The earlier works are summarized below.

E.K. Franke [21] made mechanical impedance measurements on dry human skull and on living human subjects. In experiments, the impedance transducer was not rigidly attached to head. This type of connection made it very difficult for the impedance transducer to remain in contact with head near antiresonance or resonace. A resonance of 820 Hz was found for the dry skull, and a resonace of 600 Hz for living skulls was reported. V.R. Hodgson [22] made mechanical impedance measurements on a cadaver head. An impedance transducer was rigidly attached to the skull and loaded by a 25-lb electromagnetic shaker. The shaker was not fastened rigidly to a large mass, but to a drill press stand. A resonance of 950 Hz and an antiresonance of 313 Hz for cadaver head, and a resonace of 900 Hz for skulls filled with silicon gel with a damping constant of 2 lb-sec/in were reported. R.L. Stalnaker [23] measured the mechanical impedance on a cadaver head over a frequency range of 30 to 5000 Hz. The skull was rigidly attached via the load cell to the platform of a 200 lb electromagnetic shaker and the bodies were supported by a sling hammock. A servo-controller was then set to apply a constant amplitude sinusoidal acceleration of 1, 5, and 10 g's to the head. An antiresonance of 250 Hz and a resonance of 800 Hz with a damping constant of 2.4 lb-sec/in in the lateral direction were reported. Measurements in the other three directions (A-P, P-A, and S-I) were also made.
2-3. Translation Head Injury Model (THIM) of the Adult Head

In 1985, the THIM model first was introduced by Stalnaker, Lin, and Guenther[24] in order to develop the new mean strain criteria (NMSC). The THIM model is a one-dimensional, three degrees of freedom semi-definite lumped parameter model that is composed of two masses, one spring, and two dampers. The spring and the first damper are connected to the two masses in parallel, the second damper is connected to the spring element in series as shown in Figure 1-1 in Chapter I. In 1986, Stalnaker, Low, and Lin[14] upgraded the criteria to the current translational energy criteria (TEC) by using the same THIM model. They provided four directional (A-P, P-A, L-R, and S-I) THIM models of the adult head based on the experimental mechanical impedance curves.

The parameter D, the distance between mass M1 and M2, was defined as the same as the cranium distance in each direction that was found from a geometrical study. The other model parameters were generated through fitting the model mechanical impedance response to the experimental mechanical impedance response data. To do this, the parameter study of the THIM model in four (A-P, P-A, L-R, and S-I) directions was conducted to determine the values of the model elements that give the best fit to the experimental impedance data. The lumped elements of the THIM model were found, in general, to have real physical interpretations. It appears from earlier studies that the elements of the THIM model have the following characteristics.[25]

1) Mass M1 is the mass of the skull/skin which was moving directly under a rigid impactor.
2) Summation of masses (M1 and M2) will always add up to the total head mass.

3) The damper C2 is constant for all directions and is believed to be primarily the damping of the brain.

4) The stiffness K and the damper C1 from the nonlinear skull stiffness in a given direction.

The first two characteristics of the THIM model elements were determined from the experimental mechanical impedance curve of head. At low frequency excitation, the head acts like a rigid structure. As a result, the total head mass may be obtained directly from the impedance curve as shown in Figure 2-1 since the response of the head is paralleled to the constant mass line. At high frequency excitation, only a small portion of the head mass near the loading point was responded. In the THIM model, M1 represents this small mass.

The third characteristic of the THIM model elements can be explained by comparing three related experimental impedance curves in Figure 2-2. (from whole head, skull pulse brain, and skull only) The same cadaver was used in all analysis in order to maintain consistency of the material and structural properties. Then, the best THIM model was generated for each case through parametric study as shown Table 2-1. The comparison of the skull plus brain and skull only model parameters indicate that the largest change of all model parameters is the value of the damper C2 by more than 71%. This infers that damper C2 represents primarily brain damping effects. Moreover, the brain material is
homogeneous. Thus, it is expected to be independent of impact directions. From earlier studies of the THIM model, damper C2 is estimated to be constant for all four impact directions. This information further supports the conclusion that damper C2 represents primarily brain damping effects.

Table 2-1: Comparison of Skull and Brain Effects on THIM Model Parameters

<table>
<thead>
<tr>
<th></th>
<th>Whole Head</th>
<th>Skull &amp; Brain(^1)</th>
<th>Skull only(^2)</th>
<th>% Difference (1 and 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M(_1) (kg)</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.0</td>
</tr>
<tr>
<td>M(_2) (kg)</td>
<td>4.39</td>
<td>2.50</td>
<td>1.00</td>
<td>-60.0</td>
</tr>
<tr>
<td>C(_1) (KN-sec/m)</td>
<td>8.5</td>
<td>9.5</td>
<td>10.0</td>
<td>5.3</td>
</tr>
<tr>
<td>C(_2) (N-sec/m)</td>
<td>350</td>
<td>350</td>
<td>100</td>
<td>-71.4</td>
</tr>
<tr>
<td>K (MN/m)</td>
<td>5.0</td>
<td>4.0</td>
<td>2.0</td>
<td>-50.0</td>
</tr>
</tbody>
</table>

Finally, the fourth characteristic of the THIM model elements can be explained by analyzing impact responses of the K-C1 elements in serial combination as shown in Figure 2-3. Then, the results are compared with previous skull stiffness experiments. [26] The dynamic responses of the serial K-C1 system can be derive in frequency response form as follows;

The equations of motion of the serial K-C1 system are,
\[ F(t) - K \cdot (X_1 - X_2) = 0 \quad (2-1) \]

\[ K \cdot (X_1 - X_2) - C_1 \cdot \dot{X}_1 = 0 \quad (2-2) \]

Then, solve for effective stiffness transfer function, \( F/X_1(S) \), in transfer function form as,

\[ \frac{F}{X_1}(s) = \frac{C_1 \cdot K \cdot s}{C_1 \cdot s + K} \quad (2-3) \]

Finally, substitute \( s = iw \) to obtain the stiffness frequency response function,

\[ K(w) = \left| \frac{F}{X_1}(iw) \right| = \frac{C_1 \cdot w}{\sqrt{(C_1 \cdot w/K)^2 + 1}} \quad (2-4) \]

where,

- \( K(w) \) = dynamic stiffness of the K-C1 system (N/m)
- \( F(t) \) = force function (N)
- \( X_1(t) \) = displacement function (m)
- \( s \) = Laplace differential operator
- \( C_1,K \) = THIM model parameters

Since McElhaney’s experimental data were collected in a quasi-static testing condition, the conversion of the skull structural stiffness from static to dynamic condition
was required in our analysis. In general, dynamic stiffness for most biological structures are much higher than the corresponding static stiffness. However, the exact conversion depends very much on the structural geometry, material properties, testing conditions. However, the ratio of the dynamic and static stiffness in the K-C1 system can be calculated theoretically as,

\[
R(w) = \frac{K(w)}{K_s} = \frac{C_1 \cdot w / K_s}{\sqrt{(C_1 \cdot w / K)^2 + 1}}
\]  

(2-5)

where, \( R(w) \) = dynamic/static stiffness conversion ratio
\( K_s \) = average static stiffness of human skull from McElhaney [26]

The variation of dynamic/static stiffness ratio for the K-C1 system is shown in Figure 2-4. The comparison of McElhaney's static stiffness corridors (upper and lower limits) to the theoretical prediction of the K-C1 system is shown in Figure 2-5. The good agreement between the prediction and McElhaney's experimental results indirectly implies that K-C1 in serial combination may be used to represent skull dynamic stiffness.

The parameter study of the THIM model elements was done by Rojanavanich[27] in 1988 as shown in Figure 2-6 to 2-9. The results show that adjustments of the lumped elements may be used effectively to modify the overall system dynamic responses. In most cases, only a few modifications are needed to change the system responses. This study was used to developed four different directional THIM models. The parameters of the adult THIM models in four different directions are tabulated in Table 2-2, and Figure 2-10 to 2-12 show the comparison of the mechanical impedance curves from the THIM
model and experimental data. The figures show that the response of the THIM model is well agreed with the that of experiments.

Table 2-2: The parameters of the adult THIM models

<table>
<thead>
<tr>
<th></th>
<th>A-P</th>
<th>P-A</th>
<th>L-R</th>
<th>S-I</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>0.45</td>
<td>0.27</td>
<td>0.25</td>
<td>0.67</td>
</tr>
<tr>
<td>M2</td>
<td>4.09</td>
<td>4.27</td>
<td>4.29</td>
<td>3.87</td>
</tr>
<tr>
<td>K</td>
<td>13.5</td>
<td>7.0</td>
<td>6.5</td>
<td>13.0</td>
</tr>
<tr>
<td>C1(N·sec/in)</td>
<td>17000</td>
<td>8000</td>
<td>6500</td>
<td>2600</td>
</tr>
<tr>
<td>C2(N·sec/in)</td>
<td>157.6</td>
<td>157.6</td>
<td>157.6</td>
<td>157.6</td>
</tr>
<tr>
<td>D</td>
<td>0.195</td>
<td>0.195</td>
<td>0.154</td>
<td>0.152</td>
</tr>
</tbody>
</table>

2-4. Translational Energy Criteria (TEC) and Its Injury Correlation

When the THIM model is excited by an impact, the kinetic energy is first transmitted to the mass M1. Subsequently, the kinetic energy of M1 is transferred to spring K and damper C2. Initially, the spring K stores some of the kinetic energy in form of potential energy and transfers the rest to the damper C1. Then, damper C1 dissipates some of the energy as heat or transfers the rest to the mass M2 as kinetic energy. Damper C2 also dissipates some of kinetic energy in the other parallel path and transfers the remainder of the energy to M2 as well. The proportion of energy storage, dissipation, and transfer depends primarily on impact loading rate and the values of the lumped parameters in the
THIM model. The spring element will absorb a large proportion of the impact energy in short duration impact compared to longer duration impact of same initial energy level. After the potential in the spring element reaches the maximum level, it is released back to the system until a new equilibrium is reached. The potential energy is either dissipated by dampers C1 or C2, or returned back to M1 or M2 as kinetic energy.

In the TEC, the dissipated energy by the damper C2(EC2) is correlated with the brain injury, and the power transfer by the spring K(PW) is correlated with the skull fracture potential. Specifically, the TEC used two new parameters to describe head impact injury potential. The first parameter is the equivalent AIS number(EAIS), which is calculated from the energy dissipated by the damper C2. The EAIS scale has the same physical interpretation as the standard 1985 AIS injury coding. However, it is a fractional scale developed in conjunction with the probability of death data recorded in the NASS data file (from NHTSA). The fractional scale is more detailed and allows EAIS to describe and compare the severity of multiple injuries and single injury cases. The second injury parameter of the TEC is the probability of skull fracture(POSF), which is calculated from the power transfer by the spring K. The POSF scale describes the likelihood of the occurrence of skull fracture under impact loading. This parameter is determined from the normal Gaussian distribution statistical analysis. The equations of EAIS and POSF[25] are as follows;

\[
\text{EAIS} = \alpha \times \sqrt{\text{EC2}} \quad (2-6)
\]

\[
\text{POSF} = 100 \times \frac{1}{\sqrt{2\pi}} \int_{-\alpha}^{\sigma} e^{-\frac{\delta^2}{2}} d\delta = 50 \times \left[ \text{erf} \left( \frac{\delta}{\sqrt{2}} \right) + \text{erf}(\alpha) \right] \quad (2-7)
\]
where, \( \delta = \frac{(PW - \mu)}{\sigma} \)

- \( EC2 \) = dissipated energy by the damper C2
- \( PW \) = Power transfer by the spring K
- \( \alpha \) = TEC injury constant (4.14 for adult)
- \( \mu, \sigma \) = normal Gaussian distribution mean and standard deviation
- \( \text{erf} \) = Gaussian Error Function

The injury constant, normal Gaussian distribution mean and standard deviation will be determined based on the real accident injury data.

Rojanavanich and Stalnaker[28] performed the sensitivity analysis on the TEC in 1988. They examined the effects of pulse duration, pulse shape, and pulse amplitude of impact force and the results are summarized as follows;

1) For impact with pulse duration longer than 5 msec, EC2 increases as the pulse duration increases for all three pulse shapes as shown in Figure 2-13. This suggests that for pulse duration between 5 and 20 msec, the impact force momentum, or the area under the force-time curve, is directly related to the energy dissipated by C2 in the THIM model. This seems to be consistent with the general conclusion that a harder impact (higher magnitude and/or longer pulse duration) causes a more severe head injury as predicted by higher EC2 value. For pulse duration shorter than 5 msec, the trend is not observed which seems to contradict the general conclusion just mentioned. However, the very short pulse duration represents highly concentrated load that creates high localized stress.
This type of loading causes skull fracture and possible bruising of the brain. (see Figure 2-9)

2) Figure 2-13 and 2-14 also show the effects of pulse shape on the dynamic responses of the THIM model. The figures show that for the same impact duration, the trapezoidal pulse has the highest EC2 and PW values, while the triangular pulse has the lowest. This also indicates that the impact force momentum, or the area under the force-time curve, is directly related to the energy dissipated by C2 in the THIM model.

3) The effects of amplitude variations on the EC2 and PW of the half sine pulse are shown in Figure 2-15 and 2-16 for impact duration of 6.5 msec. The figures also show that a harder impact (higher magnitude and/or longer pulse duration) causes a more severe head injury as predicted by higher EC2 and PW value.

2-5. Closure

In this chapter, the physical interpretation and parameter study of the THIM model, the derivation and sensitivity analysis of the TEC, and its injury correlation were summarized. These analyses were completed prior to the current research. Those analyses should be very important background materials in developing the THIM model and the TEC of the child head.
Figure 2-1: Cadaver Head Impedance Curve (A-P Direction)
Figure 2-2: Impedance Curves of Whole head, Skull & Brain, and Skull only
Figure 2-3: K-C1 System
Figure 2-4: Variation of $R(w)$ for the K-Cl System
Figure 2-5: Comparison of McElhaney's Experimental Data and K-Cl Model Prediction (A-P Direction)
Figure 2-6: Parameter Study of THIM -- Effects of Spring Constant K

- K-1 -- 6.0 MN/m
- K-2 -- 13.5 MN/m
- K-3 -- 18.0 MN/m
Figure 2-7: Parameter Study of THIM -- Effects of Mass M1

M-1 -- 0.2 Kg
M-2 -- 0.45 Kg
M-3 -- 0.8 Kg
Figure 2-8: Parameter Study of THIM -- Effects of Damping Coefficient C1

C1-1 -- 5.0 KN-sec/m
C1-2 -- 10.0 KN-sec/m
C1-3 -- 17.0 KN-sec/m
Figure 2-9: Parameter Study of THIM -- Effects of Damping Coefficient C2

C2-1 -- 20.0 N-sec/m
C2-2 -- 157.6 N-sec/m
C2-3 -- 400.0 N-sec/m
Figure 2-10: Mechanical Impedance of the THIM model of the adult in the A-P direction

TADA -- impedance from the THIM

EXA -- impedance from the experiments
Figure 2-11: Mechanical Impedance of the THIM model of the adult in the P-A direction

TADP -- impedance from the THIM

EXP -- impedance from the experiments
Figure 2-12: Mechanical Impedance of the THIM model of the adult in the L-R direction

TADL -- impedance from the THIM

EXL -- impedance from the experiments
Figure 2-13: Effects of Pulse Shape and Duration on the Dissipated Energy in C2(EC2)

(TRA -- Trapezoidal, SINE -- Half Sine, TRI -- Triangular)
Figure 2-14: Effects of Pulse Shape and Duration on the Power in K (PW)

(TRA -- Trapezoidal, SINE -- Half Sine, TRI -- Triangular)
Figure 2-15: Effects of Amplitude of Force on the Dissipated Energy in C2 (EC2)
Figure 2-15: Effects of Amplitude of Force on the Power in K (PW)
CHAPTER III

Development of Finite Element Head Model

3-1. Overview

In this chapter, the growth of human body will be discussed, and the physical and anatomical measurement data, and the mechanical property of the adult and child head will be surveyed. Based on the physical and anatomical measurement data, the finite element head model of adult, 6 and 2-year old child, and newborn infant will be developed.

3-2. Growth of human body

Growth and development of the human body occur continuously from infant to adult. Although there is a little difference individually, the growth and development occur according to predictable trends. Most body dimensions follow trends that involve rapid growth separated by a period of relatively slower or uniform growth.

Figure 3-1 to 3-3 [1] show the changes in body height and body proportions. In general, total body length should be double by the 4th year and tripled by the 13th year.
Figure 3-1: Percentage distribution of body segments as related to pre- and postnatal development [1]

Figure 3-2: Increase in total stature at various ages as compared to the adult.
Figure 3-3: The proportional changes in body segment with age

Figure 3-4: Sequential changes of various head and face regions
Figure 3-5: A comparison of face-braincase proportions in child and adult

Figure 3-6: Size and location of fontanelle
The height of an adult is about twice the height of a 2-year old child. And at birth the head is \( \frac{1}{4} \)th the total body length, whereas in adult it is \( \frac{1}{7} \)th. That is, in the early years of life, the infant is remarkably elongation in stature.

Children of either sex are of the same height, weight, and general body portion up to 10 or 11 year of age. Girls tend to have and earlier pubertal growth spurt between 11 and 14 year and, in general, are taller than boys of this age. In the early to mid-teens, the boys catch up, and then surpass the girls in stature.

3-3. Comparison of child and adult head

Figure 3-4 shows that at birth the facial portion of the head is smaller than cranium having a face-to-cranium ratio of 1:8.(adult ratio 1:2.5)\(^{[1]}\) Relative to the facial profile, the newborn forehead is high and quite bulged, due to massive size of the frontal lobe of the brain. This large head-small face pattern is noticeable in children even up to age seven and eight.

Infant head shape also differs significantly from that of adult as shown in Figure 3-5. In the infant the cranium is much more elongate and bulbous with large frontal and parietal prominence. Head circumference increases markedly during the first postnatal year due to the progressive and rapid growth of the brain.

Infant and child skulls are remarkably pliable, due to the segmental development and arrangement of skull bones, plus the flexibility of individual bones that are extremely thin. In infant, junctions between bones are relatively board and large leaving areas of brain covered by a thin fibrous sheath like as a skin as shown in Figure 3-6. These soft spots,
called as fontanelles, are several in number and are most obvious in the frontal and posterior skull regions. The mastoid fontanelle between the occipital and parietal bones closes about 6-8 weeks after birth. However frontal fontanelle is not closed until approximately the 17th month.

Finally, the physical and anatomical measurement data of adult, 6-year, 2-year old child, and newborn infant head were summarized in Table 3-1.[29,30,31]

Table 3-1: Physical and anatomical measurements data of adult, 6 and 2-year old child, and newborn infant head.

<table>
<thead>
<tr>
<th></th>
<th>infant</th>
<th>2-year</th>
<th>6-year</th>
<th>adult(20)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HC(cm)**</td>
<td>35</td>
<td>49</td>
<td>52</td>
<td>55</td>
</tr>
<tr>
<td>HL(cm)</td>
<td>12</td>
<td>17</td>
<td>18</td>
<td>19</td>
</tr>
<tr>
<td>HW(cm)</td>
<td>10</td>
<td>13</td>
<td>14</td>
<td>15.4</td>
</tr>
<tr>
<td>HWE(kg)</td>
<td>0.715</td>
<td>1.686</td>
<td>3.21</td>
<td>4.54</td>
</tr>
<tr>
<td>BWE(kg)</td>
<td>0.353</td>
<td>1.024</td>
<td>1.313</td>
<td>1.430</td>
</tr>
<tr>
<td>TWE(kg)</td>
<td>3.4</td>
<td>12.6</td>
<td>21.9</td>
<td>63.1</td>
</tr>
<tr>
<td>ST(mm)</td>
<td>0.86</td>
<td>2.0</td>
<td>3.5</td>
<td>8.5</td>
</tr>
<tr>
<td>MT(mm)</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

**HC - head circumference, HL - head length, HW - head width, HWE - head weight, BWE - brain weight, TWE - total body weight, ST - skull bone thickness, MT - membrane thickness
3-4. **Mechanical properties of the adult head**

Finite element methods promise the opportunity to provide mathematical models which account not only for complex geometry, but also for a constitutive relation for skull, brain, membrane, and scalp. If these relations are completely understood, the effects of dynamic loading of the head can be successfully modeled. However the mechanical characterization of the tissues of the head is a difficult biomechanical problem. It requires careful and innovative experimental methodologies as well as vigorous analysis. Many investigators suggest mechanical properties of head, but those data are considerably different according to the experimental method. The mechanical properties of the skull, brain, and membrane were summarized by Thibault[32] and tabulated in Table 3-2 to 3-5.

<table>
<thead>
<tr>
<th>reference</th>
<th>specimen</th>
<th>test method</th>
<th>property</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liu[33]</td>
<td>canine</td>
<td>wave propagation</td>
<td>shear modulus = 25 psi</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Young's moduli</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>circumferential = 3180 psi</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>axial = 520 psi</td>
</tr>
<tr>
<td>Galford[34]</td>
<td>human</td>
<td>creep compliance</td>
<td>( J(t) = a + b \times \ln(t) )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( a = 4.75 \times 10^{-4} ) psi</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( b = 0.97 \times 10^{-5} ) psi</td>
</tr>
</tbody>
</table>
Table 3-3: Mechanical property of cranial bone

<table>
<thead>
<tr>
<th>reference</th>
<th>specimen</th>
<th>test method</th>
<th>property</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goldsmith[35]</td>
<td>human</td>
<td>bending</td>
<td>modulus = 2.0×10^6 psi</td>
</tr>
<tr>
<td>Franke[21]</td>
<td>human</td>
<td>bending / vibration</td>
<td>modulus = 1.2-5.3×10^5 psi</td>
</tr>
<tr>
<td>McElhaney[36]</td>
<td>human</td>
<td>radial compression</td>
<td>modulus = 3.5×10^5 psi</td>
</tr>
<tr>
<td></td>
<td></td>
<td>tangential compression</td>
<td>modulus = 8.1×10^5 psi</td>
</tr>
<tr>
<td></td>
<td></td>
<td>tangential tension</td>
<td>modulus = 7.8×10^5 psi</td>
</tr>
<tr>
<td>Hodgson[21]</td>
<td>human</td>
<td>driving point impedance</td>
<td>resonant=800 Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>antiresonant=160 Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>viscous damping</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>c=2.0 lb-sec/in</td>
</tr>
<tr>
<td>Stalnaker[22]</td>
<td>human</td>
<td>driving point impedance</td>
<td>resonant=820 Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>antiresonant=166 Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>viscous damping</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>c=2.4 lb-sec/in</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>skull stiffness</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>k=2.6×10^4 lb/in</td>
</tr>
</tbody>
</table>
Table 3-4: Mechanical property of the brain tissue

<table>
<thead>
<tr>
<th>reference</th>
<th>specimen</th>
<th>test method</th>
<th>property</th>
</tr>
</thead>
<tbody>
<tr>
<td>Franke[21]</td>
<td>pig</td>
<td>driving point impedance</td>
<td>viscosity = 15 poise</td>
</tr>
<tr>
<td>Ommay[37]</td>
<td>Rhesus monkey</td>
<td>falling sphere viscometry</td>
<td>viscosity = 407 poise</td>
</tr>
<tr>
<td>Koeneman [38]</td>
<td>pig</td>
<td>creep and cyclic compression</td>
<td>modulus = 1.2-2.2 psi</td>
</tr>
<tr>
<td></td>
<td>rabbit</td>
<td></td>
<td>viscosity = 33-44 poise</td>
</tr>
<tr>
<td>Estes[39]</td>
<td>human</td>
<td>oscillating stress</td>
<td>ln(σ/ε) = a+b×ln(t)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>a=0.5, b=0.78</td>
</tr>
<tr>
<td>Shuck[40]</td>
<td>human</td>
<td>dynamic torsional shear</td>
<td>G=G'(ω)+iG&quot;(ω)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>G'=0.12-20 psi</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>G&quot;=0.05-12 psi</td>
</tr>
<tr>
<td>Galford[34]</td>
<td>human</td>
<td>creep compliance</td>
<td>J(t)=a+b× ln(t)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>a=0.355, b=0.026</td>
</tr>
</tbody>
</table>

Table 3-5: Mechanical property of scalp

<table>
<thead>
<tr>
<th>reference</th>
<th>specimen</th>
<th>test method</th>
<th>property</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galford[34]</td>
<td>monkey</td>
<td>creep compliance</td>
<td>J(t)=a+b× ln(t)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>a=4.2×10^{-3} psi</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>b=0.5×10^{-5} psi</td>
</tr>
</tbody>
</table>
3-5. Mechanical property of child head

The mechanical property of child head is very limited. The mechanical property of brain and membrane of child are not available unfortunately. The elastic modulus of fetal cranial bone was investigated by Mcpherson\[41\] and showed the increase of elastic modulus of cranial bone along with growth. The data are summarized in Table 3-6.

Table 3-6: Elastic modulus(GPa) of cranial bone from bending test

<table>
<thead>
<tr>
<th></th>
<th>P-PA**</th>
<th>P-PD</th>
</tr>
</thead>
<tbody>
<tr>
<td>newborn infant</td>
<td>3.3</td>
<td>0.57</td>
</tr>
<tr>
<td>6-year old child</td>
<td>7.38</td>
<td>5.86</td>
</tr>
</tbody>
</table>

**P-PA -- parietal bone, parallel to long axis of specimen,
P-PD -- parietal bone, perpendicular to long axis of specimen

Guenther and Hamilton\[42\] also show the increase of elastic modulus of the femoral bone according to the growth.

Table 3-7: Elastic moduli of femoral specimen in static bending

<table>
<thead>
<tr>
<th></th>
<th>Elastic Modulus(GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-year old child</td>
<td>82.2</td>
</tr>
<tr>
<td>4-year old child</td>
<td>98.5</td>
</tr>
<tr>
<td>adult</td>
<td>148.2</td>
</tr>
</tbody>
</table>
3-6. **Finite element head model**

When a force is applied to a structure (head), the structure will start a deformation, and if the force is excessive, the structure has a permanent change that causes a head injury. The finite element method began as a procedure for solving structural mechanics problems. In order to apply finite element method to head injury criteria, the finite element model must be made from the knowledge of:

a) the geometry of skull, brain, membrane and scalp
b) constitutive properties of the tissues
c) the boundary / interface conditions
d) the applied force

The head has an extremely complex geometric configuration. Even though the calvarium resembles a shell, it consists of eight layered bones of irregular thickness joined by sutures. The skull is covered by scalp, a loosely coupled layer of soft-tissue. The interior of skull is occupied by the brain that is gel-like medium. Furthermore, the brain floats in pressurized cerebrospinal fluid within the membrane.

Most models simplify the head as a multilayed two or three-dimensional structure. The impact responses of finite element models depend significantly on the boundary conditions and forces on the structure. Additionally, in layered models the interface
conditions must be specified where displacement continuity or relative motion is anticipated. Also, the mechanical properties, used in the model, significantly influence the responses and representativeness of the approximation.

3-7. Descriptions and Assumptions in the Finite Element Head Model

The human head is really complex in anatomical aspects. The skull (cranium) consists of eight separate bones that are knit together by sutures and are relatively immobile to one another from 17th months after birth. The brain is a soft structure composed of nerve cells, the gray and white matter. It consists of two cerebral hemispheres, the basal ganglia, the cerebellum, and the brain stem. Inside the brain are cavities (ventricles), containing cerebrospinal fluid. It can be generalized that the brain is connected to the skull by dura, bridging veins, and other connective tissues.

Due to extreme complexity, it is impossible to duplicate the actual physical behavior and the structural characteristics of the head. In order to achieve a practical model that is capable of accomplishing the desired dynamic simulation (in this study, mechanical driving-point impedance), many approximations and idealizations have to be made.

To consider such a practical head model, the following assumptions are made in this research;

1) Head is two-dimensional cylindrical model in the mid-transverse plane.

(as shown in Figure 3-7)
2) The scalp is not considered.

3) The thickness of the skull and the membrane is unique.

4) Effect of sutures of the skull is neglected in adult, 6 and 2-year old child head model.

5) The locations of fontanelles in the newborn infant head model are determined in the consideration of the anatomical locations[43] and the mass distribution of front, parietal, and occipital bone.[41]

   mass of front bone  = 0.0130 kg
   mass of parietal bone = 0.0127 kg
   mass of occipital bone = 0.0059 kg

6) The mechanical property of the fontanelle will be assumed as that of human skin as follows;

   Young's Modulus $E_s = 0.45$ MPa
   Poisson's ratio $\nu = 0.4$
   density $\rho = 1500$ kg/m$^3$

7) The head is symmetric in the anterior-posterior(A-P) direction.

Based on these assumptions, two-dimensional finite element head models of adult, 6 and 2-year old child, and newborn infant were built to simulate the impedance
experiments. The models incorporate the geometry of head in the mid-transverse plane as exactly as possible. Figure 3-8 to 3-11 show the finite element head model of adult, 6 and 2-year old child, and newborn infant. The outside layer elements represent the skull, the second outside layer elements represent the membrane, and the other inside elements are the brain. The actual model data are summarized in Table 3-8.

Table 3-8: Finite element models data

<table>
<thead>
<tr>
<th></th>
<th>infant</th>
<th>2-year</th>
<th>6-year</th>
<th>adult(20)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HC(cm)**</td>
<td>35</td>
<td>49</td>
<td>52</td>
<td>55</td>
</tr>
<tr>
<td>HL(cm)</td>
<td>12</td>
<td>17</td>
<td>18</td>
<td>19</td>
</tr>
<tr>
<td>HW(cm)</td>
<td>10</td>
<td>13</td>
<td>14</td>
<td>15.4</td>
</tr>
<tr>
<td>HWE(kg)</td>
<td>0.715</td>
<td>1.686</td>
<td>3.21</td>
<td>4.54</td>
</tr>
<tr>
<td>ST(mm)</td>
<td>0.85</td>
<td>2.0</td>
<td>3.5</td>
<td>8.5</td>
</tr>
<tr>
<td>MT(mm)</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>MOT(cm)</td>
<td>7.12</td>
<td>8.68</td>
<td>14.29</td>
<td>16.87</td>
</tr>
<tr>
<td>NE</td>
<td>440</td>
<td>260</td>
<td>260</td>
<td>260</td>
</tr>
</tbody>
</table>

**HC-head circumference, HL-head length, HW-head width, HWE-head weight, ST-skull thickness, MT-membrane thickness, MOT-model thickness in z-axis, NE-number of element
3-8. **Closure**

In this chapter, the two-dimensional finite element head models of adult, 6 and 2-year old child, and newborn infant were made based on the physical and anatomical measurement data and some reasonable assumptions. In the next chapter, the developed finite element head model will be validated by using the experimental data.
Figure 3-7: Anatomical Directions and Planes [42]
Figure 3-8: Two Dimensional Cylindrical Finite Element Model of the Adult Head
Figure 3-9: Two Dimensional Cylindrical Finite Element Model of 6 Year Old Child Head
Figure 3-10: Two Dimensional Cylindrical Finite Element Model of the 2 Year Old Child Head
Figure 3-11: Two Dimensional Cylindrical Finite Element Model of the Newborn Infant Head
CHAPTER IV

Validation of the Finite Element Head Model

4-1. Overview

The finite element head models of adult, 6 and 2-year old child, and newborn infant were made based on the physical and anatomical measurement data in the previous chapter. In this chapter the finite element head model will be validated based on the experimental impedance data that were provided by Stalnaker [14]. The mechanical property of the head will also be determined.

4-2. Experimental impedance data

Stalnaker provided the four-directional (A-P : anterior-posterior, P-A : posterior-anterior, L-R : left-right, and S-I : superior-inferior) impedance curves of the adult head that showed the relationship between driving-point velocity and sinusoidal input force as shown in Figure 4-1. The driving-point impedance method offers an aspect of the head system study of variant frequency range by a harmonic sinusoidal force input as described.
Figure 4-1: Mechanical Impedance of adult from experiments

EXA -- Impedance in A-P direction
EXP -- Impedance in P-A direction
EXL -- Impedance in L-R direction
early. To validate the finite element head model, the driving-point impedance data from the experiments will be used for the comparison with those from the finite element model.

4-3. Validation of the finite element adult head model

Due to the wide variation in the mechanical properties, it is difficult to ascertain the statistical value of the measured properties. Also, the finite element model is not a complete duplication of actual head in structural and physical aspects. To contend with these problems, the parameter study of mechanical properties will be essential. The initially estimated mechanical properties for the finite element adult head model are tabulated in Table 4-1. It should be noted that the values of mechanical properties are subject to modifications and adjustments until the dynamic responses of the model match those of experiments.

Table 4-1: Estimated mechanical property for finite element adult head model.

<table>
<thead>
<tr>
<th></th>
<th>modulus E(MPa)</th>
<th>density ρ (kg/m³)</th>
<th>Poisson's ratio ν</th>
<th>damping ratio z</th>
<th>viscoelastic frequency property (Figure 4-2)</th>
<th>bulk modulus = 200(MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>skull</td>
<td>500</td>
<td>2140</td>
<td>0.21</td>
<td>0.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>membrane</td>
<td>5</td>
<td>1133</td>
<td>0.45</td>
<td>0.0005</td>
<td></td>
<td></td>
</tr>
<tr>
<td>brain</td>
<td>1030</td>
<td></td>
<td>0.499</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**human brain tissue (white and grey matter), mean value G1, G2, at 98.6 F**

Figure 4-2: Human Brain Tissue Storage and Loss Shear Moduli in Yielded and Unyielded States.
In this study, the skull and membrane is assumed as elastic material with damping, and the brain is assumed as viscoelastic material. For brain, the frequency domain viscoelastic data provided by Shuck and Advani will be used as shown Figure 4-2[40]. The damping ratio of the skull and membrane is calculated based on two-point Rayleigh damping (at frequency 120 and 220 Hz) in order to reduce the peak at antiresonant frequency in the impedance simulation.

4-3-1. **Parametric study of finite element adult head model in L-R(left-right) direction**

The driving-point impedance response of the finite element model with L-R directional sinusoidal input, will be examined by changing the estimated mechanical properties to match the experimental impedance response.

The computer resources utilized in this research program are as follows. The ABAQUS finite element program is being used for finite element simulation and the IDEAS package is being used for solid modeling and mesh generation. A grant from the Ohio super-computer center(OSC) was awarded in 1990. The finite element simulations are performed on the OSC cray YMP8.

4-3-1-1. **Effects of elastic modulus of skull(Es)**

To examine effects of $Es$, $Es$ is only changed($Es=1000, 500, 100$ MPa), and the others properties remain as the estimated values in Table 4-1. Figure 4-3 shows that as
Es increases, the overall response increases;

a) response at antiresonant frequency increases
b) antiresonant frequency increases
c) response at high frequency (over 1000 Hz) increases

4-3-1-2. Effects of elastic modulus of membrane (Em)

To examine effects of Em, Em is only changed (Em=10, 5, 1 MPa), and the others properties remain as the estimated values in Table 4-1. Figure 4-4 shows that as Em increases;

a) response at antiresonant frequency increases
b) antiresonant frequency increases
c) response at middle frequency (200-1000 Hz) increases
d) response at high frequency (over 1000 Hz) does not change

4-3-1-3. Effects of damping ratio of skull (ξ)

To examine effects of ξ, ξ is only changed (ξ=0.1, 0.05, 0.01), and the others properties remain as the estimated values in Table 4-1. Figure 4-5 shows that as ξ increases;
a) response at antiresonant frequency reduces a little
b) antiresonant frequency increases a little
c) response over 200 Hz frequency increases

4-3-1-4. **Effects of damping ratio on membrane ($\xi_m$)**

To examine effects of $\xi_m$, $\xi_m$ is only changed ($\xi_m$ = 0.001, 0.0005, 0.0001), and the others properties remain as the estimated values in Table 4-1. Figure 4-6 shows that as $\xi_m$ increases;

a) response at antiresonant frequency reduces a little
b) antiresonant frequency increases a little
c) response over 200 Hz frequency increases

4-3-1-5. **Results and discussion**

From the parametric study, the estimated mechanical properties of the adult head in L-R direction are modified until the dynamic response of the finite element model matches with that from experiments. After several trials, it was found that the response of finite element model agreed well with that from experiments when the mechanical properties in Table 4-2 were used as shown in Figure 4-7.
Table 4-2: Calibrated mechanical property for finite element adult head model in L-R(left-right) direction

<table>
<thead>
<tr>
<th></th>
<th>modulus E(MPa)</th>
<th>density $\rho$ (kg/m$^3$)</th>
<th>Poisson's ratio $v$</th>
<th>damping ratio $\xi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>skull</td>
<td>500</td>
<td>2140</td>
<td>0.21</td>
<td>0.1</td>
</tr>
<tr>
<td>membrane</td>
<td>2.5</td>
<td>1133</td>
<td>0.45</td>
<td>0.0003</td>
</tr>
<tr>
<td>brain</td>
<td></td>
<td>1030</td>
<td>0.499</td>
<td></td>
</tr>
<tr>
<td></td>
<td>viscoelastic frequency property</td>
<td>(see Figure 4-2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>bulk</td>
<td>modulus = 200(MPa)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The calibrated mechanical properties show that the elastic moduli of skull and membrane are much less than those from experiments, and that the bulk modulus of brain is also much less. These phenomena can be explained by the locking problem of nearly incompressible material in the finite element analysis. The Poisson's ratio of the brain is nearly 0.5, so the bulk modulus goes infinite. So, the response of finite element model is too stiff in comparison with that of the real head. The other reason is that there are some empty spots (filled with air or fluid) in the brain, membrane, and skull. That means, the effective stiffness of the mechanical properties will be much less than those from experiments. Due to those reasons, the calibrated mechanical property is much less than those from experiments.
4-3-2. Parametric Study of Finite Element Adult Head Model in P-A (posterior-anterior) Direction

The head has an extremely complex geometric configuration. Even though the calvarium resembles a shell, it consists of eight layered bones of irregular thickness joined by sutures. The skull is covered by scalp, a loosely coupled layer of soft-tissue. Furthermore, the brain floats in pressurized cerebrospinal fluid within the membrane. Thus, the parametric study of model in other directions will be needed, even though the parametric study of adult head model in L-R (lateral) direction was done. The calibrated mechanical property from the parametric study in L-R direction will be used for trial value of parametric study in P-A direction. After several trials, it is found when the mechanical property in Table 4-3 is used the response of finite element model agreed well with that from experiments as shown in Figure 4-8.

Table 4-3: Calibrated mechanical property for finite element adult head model in P-A direction

<table>
<thead>
<tr>
<th></th>
<th>modulus</th>
<th>density</th>
<th>Poisson's ratio</th>
<th>damping ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>skull</td>
<td>500</td>
<td>2140</td>
<td>0.21</td>
<td>0.05</td>
</tr>
<tr>
<td>membrane</td>
<td>3.5</td>
<td>1133</td>
<td>0.45</td>
<td>0.0008</td>
</tr>
<tr>
<td>brain</td>
<td>1030</td>
<td></td>
<td>0.499</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>viscoelastic frequency property</td>
<td>(Figure 4-2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>bulk modulus</td>
<td>200(MPa)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4-3-3. **Parametric Study of Finite Element Adult Head Model**

**in A-P(anterior-posterior) Direction**

Based on the parametric study in L-R and P-A directions, it is found when the mechanical property in Table 4-4 is used, the response of finite element model agreed well with that from experiments as shown in Figure 4-9.

**Table 4-4 : Calibrated mechanical property for finite element adult head model in A-P direction.**

<table>
<thead>
<tr>
<th></th>
<th>modulus E(MPa)</th>
<th>density $\rho$ (kg/m$^3$)</th>
<th>Poisson's ratio $\nu$</th>
<th>damping ratio $\xi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>skull</td>
<td>700</td>
<td>2140</td>
<td>0.21</td>
<td>0.08</td>
</tr>
<tr>
<td>membrane</td>
<td>4.5</td>
<td>1133</td>
<td>0.45</td>
<td>0.0003</td>
</tr>
<tr>
<td>brain</td>
<td>1030</td>
<td></td>
<td>0.499</td>
<td></td>
</tr>
</tbody>
</table>

**viscoelastic frequency property** (Figure 4-2)

bulk modulus = 200(MPa)

4-4. **Closure**

The finite element model was validated based on the experimental impedance data, and the mechanical properties of the adult model in L-R, P-A, and A-P direction were
determined in this chapter. In the next chapter, the driving-point impedance curves of 6
and 2-year old child, and newborn infant will be determined.
Figure 4-3: Parameter Study -- Es(elastic modulus of skull bone) change only

- ES1 -- Es = 1000 MPa
- ES2 -- Es = 500 MPa
- ES3 -- Es = 100 MPa
- EXL -- experimental impedance data
Figure 4-4: Parameter Study -- $Em$ (elastic modulus of membrane) change only

- EM1 -- $Em = 10$ MPa
- EM2 -- $Em = 5$ MPa
- EM3 -- $Em = 1$ MPa
- EXL -- experimental impedance data
Figure 4-5: Parameter Study -- Ds(damping ratio of skull bone) change only

DS1 -- Ds = 0.1
DS2 -- Ds = 0.05
DS3 -- Ds = 0.01
EXL -- experimental impedance data
Figure 4-6: Parameter Study -- Dm (damping ratio of membrane) change only

DM1 -- Dm = 0.001
DM2 -- Dm = 0.0005
DM3 -- Dm = 0.0001
EXL -- experimental impedance data
Figure 4-7: Mechanical Impedance in L-R direction of finite element adult model

ADL - Impedance from finite element model

EXL - Impedance from experiments
Figure 4-8: Mechanical Impedance in P-A direction of finite element adult model

ADP - Impedance from finite element model

EXP - Impedance from experiments
Figure 4-9: Mechanical Impedance in A-P direction of finite element adult model

ADA - Impedance from finite element model

EXA - Impedance from experiments
CHAPTER V

Generation of Mechanical Impedance Curve of Six and Two Years Old Child, and Newborn Infant

5-1. Overview

The finite element model was validated in the previous chapter by using the experiment impedance data. In this chapter, the mechanical properties of 6 and 2-year old child, and newborn infant will be estimated, and the driving-point impedance curves in A-P, P-A, and L-R direction of child and infant will be determined.

5-2. Mechanical properties of 6 and 2-year old child, and newborn infant model

McPherson[41] and Guenther[42] showed the increase of elastic modulus of bone along with a grown-up. Their data show that the elastic modulus of 6 and 2-year old child, and newborn infant skull bone is about 80%, 55%, and 22% of the elastic modulus of adult skull bone respectively. Based on those data, the elastic modulus of the skull bone is estimated and tabulated in Table 5-1. However, the other mechanical properties of skull bone (density, Poisson's ratio, and Rayleigh damping ratio) will be used
regardless of age.

The mechanical properties of the brain and membrane of 6 and 2-year old child, and newborn infant are not available. So, the mechanical properties of the adult brain and membrane will be used as those of 6 and 2-year old child, and newborn infant brain and membrane based on the assumption that the mechanical properties of soft tissues (brain and membrane) are not changed along with a grown-up.

Table 5-1: The estimated elastic modulus of skull bone

<table>
<thead>
<tr>
<th></th>
<th>elastic modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A-P</td>
</tr>
<tr>
<td>adult</td>
<td>700</td>
</tr>
<tr>
<td>6-year</td>
<td>560</td>
</tr>
<tr>
<td>2-year</td>
<td>385</td>
</tr>
<tr>
<td>infant</td>
<td>154</td>
</tr>
</tbody>
</table>

5-3. Impedance simulations of 6 and 2-year old child, and newborn infant model in A-P, P-A, and L-R direction

Six and two years old child, and newborn infant models are simulated to find the driving-point impedance curve based on the calibrated mechanical properties in each direction in the previous chapter except the elastic modulus of skull bone. The
mechanical properties of 6 and 2-year old child, and newborn infant finite element models are tabulated in Table 5-2 to 5-4. The mechanical property of the brain is assumed not to change regardless of the age and the direction, and the fontanelle mechanical property is assumed as that of the human skin. The mechanical properties of the brain and the fontanelle are in Chapter 3.

By using ABAQUS finite element program, the finite element models were simulated to get the impedance responses. The mechanical impedance curves of 6 and 2-year old child, and newborn infant model in A-P, P-A, and L-R direction are plotted in Figure 5-1 to 5-3.

Table 5-2 : Mechanical Property of the Finite Element Model of 6-year old child in the A-P, P-A, and L-R Direction

<table>
<thead>
<tr>
<th></th>
<th>A-P</th>
<th>P-A</th>
<th>L-R</th>
</tr>
</thead>
<tbody>
<tr>
<td>skull modulus $E$ (MPa)</td>
<td>560</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>membrane modulus $E$</td>
<td>4.5</td>
<td>3.5</td>
<td>2.5</td>
</tr>
<tr>
<td>skull density $\rho$ (kg/m$^3$)</td>
<td>2140</td>
<td>2140</td>
<td>2140</td>
</tr>
<tr>
<td>membrane density $\rho$</td>
<td>1133</td>
<td>1133</td>
<td>1133</td>
</tr>
<tr>
<td>Poisson's ratio $\nu$</td>
<td>0.21</td>
<td>0.21</td>
<td>0.21</td>
</tr>
<tr>
<td>damping ratio $\xi$</td>
<td>0.08</td>
<td>0.05</td>
<td>0.1</td>
</tr>
</tbody>
</table>
Table 5-3: Mechanical Property of the Finite Element Model of the 2-year old child in the A-P, P-A, and L-R Direction

<table>
<thead>
<tr>
<th></th>
<th>A - P</th>
<th></th>
<th>P - A</th>
<th></th>
<th>L - R</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>skull</td>
<td>membrane</td>
<td>skull</td>
<td>membrane</td>
<td>skull</td>
<td>membrane</td>
</tr>
<tr>
<td>modulus E (MPa)</td>
<td>385</td>
<td>4.5</td>
<td>275</td>
<td>3.5</td>
<td>275</td>
<td>2.5</td>
</tr>
<tr>
<td>density ( \rho ) (kg/m(^3))</td>
<td>2140</td>
<td>1133</td>
<td>2140</td>
<td>1133</td>
<td>2140</td>
<td>1133</td>
</tr>
<tr>
<td>Poisson's ratio ( v )</td>
<td>0.21</td>
<td>0.45</td>
<td>0.21</td>
<td>0.45</td>
<td>0.21</td>
<td>0.45</td>
</tr>
<tr>
<td>damping ratio ( \xi )</td>
<td>0.08</td>
<td>0.0003</td>
<td>0.05</td>
<td>0.0008</td>
<td>0.1</td>
<td>0.0003</td>
</tr>
</tbody>
</table>

Table 5-4: Mechanical Property of the Finite Element Model of the Newborn Infant in the A-P, P-A, and L-R Direction

<table>
<thead>
<tr>
<th></th>
<th>A - P</th>
<th></th>
<th>P - A</th>
<th></th>
<th>L - R</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>skull</td>
<td>membrane</td>
<td>skull</td>
<td>membrane</td>
<td>skull</td>
<td>membrane</td>
</tr>
<tr>
<td>modulus E (MPa)</td>
<td>154</td>
<td>4.5</td>
<td>110</td>
<td>3.5</td>
<td>110</td>
<td>2.5</td>
</tr>
<tr>
<td>density ( \rho ) (kg/m(^3))</td>
<td>2140</td>
<td>1133</td>
<td>2140</td>
<td>1133</td>
<td>2140</td>
<td>1133</td>
</tr>
<tr>
<td>Poisson's ratio ( v )</td>
<td>0.21</td>
<td>0.45</td>
<td>0.21</td>
<td>0.45</td>
<td>0.21</td>
<td>0.45</td>
</tr>
<tr>
<td>damping ratio ( \xi )</td>
<td>0.08</td>
<td>0.0003</td>
<td>0.05</td>
<td>0.0008</td>
<td>0.1</td>
<td>0.0003</td>
</tr>
</tbody>
</table>
5-4. **Results and Discussion**

The comparisons of the mechanical impedance curve along with a grown-up are plotted in Figure 5-4 to 5-6. The figures show that along with grown-up, regardless of the directions,

a) overall response increases
b) antiresonant frequency increases
c) resonant frequency reduces.

These phenomena can be explained by the increase of the model(head) mass and the structural stiffness of the model. Overall impedance response increases due to the increase of the head mass along with grown-up. And the total structural stiffness of the model increases because the thickness and elastic modulus of the skull bone increase along with a grown-up. Therefore, in child, the rigid body motion will be finished early, and the transition mode(between two rigid body motions) will be longer compare to adult because the structural stiffness of the skull is less than that of adult. Thus, antiresonant frequency increases and resonant frequency reduces along with grown-up.

The antiresonant and resonant frequency of adult, 6 and 2-year old child, and the newborn infant model are tabulated in Table 5-5.
Table 5-5: Antiresonant and resonant frequency of models

<table>
<thead>
<tr>
<th></th>
<th>Antiresonant / Resonant freq(Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A-P</td>
</tr>
<tr>
<td>adult</td>
<td>320/900</td>
</tr>
<tr>
<td>6-year</td>
<td>224/1260</td>
</tr>
<tr>
<td>2-year</td>
<td>204/1320</td>
</tr>
</tbody>
</table>

5-5. **Closure**

The driving-point impedance curves in A-P, P-A, and L-R direction of 6 and 2-year old child, and newborn infant head model were made based on the finite element models in this chapter. Those driving-point impedance curves will be used to develop the translational head injury models in the next chapter.
Figure 5-1: Mechanical Impedance Curve of 6-year old child model

- **B6A**: Impedance in A-P direction
- **B6P**: Impedance in P-A direction
- **B6L**: Impedance in L-R direction
Figure 5-2: Mechanical Impedance Curve of 2-year old child model

B2A -- Impedance in A-P direction
B2P -- Impedance in P-A direction
B2L -- Impedance in L-R direction
Figure 5-3: Mechanical Impedance Curve of newborn infant model

NBA -- Impedance in A-P direction
NBP -- Impedance in P-A direction
NBL -- Impedance in L-R direction
Figure 5-4: Comparison of Mechanical Impedance along with grown-up in A-P direction

ADA -- Impedance from adult model
B6A -- Impedance from 6-year old child model
B2A -- Impedance from 2-year old child model
NBA -- Impedance from newborn infant model
Figure 5-5: Comparison of Mechanical Impedance along with grown-up in P-A direction

- ADP -- Impedance from adult model
- B6P -- Impedance from 6-year old child model
- B2P -- Impedance from 2-year old child model
- NBP -- Impedance from newborn infant model
Figure 5-6: Comparison of Mechanical Impedance along with grown-up in L-R direction

ADL -- Impedance from adult model
B6L -- Impedance from 6-year old child model
B2L -- Impedance from 2-year old child model
NBL -- Impedance from newborn infant model
CHAPTER VI

Development of Translational Head Injury Model of Six and Two Years Old Child, and Newborn Infant

6-1. Overview

In the previous chapter, the mechanical impedance curves were determined by using the finite element models. In this chapter, the translational head injury model (THIM) will be developed based on the mechanical impedance curves that were determined from the finite element models.

6-2. Translational Head Injury Model of 6-year Old Child

Based on the mechanical impedance curves from the finite element model of 6-year old child, the THIM model will be developed. The model parameter M1 and M2 can be directly determined from the impedance curve, and the parameter D (the distance between mass M1 and M2) is determined from the geometrical study (cranium distance). However, the other parameters (K, C1, and C2) will be generated through fitting the
mechanical impedance curve from the THIM model to that from the finite element model.

Based on the parameter study of the adult THIM model by Rojanavanich[27], the parameter study of 6-year old child THIM model in A-P, P-A, and L-R direction is performed. After several trials, it was found that the response of the THIM model agreed well with that from the finite element model as shown in Figure 6-1 to 6-3 when the model parameter data in Table 6-1 were used.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>A-P</th>
<th>P-A</th>
<th>L-R</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1 (kg)</td>
<td>0.114</td>
<td>0.072</td>
<td>0.072</td>
</tr>
<tr>
<td>M2 (kg)</td>
<td>3.096</td>
<td>3.138</td>
<td>3.138</td>
</tr>
<tr>
<td>K (MN/m)</td>
<td>6</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>C1 (N-sec/m)</td>
<td>10000</td>
<td>7800</td>
<td>6300</td>
</tr>
<tr>
<td>C2 (N-sec/m)</td>
<td>140</td>
<td>140</td>
<td>140</td>
</tr>
<tr>
<td>D (m)</td>
<td>0.180</td>
<td>0.180</td>
<td>0.140</td>
</tr>
</tbody>
</table>

6-3. **Translational Head Injury Model of 2-year Old Child**

Using the same procedure in the parameter study of the THIM model of 6-year old child, the parameters of the THIM model of 2-year old child in A-P, P-A, and L-R
direction will be determined based on the mechanical impedance response data from the finite element model. After several trials, it was found that the response of the THIM model agreed well with that from the finite element model as shown in Figure 6-4 to 6-6 when the model parameters in Table 6-2 were used.

Table 6-2: Calibrated model parameters of the THIM model of 2-year old child in A-P, P-A, and L-R direction

<table>
<thead>
<tr>
<th>Parameter</th>
<th>A-P</th>
<th>P-A</th>
<th>L-R</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1 (kg)</td>
<td>0.045</td>
<td>0.034</td>
<td>0.030</td>
</tr>
<tr>
<td>M2 (kg)</td>
<td>1.641</td>
<td>1.652</td>
<td>1.656</td>
</tr>
<tr>
<td>K (MN/m)</td>
<td>2.7</td>
<td>1.8</td>
<td>1.5</td>
</tr>
<tr>
<td>C1 (N-sec/m)</td>
<td>6000</td>
<td>5700</td>
<td>4900</td>
</tr>
<tr>
<td>C2 (N-sec/m)</td>
<td>120</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>D (m)</td>
<td>0.17</td>
<td>0.17</td>
<td>0.13</td>
</tr>
</tbody>
</table>

6-4. **Translational Head Injury Model of Newborn Infant**

Using the same procedure, the parameters of the THIM model of the newborn infant in A-P, P-A, and L-R direction will be determined based on the mechanical impedance response data from the finite element model. After several trials, it was found that the response of the THIM model agreed well with that from the finite element model as
shown in Figure 6-7 to 6-9 when the model parameters in Table 3 were used.

Table 6-3: Calibrated model parameters of the THIM model of newborn infant
in A-P, P-A, and L-R direction

<table>
<thead>
<tr>
<th>Parameter</th>
<th>A-P</th>
<th>P-A</th>
<th>L-R</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1 (kg)</td>
<td>0.0054</td>
<td>0.0044</td>
<td>0.0050</td>
</tr>
<tr>
<td>M2 (kg)</td>
<td>0.7096</td>
<td>0.7106</td>
<td>0.7100</td>
</tr>
<tr>
<td>K (MN/m)</td>
<td>0.9</td>
<td>0.5</td>
<td>0.48</td>
</tr>
<tr>
<td>C1 (N-sec/m)</td>
<td>3000</td>
<td>2900</td>
<td>2700</td>
</tr>
<tr>
<td>C2 (N-sec/m)</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>D (m)</td>
<td>0.12</td>
<td>0.12</td>
<td>0.10</td>
</tr>
</tbody>
</table>

6-5. Results and Discussion

The results show that the value of all parameters of the THIM model increases along with a grown-up. The major outcomes are as follows;

1) The damper C2 is found to be a constant regardless of the direction in the same age.

2) The value of damper C2, which is believed to be primarily the damping of the brain, increases along with a grown-up, even though the mechanical property of the brain was
assumed not to change along with a grown-up in a finite element model. The finite element results show that the increase of the damping $C_2$ is closely related to the increase of the brain mass. The relationship between the damping $C_2$ and the brain mass is follows:

$$C_{\text{child}} = C_{\text{adult}} \times \frac{M_{\text{child}}}{M_{\text{adult}}} \tag{6-1}$$

Table 6-4 shows the increase of the damping $C_2$ along with a grown-up and the comparison of the damping $C_2$ from the finite element results and from the equation (6-1).

<table>
<thead>
<tr>
<th></th>
<th>Brain Mass (g)</th>
<th>$C_2$ form FEM</th>
<th>$C_2$ from Eq. (6-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>newborn infant</td>
<td>353</td>
<td>40</td>
<td>39</td>
</tr>
<tr>
<td>6-year old child</td>
<td>1076</td>
<td>120</td>
<td>119</td>
</tr>
<tr>
<td>2-year old child</td>
<td>1300</td>
<td>140</td>
<td>143</td>
</tr>
<tr>
<td>adult</td>
<td>1430</td>
<td>157.6</td>
<td>157.6</td>
</tr>
</tbody>
</table>

3) The percentage of the parameter $M_1$ to the total head mass is increased along with a grown-up.
4) In the same age, the value of the model parameters in A-P direction is higher than that in the P-A and L-R direction, and the value of the model parameter in the P-A and L-R direction is similar except the newborn infant.

5) In the newborn infant, the M1 in the P-A direction is much higher than that in the L-R direction, and is almost similar to that in the A-P direction. This phenomenon can be explained as the effects of the fontanelles. Because of the fontanelles, the skull bones (frontal, parietal, occipital bone) can be moved individually. So, the weight of each skull bone may be the important factor of the dynamic response of the head. The weight of the parietal bone is much higher than that of occipital bone, and is similar to that of frontal bone.

Table 6-5 show the Comparison of the parameters of THIM model of adult, 6 and 2-year old child, and newborn infant.

6-6. Closure

In this chapter, the translational head injury models(THIM) of 6 and 2-year old child, and newborn infant were developed based on the mechanical impedance response data from the finite element models. In the next chapter, the off-axis THIM model will be developed.
Table 6-5: Comparison of the parameters of THIM model of adult, 6 and 2-year old child, and newborn infant

<table>
<thead>
<tr>
<th>age</th>
<th>M1</th>
<th>M2</th>
<th>K</th>
<th>C1</th>
<th>C2</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg</td>
<td>kg</td>
<td>MN/m</td>
<td>N-sec/m</td>
<td>N-sec/m</td>
<td>m</td>
</tr>
<tr>
<td>adult</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-P</td>
<td>0.45</td>
<td>4.09</td>
<td>13.5</td>
<td>17000</td>
<td>157.6</td>
<td>0.195</td>
</tr>
<tr>
<td>P-A</td>
<td>0.27</td>
<td>4.27</td>
<td>7.0</td>
<td>8000</td>
<td>157.6</td>
<td>0.195</td>
</tr>
<tr>
<td>L-R</td>
<td>0.25</td>
<td>4.29</td>
<td>6.5</td>
<td>6500</td>
<td>157.6</td>
<td>0.154</td>
</tr>
<tr>
<td>6-year</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-P</td>
<td>0.114</td>
<td>3.096</td>
<td>6.0</td>
<td>10000</td>
<td>140</td>
<td>0.18</td>
</tr>
<tr>
<td>P-A</td>
<td>0.072</td>
<td>3.138</td>
<td>4.0</td>
<td>7800</td>
<td>140</td>
<td>0.18</td>
</tr>
<tr>
<td>L-R</td>
<td>0.072</td>
<td>3.138</td>
<td>3.0</td>
<td>6300</td>
<td>140</td>
<td>0.14</td>
</tr>
<tr>
<td>2-year</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-P</td>
<td>0.045</td>
<td>1.641</td>
<td>2.7</td>
<td>6000</td>
<td>120</td>
<td>0.17</td>
</tr>
<tr>
<td>P-A</td>
<td>0.034</td>
<td>1.652</td>
<td>1.8</td>
<td>5700</td>
<td>120</td>
<td>0.17</td>
</tr>
<tr>
<td>L-R</td>
<td>0.030</td>
<td>1.656</td>
<td>1.5</td>
<td>4900</td>
<td>120</td>
<td>0.13</td>
</tr>
<tr>
<td>infant</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-P</td>
<td>0.0054</td>
<td>0.7096</td>
<td>0.9</td>
<td>3000</td>
<td>40</td>
<td>0.12</td>
</tr>
<tr>
<td>P-A</td>
<td>0.0044</td>
<td>0.7106</td>
<td>0.5</td>
<td>2900</td>
<td>40</td>
<td>0.12</td>
</tr>
<tr>
<td>L-R</td>
<td>0.0050</td>
<td>0.7100</td>
<td>0.48</td>
<td>2700</td>
<td>40</td>
<td>0.10</td>
</tr>
</tbody>
</table>
Figure 6-1: Mechanical Impedance of 6-year old child THIM in the A-P direction

TB6A -- impedance data from THIM model

B6A -- impedance data from finite element model
Figure 6-2: Mechanical Impedance of 6-year old child THIM in the P-A direction

TB6P -- impedance data from THIM

B6P -- impedance data from finite element model
Figure 6-3: Mechanical Impedance of 6-year old child THIM in the L-R direction

TB6L -- impedance data from THIM

B6L -- impedance data from finite element model
Figure 6-4: Mechanical Impedance of 2-year old child THIM in the A-P direction

TB2A -- impedance data from THIM

B2A -- impedance data from finite element model
Figure 6-5: Mechanical Impedance of 2-year old child THIM in the P-A direction

TB2P -- impedance data from THIM

B2P -- impedance data from finite element model
Figure 6-6: Mechanical Impedance of 2-year old child THIM in the L-R direction

TB2L -- impedance data from THIM

B2L -- impedance data from finite element model
Figure 6-7: Mechanical Impedance of newborn infant THIM in the A-P direction

TNBA -- impedance data from THIM

NBA -- impedance data from finite element model
Figure 6-8: Mechanical Impedance of newborn infant THIM in the P-A direction

TNBP -- impedance data from THIM

NBP -- impedance data from finite element model
Figure 6-9: Mechanical Impedance of newborn infant THIM in the L-R direction

TNBL -- impedance data from THIM

NBL -- impedance data from finite element model
CHAPTER VII

Development of "Off-Axis" Translational Head Injury Model (THIM) of Six and Two Years Old Child, and Newborn Infant

7-1. Overview

In the previous chapter, the THIM models of 6 and 2-year old child, and newborn infant in the A-P, P-A, and L-R direction were developed based on the results from the finite element models. In this chapter, the off-axis THIM model of child will be developed for the off-axis head impact evaluations.

7-2. Background

In real automobile related accidents, the location of head impact is somewhat random in nature. Statistically, some orientations of head impacts are more frequent and dangerous. So, the prediction of consequences of head impact at different impact location is very demanded. However, because of the lack of experimental data and the complexity of head shape and structure, the accurate modeling for the estimation of the off-axis head impact response is almost impossible.
In 1990, Vichai[44] developed the off-axis THIM model of adult based on the experimental human impedance response in the A-P, P-A, L-R, and S-I directions. The basic assumptions to develop the off-axis THIM model were that the impedance response of the off-axis head impact has the similar trend with two adjacent reference impedance responses that were determined by experiments, and that the impedance value of the off-axis head impact is the middle value comparing with two adjacent reference impedance values. Based on the above assumptions, the off-axis impedance curve at the middle point or 45 degree rotation from the reference point (A-P, P-A, L-R, or S-I) was generated, and the parameters of the THIM model were determined by matching the off-axis impedance curve. Table 7-1 shows the lumped parameters of the off-axis THIM model of adult. In the table, "AP-LR" direction means the middle direction between A-P and L-R direction. (45 degree rotation from A-P to L-R direction)

Table 7-1: Parameters of the Off-Axis THIM Model of Adult

<table>
<thead>
<tr>
<th>age</th>
<th>direction</th>
<th>M1</th>
<th>M2</th>
<th>K</th>
<th>C1</th>
<th>C2</th>
</tr>
</thead>
<tbody>
<tr>
<td>adult</td>
<td>AP-LR</td>
<td>0.31</td>
<td>4.23</td>
<td>9.6</td>
<td>9900</td>
<td>157.6</td>
</tr>
<tr>
<td></td>
<td>PA-LR</td>
<td>0.25</td>
<td>4.29</td>
<td>6.9</td>
<td>7100</td>
<td>157.6</td>
</tr>
<tr>
<td></td>
<td>AP-SI</td>
<td>0.54</td>
<td>4.00</td>
<td>13.3</td>
<td>20500</td>
<td>157.6</td>
</tr>
<tr>
<td></td>
<td>LR-SI</td>
<td>0.41</td>
<td>4.13</td>
<td>9.8</td>
<td>12500</td>
<td>157.6</td>
</tr>
<tr>
<td></td>
<td>PA-LR</td>
<td>0.43</td>
<td>4.11</td>
<td>10.0</td>
<td>13500</td>
<td>157.6</td>
</tr>
</tbody>
</table>
7-3. **Off-Axis THIM Model of Six and Two Years Old Child, and Newborn Infant**

By using the same procedure suggested by Vichai, the off-axis THIM model of 6 and 2-year old child, and newborn infant in the AP-LR and PA-LR direction will be developed. The off-axis impedance curves at the middle point (45 degree rotation) from the reference points are generated by trial and error as shown in Figure 7-1 to 7-6. And the parameter D, the distance between M1 and M2 (cranium distance), was found from a geometrical study. Table 7-2 shows the parameters of the off-axis THIM model of child.

<table>
<thead>
<tr>
<th>age</th>
<th>direction</th>
<th>M1</th>
<th>M2</th>
<th>K</th>
<th>C1</th>
<th>C2</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-year</td>
<td>AP-LR</td>
<td>0.091</td>
<td>3.119</td>
<td>4.6</td>
<td>7700</td>
<td>140</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>PA-LR</td>
<td>0.072</td>
<td>3.138</td>
<td>3.4</td>
<td>6900</td>
<td>140</td>
<td>0.16</td>
</tr>
<tr>
<td>2-year</td>
<td>AP-LR</td>
<td>0.037</td>
<td>1.649</td>
<td>1.9</td>
<td>5300</td>
<td>120</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>PA-LR</td>
<td>0.032</td>
<td>1.654</td>
<td>1.6</td>
<td>5200</td>
<td>120</td>
<td>0.15</td>
</tr>
<tr>
<td>infant</td>
<td>AP-LR</td>
<td>0.0052</td>
<td>0.7098</td>
<td>0.65</td>
<td>2820</td>
<td>40</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>PA-LR</td>
<td>0.0047</td>
<td>0.7103</td>
<td>0.49</td>
<td>2780</td>
<td>40</td>
<td>0.11</td>
</tr>
</tbody>
</table>
7-4. **Closure**

In this chapter, the off-axis THIM models of 6 and 2-year old child, and newborn infant were developed. In the next chapter, the procedure of the experimental data processing will be explained.
Figure 7-1: Off-Axis Impedance Curve of Six Years Old Child THIM Model in the AP-LR Direction

Figure 7-2: Off-Axis Impedance Curve of Six Years Old Child THIM Model in the PA-LR Direction
Figure 7-3: Off-Axis Impedance Curve of Two Years Old Child THIM Model in the AP-LR Direction

Figure 7-4: Off-Axis Impedance Curve of Two Years Old Child THIM Model in the PA-LR Direction
Figure 7-5: Off-Axis Impedance Curve of Newborn Infant THIM Model in the AP-LR Direction

Figure 7-6: Off-Axis Impedance Curve of Newborn Infant THIM Model in the PA-LR Direction
CHAPTER VIII

Experimental Data Processing

8-1. Overview

In the previous chapter, the off-axis THIM models of 6 and 2-year old child, and newborn infant were developed. In this chapter, the procedure of the experimental data processing will be explained.

8-2. Experimental Child Head Injury Data

In 1986, the National Highway Traffic Safety Administration (NHTSA) conducted research to develop methods of reducing pedestrian head injury due to automobile hood contract at speeds less than or equal to 30 mph (48 kph). One task was to analyze a set of pedestrian cadaver tests, primarily to develop test methods for accident reconstructions. The second task was to complete an extensive set of accident reconstructions for the purpose of relating laboratory impactor response to real-world injury.
A 9-accelerometer array mounted on the side of the head, a triaxial accelerometer array mounted in the mouth, and film coverage have provided a set of data sufficient to allow analysis of the head impact response of the subjects. Additionally, the vehicle hoods have been saved and studied for the purpose of measuring dents. Accelerometer data, high speed films, and damaged vehicle hoods were used for analysis. With this information it was possible to determine the effective head mass of each cadaver upon impact. The head impact velocity could be determined by digitizing the head trajectory in the films. Previous research results [46] had established that similar energy impacts to the hood produce similar dents. The approach used to determine effective head mass was to reconstruct a cadaver head impact using the digitized impact velocity and varying the mass until a test reproduced the cadaver hood deformation. Cadaver test accelerations agreed fairly well with the accelerations from the best reconstructions.

Thirty-five pedestrian accident tests were analyzed and the extensive sets of accident reconstruction test data were provided for the purpose of relation laboratory impact response to real-world injury. One of examples of the original impact data is shown in Figure 8-1. From the figure, impact duration and magnitude of impact acceleration can be determined. In this study, thirteen child reconstruction data among the thirty-five pedestrian accident reconstruction test data will be used to develop the TEC for child head injury analysis. Table 8-1 shows thirteen child reconstruction test data.
<table>
<thead>
<tr>
<th>Accident Case No.**</th>
<th>Recon. Test No.</th>
<th>Age accident</th>
<th>Vel. (mph)</th>
<th>R-Head Mass,kg</th>
<th>R-Max. Acc(g)</th>
<th>AIS</th>
<th>Direction</th>
<th>Injury*</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAIDS 81-08-022</td>
<td>S86244</td>
<td>7</td>
<td>10-15</td>
<td>12.9</td>
<td>2.517</td>
<td>99</td>
<td>2,1,0</td>
<td>AP-LR</td>
</tr>
<tr>
<td>PICS 99-07-201</td>
<td>S86248</td>
<td>7</td>
<td>15-19</td>
<td>14.0</td>
<td>2.517</td>
<td>115</td>
<td>2,1,0</td>
<td>LR Cont.</td>
</tr>
<tr>
<td>PAIDS 82-05-201</td>
<td>S86258</td>
<td>2</td>
<td>15-24</td>
<td>13.3</td>
<td>1.769</td>
<td>188</td>
<td>2,2,1</td>
<td>AP</td>
</tr>
<tr>
<td>PAIDS 83-01-202</td>
<td>S86259</td>
<td>8</td>
<td>20-25</td>
<td>11.9</td>
<td>1.769</td>
<td>74</td>
<td>1,1,1</td>
<td>AP</td>
</tr>
<tr>
<td>PAIDS 82-05-201</td>
<td>S86260</td>
<td>3</td>
<td>18-24</td>
<td>14.0</td>
<td>1.769</td>
<td>199</td>
<td>2,2,1</td>
<td>AP</td>
</tr>
<tr>
<td>PAIDS 81-08-211</td>
<td>S86261</td>
<td>7</td>
<td>19-22</td>
<td>13.8</td>
<td>1.769</td>
<td>194</td>
<td>1,0,0</td>
<td>PA-LR</td>
</tr>
<tr>
<td>PICS 19-12-208</td>
<td>S86262</td>
<td>8</td>
<td>20</td>
<td>18.4</td>
<td>1.769</td>
<td>369</td>
<td>2,1,0</td>
<td>AP-LR  Conc.</td>
</tr>
<tr>
<td>PICS 87-12-208</td>
<td>S86263</td>
<td>6</td>
<td>19</td>
<td>16.4</td>
<td>1.769</td>
<td>383</td>
<td>3,3,1</td>
<td>LR Skull-F</td>
</tr>
<tr>
<td>PICS 68-05-201</td>
<td>S86264</td>
<td>6</td>
<td>10-15</td>
<td>12.8</td>
<td>1.860</td>
<td>129</td>
<td>2,1,0</td>
<td>AP-LR  Conc.</td>
</tr>
<tr>
<td>PICS 88-07-209</td>
<td>S86266</td>
<td>9</td>
<td>9</td>
<td>16.3</td>
<td>2.404</td>
<td>130</td>
<td>1,0,0</td>
<td>PA Cont.</td>
</tr>
<tr>
<td>PICS 79-06-201</td>
<td>S86268</td>
<td>9</td>
<td>15</td>
<td>17.5</td>
<td>2.404</td>
<td>141</td>
<td>1,0,0</td>
<td>AP Cont.</td>
</tr>
<tr>
<td>PICS 99-07-201</td>
<td>S86269</td>
<td>7</td>
<td>15-19</td>
<td>17.1</td>
<td>2.631</td>
<td>145</td>
<td>1,0,0</td>
<td>AP-LR</td>
</tr>
<tr>
<td>PICS 87-11-211</td>
<td>S86271</td>
<td>6</td>
<td>40-45</td>
<td>26</td>
<td>1.860</td>
<td>227</td>
<td>4,4,0</td>
<td>AP-LR</td>
</tr>
</tbody>
</table>

**Injury Description**  
Conc. = Concussion  
Cont. = Contusion  
Skull-F = Skull Fracture  

**Accident Case Number**  
PAIDS = Pedestrian Accident Investigation Data Support  
PICS = Pedestrian Injury Causation Study
8-3. Experimental Data Processing

Before the experimental impact signal (acceleration) is loaded to the THIM model, the appropriate adjustments of the impact signal must be needed. These adjustments are accomplished in order to remove unrelated sections of the test signal, and to reduce attenuation of the electronic measuring devices and test setup, and so forth. In this research, the following five processing steps are carried out in the sequence to adjust the impact acceleration.

1. Condensation of the impact acceleration
2. Zeroing of the impact acceleration
3. Making the resultant acceleration
4. Normalization of the impact acceleration
5. Filtering of the impact acceleration

8-3-1. Condensation of the impact acceleration

Data condensation means the removal of all unnecessary and unrelated fragments of the raw data. However, the condensed signal still preserves all the important information of the test related to the head impact. In particular, only time duration of the original signal that is close to the actual impact is retained for further analysis. Thus, this step will save considerable analysis time. One of the examples of pre- and post-condensed acceleration is shown in Figure 8-2.
8-3-2. **Zeroing of the impact acceleration**

The process of zeroing is needed to remove the horizontal bias from the condensed signal. In actual impact environments, the accelerometer at the head is setting in zero acceleration point to the impact event. However, there is a horizontal bias in the experimental data. The problem seems to be the arbitrary zero acceleration point in the data acquisition system that was set manually, and thus was not very accurate. However, this error did not affect the accuracy of the rest of the signal acquisition process. Thus, the horizontal bias should be calibrated to zero acceleration prior to the occurrence of impact. One of the examples of pre- and post-zeroed acceleration is shown in Figure 8-3.

8-3-3. **Making the resultant acceleration**

After zeroing of the impact acceleration, the resultant acceleration was calculated. Simply, resultant acceleration is computed as

\[ A_r(t) = \sqrt{A(t)^2} \]  

(8-1)

Where,  
\( A_r(t) \) = resultant acceleration  
\( A(t) \) = acceleration from reconstruction test

One of the examples of pre- and post-resultant acceleration is shown in Figure 8-4.
8-3-4. **Normalization of the impact acceleration**

The main purpose of normalizing the impact acceleration is to convert the impact data to a standardized format. This was to ensure that all impact tests were to be compared on the same reference basis. In the reconstruction tests headform mass ranged from approximately 1.81 to 5.44 kg. However, the TEC performed its analysis assuming the head mass as 4.54 kg for adult, 3.21 kg for 6-year old child, 1.686 kg for 2-year old child, and 0.715 kg for newborn infant. Therefore, it is necessary to scale the reconstruction acceleration-time pulse to make it representative of 4.54 kg head for adult, 3.21 kg head for 6-year old child, 1.686 kg head for 2-year old child, and 0.715 kg head for newborn infant.

The method used in this research is based on a normalizing procedure for dummy head impact responses introduced by Mertz[47] based on volumetric(or mass) correction. In this technique, a scaling factor, $\lambda$, and normalized acceleration and time are defined as follows;

$$\lambda = \left[ \frac{M_T}{M_i} \right]^{1/2}$$  \hspace{1cm} (8-2)

$$A_n = \frac{A_r}{\lambda}$$  \hspace{1cm} (8-3)

$$t_n = \lambda \times t$$  \hspace{1cm} (8-4)
where, $M_r = \text{Model mass in the THIM model}$

$M_i = \text{Mass of impactor(assumed actual head mass) use in the reconstruction}$

$A_n = \text{Normalized acceleration}$

$A_r = \text{Resultant acceleration}$

$t_n = \text{Normalized time}$

$t = \text{Time from reconstruction test}$

The reconstruction test data of 6 to 9-year old child are normalized for the THIM model of 6-year old child, and the reconstruction test data of 2 and 3-year old child are normalized for the THIM model of 2-year old child. The scaling factors of the reconstruction test data are summarized in Table 8-2 and 8-3. One of the examples of pre- and post-normalized acceleration is shown in Figure 8-5.

<table>
<thead>
<tr>
<th>Recon. Test #</th>
<th>Age(year)</th>
<th>$M_r$ (kg)</th>
<th>$M_i$ (kg)</th>
<th>$\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S86258</td>
<td>2</td>
<td>1.686</td>
<td>1.769</td>
<td>0.98437</td>
</tr>
<tr>
<td>S86260</td>
<td>3</td>
<td>1.686</td>
<td>1.769</td>
<td>0.98437</td>
</tr>
</tbody>
</table>
Table 8-3: Scaling Factor for the THIM Model of Six Years Old Child

<table>
<thead>
<tr>
<th>Recon. Test #</th>
<th>Age(year)</th>
<th>Mt (kg)</th>
<th>Mi (kg)</th>
<th>λ</th>
</tr>
</thead>
<tbody>
<tr>
<td>S86244</td>
<td>7</td>
<td>3.21</td>
<td>2.517</td>
<td>1.08454</td>
</tr>
<tr>
<td>S86248</td>
<td>7</td>
<td>3.21</td>
<td>2.517</td>
<td>1.08454</td>
</tr>
<tr>
<td>S86259</td>
<td>8</td>
<td>3.21</td>
<td>1.769</td>
<td>1.21990</td>
</tr>
<tr>
<td>S86261</td>
<td>7</td>
<td>3.21</td>
<td>1.769</td>
<td>1.21990</td>
</tr>
<tr>
<td>S86262</td>
<td>8</td>
<td>3.21</td>
<td>1.769</td>
<td>1.21990</td>
</tr>
<tr>
<td>S86263</td>
<td>6</td>
<td>3.21</td>
<td>1.769</td>
<td>1.21990</td>
</tr>
<tr>
<td>S86264</td>
<td>6</td>
<td>3.21</td>
<td>1.860</td>
<td>1.19973</td>
</tr>
<tr>
<td>S86266</td>
<td>9</td>
<td>3.21</td>
<td>2.404</td>
<td>1.10133</td>
</tr>
<tr>
<td>S86268</td>
<td>9</td>
<td>3.21</td>
<td>2.404</td>
<td>1.10133</td>
</tr>
<tr>
<td>S86269</td>
<td>7</td>
<td>3.21</td>
<td>2.631</td>
<td>1.06873</td>
</tr>
<tr>
<td>S86271</td>
<td>6</td>
<td>3.21</td>
<td>1.860</td>
<td>1.19973</td>
</tr>
</tbody>
</table>

8-3-5. Filtering of the impact acceleration

In real world accident environments, human head impact with frequency above 800 Hz is very rare, if not outright impossible to obtain. In addition, the high frequency random attenuation is not present in the normal head impacts. So, the elimination of the high frequency contents from the impact pulse is needed. Therefore, after normalizing
the impact acceleration, and the acceleration was processed by a low pass filter with 800 Hz cut-off frequency and -3 db/decade slope by using the CONTROL-C package. This was done to ensure that attenuation by impact instrumentation and boundary conditions was removed. One of the examples of pre- and post-filtered acceleration is shown in Figure 8-6.

8-4. Closure

In this chapter, the procedure of the experimental data processing was explained in detail, and the experimental data were adjusted for the translational energy criteria (TEC) analysis. In the next chapter, TEC criteria of child will be developed.
Figure 8-1: Original Impact Data --- Event Indicator and Acceleration Signal
Figure 8-2: Pre- and Post-Condensed Acceleration Signals
Figure 8-3: Pre- and Post-Zeroing Acceleration Signals
Figure 8-4: Pre- and Post-Resultant Acceleration Signals
Figure 8-5: Pre- and Post-Normalizing Acceleration Signals
Figure 8-6: Pre- and Post-Filtering Acceleration Signals
CHAPTER IX

Development of Translational Energy Criteria (TEC) of Child

9-1. Overview

In this chapter, the TEC criteria of child will be developed for the child head impact analysis. The child THIM models will be used to evaluate potential head impact injury severity by loading the reconstruction acceleration-time pulse. The dissipated energy by the damper C2 and the power transfer by the spring K in the THIM model will be correlated with the accident AIS number and the experimental skull fracture data in order to develop TEC criteria.

9-2. Simulations of the Child THIM Model Using Reconstruction Test Data

The child THIM models that were developed in the previous chapters and the reconstruction impact accelerations (as an input to the THIM models) were used to develop the TEC criteria of child. Thirteen child head injury reconstruction test data (SRL-86) as shown in Table 8-1 will be used in this research. Eleven reconstruction test data of 6 to 9-year old child were normalized based on the 6-year old child THIM.
model, and two reconstruction test data of 2 and 3-year old child were normalized based on the 2-year old child THIM model. However, unfortunately, the newborn infant experimental test data are not available at the present time.

The filtered impact head acceleration was loaded to the THIM model. Then, the model was solved for the dissipated energy by damper C2(EC2) and the rate of energy(power) transfer by the spring K(PWK) to determine two TEC parameters, EAIS and POSF. The EC2, PWK, HIC, and POD were calculated based on the following equations;

\[ EC2 = \int_{0}^{t_f} C2 \cdot (V_1 - V_2)^2 \, dt \]  
\[ PWK = \frac{d}{dt} \left[ \frac{1}{2} K(X_1 - X_3)^2 \right] \]  
\[ HIC = (t_2 - t_1) \left[ \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t) \, dt \right]^{25} \]  
\[ POD = 10^{\left(\frac{AJS-2.31}{1.85}\right)} \]

where, EC2 = Total Dissipation Energy by the damper C2  
PWK = Rate of Potential Energy Transfer by Spring K  
t f = Total Impact Time Duration  
d/dt = Notation for Time Duration  
POD = Probability of Death (%)
The simulation results were presented in Table 9-1 and 9-2, and Figure 9-1 through 9-3 show one of the examples of the energy and power of the elements of the THIM model.

Table 9-1: The Simulation Results of the Six Years Old THIM Model

<table>
<thead>
<tr>
<th>Recon. Test No.</th>
<th>Direction</th>
<th>EC2 (J)</th>
<th>PW** (watts)</th>
<th>N-M-A* (g)</th>
<th>HIC</th>
<th>AIS</th>
<th>POD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S86261</td>
<td>PA-LR</td>
<td>0.5520</td>
<td>2829</td>
<td>159</td>
<td>570</td>
<td>1,0,0(1)</td>
<td>0.2</td>
</tr>
<tr>
<td>S86266</td>
<td>PA</td>
<td>0.3071</td>
<td>1861</td>
<td>118</td>
<td>497</td>
<td>1,0,0(1)</td>
<td>0.2</td>
</tr>
<tr>
<td>S86268</td>
<td>AP</td>
<td>0.1782</td>
<td>1248</td>
<td>129</td>
<td>611</td>
<td>1,0,0(1)</td>
<td>0.2</td>
</tr>
<tr>
<td>S86269</td>
<td>AP-LR</td>
<td>0.2788</td>
<td>1869</td>
<td>136</td>
<td>409</td>
<td>1,0,0(1)</td>
<td>0.2</td>
</tr>
<tr>
<td>S86259</td>
<td>AP</td>
<td>0.0532</td>
<td>193</td>
<td>59</td>
<td>229</td>
<td>1,1,1(1)</td>
<td>0.2</td>
</tr>
<tr>
<td>S86244</td>
<td>AP-LR</td>
<td>0.1567</td>
<td>747</td>
<td>91</td>
<td>368</td>
<td>2,1,0(2)</td>
<td>0.68</td>
</tr>
<tr>
<td>S86248</td>
<td>LR</td>
<td>0.3300</td>
<td>1407</td>
<td>105</td>
<td>244</td>
<td>2,1,0(2)</td>
<td>0.68</td>
</tr>
<tr>
<td>S86262</td>
<td>AP-LR</td>
<td>1.4210</td>
<td>7437</td>
<td>302</td>
<td>1856</td>
<td>2,1,0(2)</td>
<td>0.68</td>
</tr>
<tr>
<td>S86264</td>
<td>AP-LR</td>
<td>0.1733</td>
<td>1041</td>
<td>107</td>
<td>294</td>
<td>2,1,0(2)</td>
<td>0.68</td>
</tr>
<tr>
<td>S86263</td>
<td>LR</td>
<td>3.3900</td>
<td>14130</td>
<td>316</td>
<td>2951</td>
<td>4,3,1(4)</td>
<td>8.19</td>
</tr>
<tr>
<td>S86271</td>
<td>AP-LR</td>
<td>0.6177</td>
<td>2750</td>
<td>178</td>
<td>2196</td>
<td>4,4,0(4)</td>
<td>8.19</td>
</tr>
</tbody>
</table>

N-M-A* = normalized maximum acceleration from reconstruction test data
PW** = maximum value of the power transfer by spring K in the THIM model
Table 9-2: The Simulation Results of the Two Years Old THIM Model

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Direction</th>
<th>EC2 (J)</th>
<th>PW (watts)</th>
<th>N-Max (Acc. g)</th>
<th>HIC</th>
<th>AIS</th>
<th>POD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S86258</td>
<td>AP</td>
<td>0.3681</td>
<td>2286</td>
<td>188</td>
<td>1189</td>
<td>2,2,1(2)</td>
<td>0.68</td>
</tr>
<tr>
<td>S86260</td>
<td>AP</td>
<td>0.3398</td>
<td>2125</td>
<td>203</td>
<td>1230</td>
<td>2,2,1(2)</td>
<td>0.68</td>
</tr>
</tbody>
</table>

9-3. Development of Translational Energy Criteria (TEC) of Child

In the TEC, the dissipated energy by damper C2, EC2, is related to brain injury, and the maximum power transfer by spring K, PW, is correlated with the skull fracture potential. Specifically, the TEC used two parameters to describe the head impact injury potential. The first parameter is the equivalent AIS (EAIS) that is calculated from EC2, and the second parameter is the probability of the skull fracture (POSF) that is based on PW. The TEC parameters, EAIS and POSF, will be defined as follows:

\[
\text{EAIS} = \alpha \times \sqrt{\text{EC2}} \tag{9-5}
\]

\[
\text{POSF} = 100 \times \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\delta} e^{-\frac{\delta^2}{2}} d\delta = 50 \times \left[ \text{erf}\left(\frac{\delta}{\sqrt{2}}\right) + 1 \right] \tag{9-6}
\]

\[
\delta = \frac{(\text{PW} - \mu)}{\sigma} \tag{9-7}
\]
where, \( \text{EAIS} = \) Equivalent AIS \\
\( \text{POSF} = \) Probability of Skull Fracture (\%) \\
\( \text{erf} = \) Gaussian Error Function \\
\( \text{PW} = \) Maximum value of PWK \\
\( \alpha = \) Injury Constant \\
\( \mu = \) Normal Gaussian Mean \\
\( \sigma = \) Normal Gaussian Standard Deviation

For EAIS calculation, the injury constant \( \alpha \) is the same for all impact directions because the brain tissue is assumed to be homogeneous. The injury constant \( \alpha \) will be determined by matching the EAIS number with the accident AIS number. On the other hand, in the POSF, the constant \( \mu \) and \( \sigma \) are different for each direction because the thickness of the skull is not unique. The constant \( \mu \) and \( \sigma \) are defined as the normal Gaussian distribution mean and standard deviation for the adult case.

9-3-1. Translational Energy Criterion (TEC) of Six Years Old Child

Eleven simulation results in Table 9-1 were used to develop the TEC criterion of 6-year old child. The relationship between the accident AIS number and the dissipated energy of the damper C2(EC2) was plotted in Figure 9-4. From the figure, the upper- and lower-boundary of the injury constant \( \alpha \) were determined as 4.83 and 1.73 respectively. The best correlation between the equivalent AIS(EAIS) number and the accident AIS number was gotten when the injury constant \( \alpha \) was 2.95. The relationship
between EAIS and AIS number was presented in Figure 9-5.

Figure 9-6 shows the relationship between the skull fracture and the maximum power transfer by the spring $K(PW)$. The evaluations of normal Gaussian distribution mean and standard deviation in order to develop the probability of the skull fracture function(POSF), are impossible because there are not enough experimental data. However, by trial and error, the best correlation was gotten when $\mu$ was 8000 watts and $\sigma$ was 700 watts for all directions.

The TEC criterion of 6-year old child and the results of the TEC analysis were presented in Table 9-3 and 9-4 respectively.

Table 9-3 : TEC Criterion of Six Years Old Child

<table>
<thead>
<tr>
<th>Description</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>EAIS</td>
<td>$= 2.95 \sqrt{EC2}$</td>
</tr>
<tr>
<td>POSF</td>
<td>$= 50 \times \left[ \text{erf}\left(\frac{\delta}{\sqrt{2}}\right)+1 \right]$ where, $\delta = \frac{(PW-\mu)}{\sigma}$</td>
</tr>
</tbody>
</table>

$\mu=8000$, $\sigma=700$ for all directions
Table 9-4: Comparison between Experimental Test Results and TEC Analysis Results of Six Years Old Child

<table>
<thead>
<tr>
<th>Recon. Test No.</th>
<th>Direction</th>
<th>Accident AIS</th>
<th>Skull Fracture</th>
<th>EAIS</th>
<th>POSF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S86261</td>
<td>PA-LR</td>
<td>1,0,0(1)</td>
<td>no</td>
<td>2.19</td>
<td>0</td>
</tr>
<tr>
<td>S86266</td>
<td>PA</td>
<td>1,0,0(1)</td>
<td>no</td>
<td>1.63</td>
<td>0</td>
</tr>
<tr>
<td>S86268</td>
<td>AP</td>
<td>1,0,0(1)</td>
<td>no</td>
<td>1.24</td>
<td>0</td>
</tr>
<tr>
<td>S86269</td>
<td>AP-LR</td>
<td>1,0,0(1)</td>
<td>no</td>
<td>1.55</td>
<td>0</td>
</tr>
<tr>
<td>S86259</td>
<td>AP</td>
<td>1,1,1(1)</td>
<td>no</td>
<td>0.68</td>
<td>0</td>
</tr>
<tr>
<td>S86244</td>
<td>AP-LR</td>
<td>2,1,0(2)</td>
<td>no</td>
<td>1.17</td>
<td>0</td>
</tr>
<tr>
<td>S86248</td>
<td>LR</td>
<td>2,1,0(2)</td>
<td>no</td>
<td>1.70</td>
<td>0</td>
</tr>
<tr>
<td>S86262</td>
<td>AP-LR</td>
<td>2,1,0(2)</td>
<td>no</td>
<td>3.50</td>
<td>23</td>
</tr>
<tr>
<td>S86264</td>
<td>AP-LR</td>
<td>2,1,0(2)</td>
<td>no</td>
<td>1.23</td>
<td>0</td>
</tr>
<tr>
<td>S86263</td>
<td>LR</td>
<td>4,3,1(4)</td>
<td>yes</td>
<td>5.43</td>
<td>100</td>
</tr>
<tr>
<td>S86271</td>
<td>AP-LR</td>
<td>4,4,0(4)</td>
<td>no</td>
<td>2.32</td>
<td>0</td>
</tr>
</tbody>
</table>

9-3-2. TEC Criterion of Two Years Old Child

Only two experimental test data were available for the 2-year old child case as shown in Table 9-2. The relationship between the accident AIS number and the dissipated energy of the damper C2(EC2) was plotted in Figure 9-7. The best correlation between
the equivalent AIS(EAIS) number and the accident AIS number was gotten when the
injury constant $\alpha$ was 3.35 as shown in the figure. The relationship between EAIS and
AIS number was presented in Figure 9-8.

Unfortunately, it is impossible to determine POSF because of lack of the
experimental data. However, no skull fracture occurred when the maximum power
transfer by the spring $K(PW)$ was less than 2286 watts.

The TEC criterion of 2-year old child and the results of the TEC analysis were
presented in Table 9-5 and 9-6 respectively. The results are not reliable because
of the lack of experimental data.

Table 9-5 : TEC Criterion of Two Years Old Child

<table>
<thead>
<tr>
<th>EAIS $= 3.35 \cdot \sqrt{EC2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PW $\leq$ 2286 watts $\Rightarrow$ No Skull Fracture</td>
</tr>
</tbody>
</table>

Table 9-6 : Comparison between Experimental Test Results and TEC Analysis Results
of Two Years Old Child

<table>
<thead>
<tr>
<th>Recon. Test No.</th>
<th>Direction (AIS)</th>
<th>Accident Fracture</th>
<th>Skull Fracture</th>
<th>EAIS</th>
<th>POSF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S86258</td>
<td>AP, 2,2,1(2)</td>
<td>no</td>
<td>no</td>
<td>2.03</td>
<td>---</td>
</tr>
<tr>
<td>S86260</td>
<td>AP, 2,2,1(2)</td>
<td>no</td>
<td>no</td>
<td>1.95</td>
<td>---</td>
</tr>
</tbody>
</table>
9.4. **Comparison of TEC Criteria**

The impact acceleration from pedestrian accident reconstruction test was loaded as an input to the THIM models to develop the TEC criteria of the child. Then, the dissipated energy by damper C2(EC2) was correlated with the accident AIS number to determine EAIS number, and the maximum power transfer by spring K(PW) was correlated with the skull fracture to determine POSF. The comparison of the TEC criteria of adult and child was tabulated in Table 9-7, and plotted in Figure 9-9 and 9-10.

### Table 9-7: Comparison of TEC Criteria of Adult and Child

<table>
<thead>
<tr>
<th>Age</th>
<th>EAIS</th>
<th>POSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adult</td>
<td>EAIS = 4.14 $\sqrt{EC2}$</td>
<td>$POSF = 50 \left[ erf\left( \frac{\delta}{\sqrt{2}} \right) + 1 \right] \delta = \frac{(PW - \mu)}{\sigma}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Where $\mu=4000$, $\sigma=1000$ for AP direction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\mu=1500$, $\sigma=500$ for LR direction</td>
</tr>
<tr>
<td>Child</td>
<td>EAIS = 2.95 $\sqrt{EC2}$</td>
<td>$POSF = 50 \left[ erf\left( \frac{\delta}{\sqrt{2}} \right) + 1 \right] \delta = \frac{(PW - \mu)}{\sigma}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Where $\mu=8000$, $\sigma=700$ for all directions</td>
</tr>
<tr>
<td>2*</td>
<td>EAIS = 3.35 $\sqrt{EC2}$</td>
<td>PW $\leq$ 2286 $\Rightarrow$ No Skull Fracture</td>
</tr>
</tbody>
</table>

$2^* = $ Not reliable because of too little data
Figure 9-9 shows that the EAIS number of adult is higher than that of child if the EC2 value is same. In other word, the child brain can dissipate more energy without damage compared with the adult brain. And, Figure 9-10 shows that the percentage of POSF of adult is much higher than that of child if the PW value is same. Based on these results, we can say the child head tolerates more higher impact acceleration compared with the adult head.

9-5. Comparison of HIC Criteria

Based on the pedestrian accident reconstruction test data (SRL-10, SRL-39, and SRL-86), the comparison of the HIC of adult and child was tabulated in Table 9-8, and presented in Figure 9-11. The figure shows that the HIC value of the child is much higher than that of adult if the accident AIS number is same. If the child HIC criterion is determined based on that the AIS number is less than 4 like as the adult case, the HIC criterion of the 6-year old child was proposed as follows;

for the adult : $HIC \leq 1000$

for the 6-year old child : $HIC \leq 2000$
Table 9-8: Comparison of HIC of Adult and Child

<table>
<thead>
<tr>
<th>Recon. Test No</th>
<th>AIS</th>
<th>HIC</th>
<th>Recon. Test No.</th>
<th>AIS</th>
<th>HIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>S86243</td>
<td>1</td>
<td>527</td>
<td>S86261</td>
<td>1</td>
<td>570</td>
</tr>
<tr>
<td>S39109</td>
<td>1</td>
<td>758</td>
<td>S86266</td>
<td>1</td>
<td>497</td>
</tr>
<tr>
<td>S39145</td>
<td>1</td>
<td>839</td>
<td>S86268</td>
<td>1</td>
<td>611</td>
</tr>
<tr>
<td>S86242</td>
<td>2</td>
<td>365</td>
<td>S86269</td>
<td>1</td>
<td>409</td>
</tr>
<tr>
<td>S86245</td>
<td>2</td>
<td>483</td>
<td>S86259</td>
<td>1</td>
<td>229</td>
</tr>
<tr>
<td>S39135</td>
<td>2</td>
<td>1074</td>
<td>S86244</td>
<td>2</td>
<td>368</td>
</tr>
<tr>
<td>S39090</td>
<td>2</td>
<td>186</td>
<td>S86248</td>
<td>2</td>
<td>244</td>
</tr>
<tr>
<td>S86254</td>
<td>3</td>
<td>524</td>
<td>S86262</td>
<td>2</td>
<td>1856</td>
</tr>
<tr>
<td>S86257</td>
<td>3</td>
<td>657</td>
<td>S86264</td>
<td>2</td>
<td>294</td>
</tr>
<tr>
<td>S86240</td>
<td>4</td>
<td>1677</td>
<td>S86263</td>
<td>4</td>
<td>2951</td>
</tr>
<tr>
<td>S86252</td>
<td>4</td>
<td>1555</td>
<td>S86271</td>
<td>4</td>
<td>2195</td>
</tr>
<tr>
<td>S86255</td>
<td>4</td>
<td>1128</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S86241</td>
<td>5</td>
<td>512</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S39015</td>
<td>5</td>
<td>2613</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Recon. Test No</th>
<th>AIS</th>
<th>HIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>S39013</td>
<td>5</td>
<td>1128</td>
</tr>
<tr>
<td>S39056</td>
<td>5</td>
<td>1410</td>
</tr>
<tr>
<td>S10RRE</td>
<td>6</td>
<td>3260</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Recon. Test No</th>
<th>AIS</th>
<th>HIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>S86258</td>
<td>2</td>
<td>1189</td>
</tr>
<tr>
<td>S86260</td>
<td>2</td>
<td>1230</td>
</tr>
</tbody>
</table>
9-6. Closure

In this chapter, the TEC criteria of the child were developed. First, the THIM model of the child head was used to evaluate potential head impact injury severity by loading the reconstruction acceleration-time pulse. Then, the energy dissipation by damper C2(EC2) and the maximum power transfer by spring K(PW) of the THIM model were correlated with the accident AIS number and the skull fracture potential. Finally, two TEC parameters, EAIS and POSF, were determined.
Figure 9-1: The Dissipated Energy at Element C1 and C2 in the THIM Model

Figure 9-2: The Energy at Element M1 and M2 in the THIM Model
Figure 9-3: The Power Transfer by the Spring $K$ in the THIM Model
Number on figure -- age of child
1.73 -- \( \alpha = 1.73 \) in EAIS (lower boundary)
4.83 -- \( \alpha = 4.83 \) in EAIS (upper boundary)
2.95 -- \( \alpha = 2.95 \) in EAIS (suggested injury constant for 6-year old child)

Figure 9-4: Relationship between AIS Number and EC2 of Six Years Old Child
Figure 9-5: Relationship between EAIS and AIS Number of Six Years Old Child

Figure 9-6: Probability of Skull Fracture (POSF) of Six Years Old Child
Number on figure -- age of child
EC2(3.35) -- EAIS when \( \alpha = 3.35 \)

Figure 9-7: Relationship between AIS Number and EC2 of Two Years Old Child

Figure 9-8: Relationship between EAIS and AIS Number of Two Years Old Child
Figure 9-9: Comparison of the EAIS parameter of TEC Criteria

Figure 9-10: Comparison of the POSF parameter of TEC Criteria
Figure 9-11: Comparison of HIC of Adult and Child

*number in () is the age of child
CHAPTER X

Conclusions and Recommendations

10-1. Summary

The objective of this research was to develop the child head injury criteria for the better protection of a child head. The objective has been successfully completed in this dissertation. The summary of this research works will be presented in chronological order as follows;

1. Development of Finite Element Head Model of Adult and Child

   Based on the physical and anatomical measurement data and reasonable assumptions, the finite element head models of adult, 6 and 2-year old child, and newborn infant were developed in Chapter III. Due to extreme complexity in anatomical aspects, the following assumptions were made;

   1) head is two dimensional cylindrical model in the mid-transverse plane

   2) thickness of the skull and membrane is unique regardless of the location

   1 5 3
in the same age

3) scalp is not considered

4) head is symmetric in the anterior-posterior (A-P) direction

5) effects of sutures of the skull is neglected

6) mechanical property of the fontanelle was assumed as that of human skin

2. Validation of Finite Element Head Model

Due to wide variation in mechanical properties, it is impossible to ascertain the static value of the measured properties. Also, the finite element head model was not a complete duplication of actual head in structural and physical aspects. To contend with these problems, the parametric study of mechanical property was made. The values of mechanical properties were subject to modifications and adjustments until the dynamic responses of the model match those of experiments. Finally, the validation of finite element head model was made as shown in Chapter IV.

3. Generation of Mechanical Impedance Curve of Child
At first, the mechanical property of the child head was surveyed. Macperson and Guenther showed the increase of the elastic modulus of bone along with a grown-up. Using their data, the elastic modulus of 6 and 2-year old child, and newborn infant skull bone was determined as 80%, 55%, and 22% of the elastic modulus of the adult skull bone respectively. Unfortunately, the mechanical property of the brain and membrane of the child head was not available. Thus, the mechanical property of the adult brain and membrane was used as those of the child brain and membrane based on the assumption that the mechanical property of the soft tissues is not changed along with a grown-up. Based on the above assumptions, the driving-point mechanical impedance responses of child in the A-P, P-A, and L-R direction were determined by using finite element model as shown in Chapter V.

4. Development of Translational Head Injury Model (THIM) of Child

Based on the mechanical impedance curves from the finite element models, the THIM models of child were developed in Chapter VI. The model parameter M1 and M2 were directly determined from the impedance curve. However, the other parameter K, C1, and C2 were determined through the parametric study to match the mechanical impedance curve from the finite element model to that from the THIM model. The major outcomes of the parametric study were as follows;

1) Damper C2 is found to be a constant regardless of the direction in the same age
2) The value of damper C2, which is believed to be primarily the damper of the brain, increases along with a grown-up, even though the mechanical property of the brain was assumed not to change along with a grown-up in the finite element model. The increase of the damping C2 is closely related to the increase of the brain mass as follows:

\[ C_{\text{child}} = C_{\text{adult}} \times \frac{M_{\text{child}}}{M_{\text{adult}}} \]

3) The percentage of the mass M1 to the total head mass is increased along with a grown-up.

4) In the same age, the value of the model parameters in the A-P direction is higher than that in the P-A and L-R direction, and the value of the model parameters in the P-A and L-R direction is similar except the newborn infant.

5) In the newborn infant, because of the fontanelles, the M1 in the P-A direction is much higher than that in the L-R direction, is almost similar to that in the A-P direction.

5. Development of the "Off-Axis" THIM Model of Child

In real automobile related accidents, the location of the head impact is somewhat random in nature. Thus, the prediction of consequences of head impact at different
impact location is very demanded. However, because of the lack of experimental data and the complexity of head shape and structure, the accurate modeling for the estimation of the off-axis head impact response is almost impossible. In this research, "off-axis" means the middle point or 45 degree rotation from the reference points (AP-LR and PA-LR). Therefore, to develop the off-axis THIM model, the following assumptions were made.

1) The impedance response of the off-axis head impact has the similar trend with two adjacent reference (AP and LR, or PA and LR) impedance responses which were determined by experiments or from the THIM model

2) The impedance value of the off-axis head impact is the middle value comparing with two adjacent reference impedance values

Based on the above assumptions, the off-axis impedance curves of child were generated, then the off-axis THIM models were determined through the parametric study as shown in Chapter VII.

6. Experimental Data Processing

In this research, thirteen child reconstruction test data from SRL-86 were used to develop the child head injury criteria. Before the experimental impact signal (acceleration) is loaded to the THIM model, the appropriate adjustments of the impact
signal were made. These adjustments were accomplished in order to remove unrelated sections of the test signal and to reduce attenuation of the electronic measuring devices and test setup, and so forth. The following five processing steps are carried out in the sequence to adjust the impact acceleration.

1) Condensation of the impact acceleration
to remove all unnecessary and unrelated fragments of the raw data

2) Zeroing of the impact acceleration
to remove the horizontal bias from the condensed acceleration

3) Making the resultant acceleration
to make the resultant acceleration from the zeroed acceleration

4) Normalization of the impact acceleration
to convert the impact acceleration to a standard format. This was to ensure that all impact tests were to be compared on the same reference basis.

5) Filtering of the impact acceleration
to remove the high frequency attenuation above human head fundamental resonant and antiresonant frequencies (approximately 800 Hz)
7. Development of Translational Energy Criteria (TEC) of Child

Thirteen child reconstruction test data were used in this research. Eleven reconstruction test data of 6 to 9-year old child were normalized based on the 6-year old child THIM model, two reconstruction test data of 2 and 3-year old child were normalized based on the 2-year old child THIM model. However, the newborn infant experimental test data are not available at the present time. The filtered impact acceleration was loaded to the THIM model. Then, the model was solved for the dissipated energy by the damper \( C_2(\text{EC}2) \) and the power transfer by the spring \( K(\text{PW}K) \) to determine two TEC parameters. The dissipated energy by the damper \( C_2(\text{EC}2) \) was correlated with the brain injury (EAIS) and the maximum power transfer by the spring \( K(\text{PW}) \) was correlated with the skull fracture potential (POSF). The EAIS number was determined by matching the EAIS number with the accident AIS number, and the POSF was determined from the relationship between the accident skull fracture information and the power transfer by the spring \( K \). The new TEC criteria of 6 and 2-year old child were developed in Chapter IX.

10-2. Conclusions

The primary scopes and objectives of this program have been fulfilled. The contributions to the state of the art have been demonstrated by the new approach to the solution of the impact dynamic effects of the child head by using finite element head model that was successfully validated. In addition, 6 and 2-year old child TEC criteria have been developed in conjunction with the experimental reconstruction test data. The
comparison of the TEC criteria of adult and child shows that the child head tolerates more higher impact acceleration compared with the adult head. All of these findings have significantly improved the understanding of the child head injury mechanism and will be used to design the interior structure of the automobile, a child car seat, and helmet in order to protect the child head from serious injuries.

10-3. Recommendations for Future Works

The objective of this research had been accomplished. However, there are still many improvements that need to make a comprehensive child head injury criterion. Some recommendations are listed below for future research in this field.

1. Research about Mechanical Properties of Child Head

The mechanical property of child head is very limited. The mechanical property of the brain and membrane of child head is not available at the present time. To overcome this problem, several assumptions were mad in this research. Thus, the research about the mechanical properties of child head is very necessary because the mechanical properties significantly influence the responses and representativeness of the approximation in the finite element analysis.
2. Research about the Superior-Inferior (S-I) Directional Impact

In this research, the two-dimensional finite element head model in the mid-transverse plane was made due to the complexity of the head shape. Therefore, the research in the S-I directional impact was not conducted. To make more comprehensive child head injury criteria, the research about the S-I directional impact is also needed by making the three-dimensional model or two-dimensional model in the mid-sagittal plane.

3. Conducting Experiments for Child Head Injury Analysis

Experimental test data of child head injury analysis are very limited. Therefore, very little child head injury information is available. In this research, just thirteen child reconstruction test data were used to evaluated the child head injury criteria. To get the more reliable child head injury criteria, many experimental test data are needed.

4. Duplication of the Structural Characteristics of Head As Close As Possible

In this research, the effect of the scalp was neglected, and the change of the thickness of skull bone according to the location was not considered. Improvements will be obtained through these design modifications.
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Appendix-A

Experimental Test Data Processing
Figure A-1: Reconstruction Test Data Processing of S86244
continued from Figure A-1

Reconstruction Test Number -- S86244

Resultant

Post-Normalized

Post-Filtered

Time (sec)
Figure A-2: Reconstruction Test Data Processing of S86248
continued from Figure A-2
Figure A-3: Reconstruction Test Data Processing of S86258
continued from Figure A-3
Figure A-4: Reconstruction Test Data Processing of S86259
continued from Figure A-4

Reconstruction Test Number -- S86259

Resultant

Post-Normalized

Post-Filtered

Time (sec)
Figure A-5: Reconstruction Test Data Processing of S86260
continued from Figure A-5

Reconstruction Test Number -- S86260

Resultant

Post-Normalized

Postr-Filtered
Figure A-6: Reconstruction Test Data Processing of S86261
continued from Figure A-6

Reconstruction Test Number -- S86261

Resultant

Post-Normalized

Post-Filtered

Time (sec)
Reconstruction Test Number -- S86263

Original Impact Data

Post-Condensed

Post-Zeroed

Figure A-7: Reconstruction Test Data Processing of S86263
continued from Figure A-7

Reconstruction Test Number -- S86263

Resultant

Post-Normalized

Post-Filtered
Figure A-8: Reconstruction Test Data Processing of S86264
continued from Figure A-8
Figure A-9: Reconstruction Test Data Processing of S86266
continued from Figure A-9

**Reconstruction Test Number -- S86266**

**Resultant**

**Post-Normalized**

**Post-Filtered**
Figure A-10: Reconstruction Test Data Processing of S86268
continued from Figure A-10

Reconstruction Test Number -- S86268

resultant

Post-Normalized

Post-Filtered

Time (sec)
Figure A-11: Reconstruction Test Data Processing of S86269
continued from Figure A-11

Reconstruction Test Number --S86269

Resultant

Post-Normalized

Post-Filtered

Time (sec)
Figure A-12: Reconstruction Test Data Processing of S86271
continued from Figure A-12
APPENDIX-B

Simulation Results of Translational Head Injury Model
Using Reconstruction Test Data
** EC1, EC2, EK, EM1, EM2 -- Energy of element C1, C2, K, M1, and M2
PWK -- Power Transfer by Spring K

Figure B-1: Simulation Results of THIM Model of Reconstruction Test Number S86244
** EC1, EC2, EK, EM1, EM2 -- Energy of element C1, C2, K, M1, and M2
PWK -- Power Transfer by Spring K

Figure B-2: Simulation Results of THIM Model of Reconstruction Test Number S86248
** EC1, EC2, EK, EM1, EM2 -- Energy of element C1, C2, K, M1, and M2
PWK -- Power Transfer by Spring K

Figure B-3: Simulation Results of THIM Model of Reconstruction Test Number S86258
** EC1, EC2, EK, EM1, EM2 -- Energy of element C1, C2, K, M1, and M2  
PWK -- Power Transfer by Spring K  

Figure B-4: Simulation Results of THIM Model of Reconstruction Test Number S86259
**EC1, EC2, EK, EM1, EM2** -- Energy of element C1, C2, K, M1, and M2

**PWK** -- Power Transfer by Spring K

Figure B-5: Simulation Results of THIM Model of Reconstruction Test Number S86260
** EC1, EC2, EK, EM1, EM2 -- Energy of element C1, C2, K, M1, and M2
PWK -- Power Transfer by Spring K

Figure B-6: Simulation Results of THIM Model of Reconstruction Test Number S86261
** EC1, EC2, EK, EM1, EM2 -- Energy of element C1, C2, K, M1, and M2
PWK -- Power Transfer by Spring K

Figure B-7: Simulation Results of THIM Model of Reconstruction Test Number S86263
** EC1, EC2, EK, EM1, EM2 -- Energy of element C1, C2, K, M1, and M2
PWK -- Power Transfer by Spring K

Figure B-8: Simulation Results of THIM Model of Reconstruction Test Number S86264
**EC1, EC2, EK, EM1, EM2 -- Energy of element C1, C2, K, M1, and M2**

**PWK -- Power Transfer by Spring K**

Figure B-9: Simulation Results of THIM Model of Reconstruction Test Number S86266
** EC1, EC2, EK, EM1, EM2 -- Energy of element C1, C2, K, M1, and M2
PWK -- Power Transfer by Spring K

Figure B-10 : Simulation Results of THIM of Reconstruction Test Number S86268
** EC1, EC2, EK, EM1, EM2 -- Energy of element C1, C2, K, M1, and M2

PWK -- Power Transfer by Spring K

Figure B-11: Simulation Results of THIM of Reconstruction Test Number S86269
** EC1, EC2, EK, EM1, EM2 -- Energy of element C1, C2, K, M1, and M2
PWK -- Power Transfer by Spring K

Figure B-12: Simulation Results of THIM of Reconstruction Test Number S86271