ABSTRACT: The purpose of the present research is to enable verification of occupant protection performance, including neck injury, under full-width frontal crash test conditions, using a THOR 5F dummy during the primary phase of automobile development. A THOR 5F neck injury would be considered as important as that of a Hybrid III dummy. To achieve this purpose, a two-dimensional degenerated model was formulated by combining a neck element with a four-rigid-body model consisting of a head, upper body, sternum, and lower body. It was observed that the obtained results were similar to those of the finite element method.

KEY WORDS: Safety, Passive safety, Crash test dummy, Computer aided engineering / THOR, [C1]

1. Introduction

Vehicle specifications related to frontal collision performance cover a wide range of characteristics, including the crash stroke, occupant restraint load, and layout of parts (Fig. 1). These specifications affect not only occupant protection performance in the case of a collision, but also the product appeal of the vehicle as a whole. Therefore, the decision process of defining appropriate specifications in the primary phase of development is important in developing an attractive vehicle. In the primary phase of development, the layout of parts is determined roughly, and it is necessary to verify many design proposals in short order. Among verification methods, it is worth mentioning the software package MADYMO and the precise finite element method (FEM), which can perform three-dimensional calculations after creating detailed shapes of parts. However, these methods require computation times too long to accomplish in the primary phase. Therefore, degenerated models that can be used to complete calculations in a short period of time are required. Therefore, degenerated models can be applied in cases for which calculation results are available with approximate accuracy.

Since occupant protection performance needs to take into account the physique differences among potential occupants, several dummies representing different physiques have been developed. The Hybrid III 5F dummy, simulating a small-stature female with low physical tolerance, has been developed to measure airbag aggressivity. Hybrid III 5F has been widely used in regulations of collisions and car assessment programs. Wu et al. have conducted a detailed analysis of the mechanism associated with neck injury waveforms in the United States new car assessment program (US NCAP). In this study, they have demonstrated that even within the time band preceding the contact between a head and an airbag, there are cases in which local peaks in the neck injury waveform occur due to vehicle deceleration and the restraint load of a seatbelt. This finding indicates that there is a close relationship, possibly related to vehicle specifications, between deceleration and neck injury. Therefore, it is important to verify the neck injury waveform in the primary phase of development. In turn, the small-stature female dummy THOR 5F, with human body fidelity superior to that of Hybrid III 5F, has been developed as a next-generation crash test dummy. While the THOR 5F dummy has been improved to be closer to the human body, its role is the same as that of the Hybrid III 5F dummy, and it plays an important role in evaluating the aggressiveness of airbags. For these reasons, the neck injury aspect of THOR 5F is an important consideration, just as it is for Hybrid III 5F.

Kurano et al. proposed a two-dimensional degenerated model of THOR 50M to verify occupant protection performance in the...
primary phase of development\(^9\). According to their model, THOR 50M is divided into four rigid bodies: head, upper body, sternum, and lower body. However, as the head and the upper body are connected by a translational spring, it is difficult to use this model in the evaluation of neck moment. Although the research conducted by Wu et al.\(^5\) proposed a simple beam method of neck deformation simulation in Hybrid III 5F, this research degenerates the neck alone, and does not quantitatively describe the relationship with the behavior of the entire dummy body.

The purpose of the present research is to enable verification of occupant protection performance including neck injury under full-width frontal crash test conditions, using a THOR 5F dummy in the primary phase of automobile development. To achieve this purpose, a two-dimensional degenerated model has been formulated by combining a neck element with a multi-rigid body model consisting of the head, upper body, sternum, and lower body. The neck element represents the neck structure of THOR 5F. The reproducibility of occupant displacement, neck moment, and chest deflection was verified by comparing the calculation results of the degenerated model with those of the precise FEM using LS-DYNA\(^{10}\). Concerning the reproducibility of the neck moment waveform, the differences between the results of the degenerated model and those of the precise FEM were estimated considering the neck structure of THOR 5F. The estimation was performed as follows. First, in line with the study by Wu et al.\(^6\), a neck element was formulated using a simple beam at the neck. Next, an improved neck element was formulated to achieve a structure more similar to that of THOR 5F.

### 2. Model construction method

#### 2.1. Model construction method

Fig. 2 shows the motion trajectory of head, upper body, and lower body of THOR 5F in a precise FEM calculation result that simulates full-width frontal crash test conditions, at a speed of 56 km/h, with an airbag and seat belt. The dummy model Ver.0.5, developed by Humanetics\(^{11}\), has been used to implement the precise FEM dummy model. LS-DYNA Version 971 R6.1.2\(^{12}\) was applied as the FEM solver. These motion trajectories indicate that the upper and lower bodies move almost horizontally at first, and then the upper body swings forward around the lower body. The tendency of this motion was similar to that shown by the degenerated model of THOR 50M proposed by Kurano et al.\(^9\). Therefore, while developing the degenerated model of THOR 5F, the body was degenerated similarly into the four rigid bodies (head, upper body, sternum, and lower body), and the forward movement of the upper body was reproduced by connecting the upper and lower bodies using a hinge, as in the model of THOR 50M proposed by Kurano et al\(^9\).

![Fig. 2 Motion trajectory of THOR 5F based on calculation results obtained by precise finite element modeling](image)

#### 2.2. Components of the degenerated model

Fig. 3 shows a schematic diagram of the positions of the rigid bodies and the degrees of freedom in the degenerated model. Table 1 provides the detailed description of the parameters used in Fig. 3. The rigid bodies were arranged to reproduce the initial position of the THOR 5F dummy in the vehicle. The values reported by Wang et al.\(^7\) were referenced to set the mass, center of gravity, and moment of inertia of the head, upper body, and lower body. The weight of the sternum was determined by scaling that of the THOR 50M degenerated model proposed by Kurano et al.\(^9\), taking into account the physique and weight differences between THOR 50M and THOR 5F. The direction of sternum displacement was formulated similarly, as in the degenerated model of THOR 50M, as follows: the angle to the horizontal direction at the initial position was \(\theta_{0}\), and changes in the same angle were similar to that of the upper body during a collision. With regard to the neck, Wu et al.\(^5\) proposed a method to simplify the neck structure using a simple beam, as shown in Fig. 4. The relative displacement is denoted as \(x_n\); the relative angle between the head and the upper body is \(\theta_n\); and the relationship between neck load \(f_{xn}\) and moment \(M_{yn}\) is defined as per equation (1).

\[
\begin{bmatrix}
  f_{xn} \\
  M_{yn}/l
\end{bmatrix} = \begin{bmatrix}
  k \\
  l^2
\end{bmatrix} \begin{bmatrix}
  x_n/l \\
  \theta_n
\end{bmatrix}
\]  

(1)

In equation (1), \(l\) denotes the length of the neck, while \(k\) denotes its stiffness. To combine the multi-rigid body model and the simple beam model, \(f_{xn}\) and \(M_{yn}\) were applied to the neck joint position of the head, and \(-f_{xn}\) and \(-M_{yn}\) were applied to the neck joint position of the upper body as a reaction.

Original Publication: Yutaro Kurano et al / International Journal of Automotive Engineering Vol.11, No.3(2020)
With regard to the restraint force applied to the head by the airbag (magnitude, direction, position of the application point), Wu et al.\(^\text{(5)}\) demonstrated that these parameters could be calculated by means of the equation of head motion using the acceleration and angular acceleration of the head, the neck force, and the neck moment. Using this method, the restraint force applied to the head by the airbag can be estimated based on the result of the precise FEM. Fig. 6 presents a schematic diagram of the airbag restraint force \((f_{\text{ab}})\) applied to the head and its components \((f_{\text{abs}}, f_{\text{abc}}, M_{\text{ab}})\), the position of the force application point \((l_{\text{ab}}, l_{\text{ab}})\), the distance between center of gravity of head and the restraint force \((d)\), the neck force, and the neck moment \((f_{\text{nx}}, f_{\text{nz}}, M_{\text{ny}})\). The application point of the airbag restraint force was not uniquely determined. For example, \(f_{\text{ab}}\) and \(f'_{\text{ab}}\) are applied at the same moment to center of gravity of head as long as \(d\) is the same. Therefore, the vertical position of the application point \((l_{\text{ab}})\) was calculated by setting the longitudinal position \((l_{\text{ab}})\) to a fixed value. The airbag restraint force was defined as \(f_{\text{abs}}, f_{\text{abc}}, l_{\text{ab}}\) as a function of head displacement.

Table 2 Parameters corresponding to external force

| Parameter | Explanation                                      |
|-----------|--------------------------------------------------|
| \(f_{\text{h}}\) | Inertial Force of Head                           |
| \(f_{\text{u}}\) | Inertial Force of Upper Body                     |
| \(f_{\text{s}}\) | Inertial Force of Sternum                        |
| \(f_{\text{a}}\) | Inertial Force of Lower Body                     |
| \(f_{\text{abs}}\) | Longitudinal Component of External Force on Head (Airbag Force) |
| \(f_{\text{abc}}\) | Vertical Component of External Force on Head (Airbag Force) |
| \(f_{\text{sl}}\) | External Force on Shoulder (Sum of Left and Right) |
| \(f_{\text{sL}}\) | External Force on Upper Sternum (Shoulder Belt Upper Force) |
| \(f_{\text{sL}}\) | External Force on Lower Sternum (Shoulder Belt Lower Force) |
| \(f_{\text{sl}}\) | External Force on Lap Belt (Sum of Left and Right) |
| \(f_{\text{h}}\) | External Force on Lower Body (Sum of Knees and Seat Force) |

Fig. 5 Schematic of the (i) inertial and (ii) restraint forces

Fig. 6 Schematic of external force applied to the head
Chest deflection is the relative displacement when the distance between the sternum and the upper body decreases. As presented in Fig. 7, THOR 5F has four chest deflection measurement points (upper right, upper left, lower left, and lower right). In the calculation results of the precise FEM, the point at which chest deflection was the largest was the inboard lower measurement point. Therefore, the degenerated model was formulated to reproduce a chest deflection corresponding to this measurement point.

Hereinafter, the spring characteristic between the sternum and the upper body was referred to as the rib stiffness characteristic. Rib stiffness was estimated based on the relationship between the horizontal component of the shoulder belt restraint force and chest deflection, as in the method proposed by Kurano et al.\(^9\). They showed that the THOR 50M degenerated model reproduced the peak value of chest deflection without viscosity between the upper body and sternum. In the THOR 5F degenerated model, the mass of the sternum determined by scaling was smaller than that of THOR 50M, prompting concern that high-frequency vibration would be generated by the movement of the sternum. Therefore, a minimum viscosity to suppress this vibration was incorporated in the model.

3. Results

The same conditions were used for the degenerated model calculation as for the precise FEM calculation, which simulates full-width frontal crash test conditions at a speed of 56 km/h with an airbag and seat belt. Figs. 8–10 represent the time history of the displacement of the head, upper body, and lower body. Fig. 11 shows the time history of the neck moment. Fig. 12 depicts the time history of chest deflection. The vertical axes of Figs. 8–10 and 12 have been normalized by dividing by the maximum value of the calculation result of the precise FEM, such that the maximum value of the calculation result of the precise FEM normalizes to 1.0 on the vertical axis. With regard to the polarity of the vertical axis of Fig. 11, the positive direction corresponds to the flexion moment, while the negative direction is the extension moment; the axis has been normalized by dividing by the minimum value of the extension moment according to the calculation result of the precise FEM, such that the minimum value of the extension moment of the calculation result of the precise FEM normalizes to -1.0 on the vertical axis. Zero on the vertical axis means no moment was measured in both flexion and extension.
With regard to the maximum values of occupant displacement, the observed differences between the degenerated model and the precise FEM were -5.5%, -6.2%, and -15.4% for the head, upper body, and lower body, respectively. Considering the neck moment maximum values, the differences between the degenerated model and the precise FEM were +63.5% and +8.4% for flexion and extension, respectively. In terms of chest deflection maximum values, the difference between the degenerated model and the precise FEM was -4.8%.

The increase in chest deflection at approximately 30 ms was larger in the precise FEM than in the degenerated model. The neck moment waveforms corresponding to the calculation results of the precise FEM and degenerated model were basically similar in terms of the time bands in which flexion and extension occurred; however, the waveform inflection points generated at 30 and 60 ms in the calculation results of the precise FEM were not reproduced in the degenerated model.

4. Discussion

Fig. 12 shows a considerable increase in chest deflection at approximately 30 ms was observed in the calculation results of the precise FEM. Fig. 13 shows the relationship between the position of the shoulder belt and chest at 0 and 30 ms in the precise FEM. Focusing on the relationships between the positions of the shoulder belt, breast, and the measurement point of the chest deflection, the breast is in the position that is first pressed by the shoulder belt when it is tightened by the pretensioner, since they are located in the region that protrudes most around the chest. The measurement point of chest deflection was located below the breast. Focusing on the change in breast thickness at approximately 30 ms, it was confirmed that almost no deformation was observed. The precise FEM exhibited a considerable increase in chest deflection at approximately 30 ms due to the shoulder belt pressing onto the breast. In the case of the degenerated model, the increase in the tension of the shoulder belt due to tightening of the pretensioner was reproduced. However, the shape of the breast protruding around the chest was not geometrically reproduced. Therefore, the measurement point of chest deflection was not pressed by the breast. Consequently, that the calculation result obtained using the degenerated model notably did not reproduce the considerable increase in chest deflection observed at approximately 30 ms in the precise FEM.

As shown in Fig. 11, the inflection points observed at 30 and 60 ms in the neck moment waveform in the precise FEM which were not reproduced in the degenerated model. An improved model was formulated to resolve such differences.

5. Improved model

Fig. 14 shows the structure of the neck assembly of THOR 5F at the initial position and during deformation of the neck in a collision. The neck structure includes the following components order from bottom to top: the deformable part of the neck, the measurement plane of the neck load cell, and the occipital condyle (O.C.) joint. The deformable part of the neck is mainly composed of an elastic body, and the O.C. joint has a pivot structure with the rotational restoring force. As the position of the measurement plane of the neck load cell is located between these two parts, the neck moment is measured as the moment from both the deformable part of the neck and the O.C. joint. In contrast, the neck moment is measured as the moment at the upper end of the simple beam in the structure of the neck in the degenerated model, as shown in Fig. 4. Therefore, the neck structure of the degenerated model reproduces the deformable part and the measurement plane of the neck load cell of THOR 5F, but reproduces neither the degree of freedom nor the rotational restoring force of the O.C. joint. Based on this observation, the following hypothesis was considered: the neck structural difference between THOR 5F and the degenerated model affects the reproducibility of inflection points.

To verify this hypothesis, an improved degenerated model was formulated that is capable of reproducing the position of the measurement plane in the neck load cell, the degree of freedom of the O.C. joint, and the rotational restoring force. Hereinafter, the degenerated model before improvement is denoted as Model 1, while that after improvement is referred to as Model 2. Fig. 15 represents the schematic diagram of the improved structure of Model 2. In Model 2, the neck load cell block is positioned above the simple beam as an independent rigid body. The head and neck load cell block are connected by a rotating pivot, and a rotating spring is applied to generate the restoring force in relation to the relative angular displacement of the head and neck load cell blocks. Fig. 16 presents a schematic diagram of the load and moment in the neck load cell block. Table 3 shows the parameters used in Model 2. Here the distances from the measurement plane of the neck load cell to the O.C. joint and to the simple beam connection point are
denoted as L1 and L2. The moment and shear forces that the neck load cell block receives from the O.C. joint are are Mr and fs, respectively, while those that the neck load cell block receives from the simple beam connection point are Mx and fx, respectively. When L1 \( \cong \) L2, \( M_{y} \) measured at the measurement plane is formulated as per equation (2):

\[
M_{y(\cdot)c} = \frac{M_{yn} + M_{yh} + (f_{xn} + f_{xh})L_{1}}{2} \quad (2)
\]

Moreover, the relative translational motion of the head and neck block is small. Thus if it is considered that \( f_{xh} + f_{xn} = 0 \) approximately, then \( M_{y} \) is expressed by equation (3):

\[
M_{y(\cdot)c} = \frac{M_{yn} + M_{yh}}{2} \quad (3)
\]

The neck moment of Model 2 was calculated using equation (3).

In order to verify the improved neck structure of the Model 2, the \( \theta_{h} \) and \( \theta_{n} \) values of the precise FEM and Model 2 were compared. Fig. 18 shows the time history of \( \theta_{h} \), while Fig.19 shows the time history of \( \theta_{n} \). The axis polarities of for Figs. 18 and 19 are the same as for Fig. 15: the positive direction corresponds to flexion rotation, while the negative direction corresponds to extension rotation.
precise FEM normalizes to \(-1.0\) on the vertical axis. Zero on the vertical axis means no rotation was measured in both flexion and extension. \(\theta_s\) is angled in the extension direction beginning at 20 ms and reaches its minimum extension angle value around 40 ms. After that, it turns to the flexion direction and attains its maximum flexion angle value after 60 ms. This tendency is seen in both the precise FEM and Model 2. With regard to maximum \(\theta_s\) values, the differences between the precise FEM and Model 2 were \(+205.4\%\) and \(+9.4\%\) for flexion and extension, respectively.

With regard to Fig. 19, the vertical axis has been normalized by dividing by the maximum value of the flexion rotation angle according to the calculation result of the precise FEM, such that the maximum value of the flexion rotation angle of the calculation result of the precise FEM normalizes to \(1.0\) on the vertical axis. Zero on the vertical axis means no rotation was measured in both flexion and extension. The time at which \(\theta_s\) reaches its maximum value is the similar between the precise FEM and Model 2, and the difference between the maximum values observed in these two models is \(+12.9\%\). Model 2 begins flexion rotation at an earlier time than the precise FEM. Since the extension rotation of \(\theta_s\) is significantly smaller than the flexion rotation, flexion rotation is dominant.

The results of comparing \(\theta_s\) and \(\theta_o\) can be summarized as follows in terms of each neck moment maximum flexion or minimum extension value. In the 40 ms during which the neck moment reached its minimum extension value, \(\theta_s\) was similar, while \(\theta_o\) showed an earlier flexion rotation start time in Model 2 than in the precise FEM. In the 80 ms where during which the neck moment reached its maximum flexion value, \(\theta_s\) was similar, while \(\theta_o\) showed a larger maximum flexion value in Model 2 than in the precise FEM. Since the difference between the precise FEM and Model 2 in the minimum neck moment value was \(+0.4\%\) for extension and maximum neck moment value was and \(+13.3\%\) for flexion, Model 2 can may yet play a role in verifying neck injury in the primary phase, which is the purpose of this study.

6. Conclusion

The purpose of the present research is to enable verification of occupant protection performance including neck injury under full-width frontal crash test conditions, using a THOR 5F dummy in the primary phase of automobile development. To accomplish this purpose, a two-dimensional degenerated model was formulated, combining the neck element with a four-rigid-body model consisting of the head, upper body, sternum, and lower body as proposed by Kurano et al.\(^{(9)}\). The neck element was formulated using two methods: Model 1, a model that implied positioning a measurement plane of the neck load cell above a simple beam; and Model 2, a model in which the neck load cell block was placed between a rotating pivot and a simple beam. Model 2 reproduces the neck structure of THOR 5F.

The reproducibility of occupant displacement, chest deflection, and neck moment were verified by comparing the results of the degenerated model with those obtained under the same conditions by the precise FEM using LS-DYNA. Concerning the displacement of the head, chest, and lower body, the two models produced similar results. Regarding chest deflection, similar peak values were observed; however, the waveform shape differed between the degenerated model and the precise FEM. It was observed that this difference occurred as the degenerated model did not accurately reproduce the breast shape of THOR 5F. Concerning the neck moment waveform, similar peak values of flexion and extension were observed; however, the inflection points, which were not reproduced accurately in Model 1, were reproduced in Model 2. Thus, it was concluded that the accuracy with which Model 2 reproduced the neck structure of THOR 5F was related to the presence of inflection points.

The observed results suggest that the degenerated model can be considered a suitable approach satisfying the approximate accuracy condition required during the primary phase of automobile development.

"This paper is written based on a proceeding presented at JSAE 2019 Annual Congress"

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