

Study of Occupant Deceleration Control During a Crash Due to Vehicle Mass Separation

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ABSTRACT

In order to reduce the maximum value of occupant deceleration in a vehicle crash, a physical model which utilizes the separated mass of a vehicle was devised to yield an optimal vehicle deceleration wave form. The validity of this model has been certified by a mathematical study and a three-dimensional dummy simulation.

1. Introduction

When considering vehicle crash safety performance, optimizing the change in vehicle deceleration over time in a crash (hereafter referred to as the “vehicle deceleration wave form”) is an important issue for simultaneously securing survival space and reducing injury severity. Previous research mainly performed optimization using the sensitivity analysis method, but the authors have derived and generalized mathematical solutions for the optimal vehicle deceleration wave forms for chest deceleration of the occupant through mathematical studies using a two-mass model. These mathematical solutions have in common a three-part structure consisting of high initial deceleration, low or negative middle deceleration, and then constant deceleration later on.⁽¹⁾

However, the vehicle deceleration in a general crash is determined by the vehicle structure deformation load applied to the vehicle mass. Therefore, the direction of the load relative to the vehicle mass is constant. This makes it difficult to generate negative deceleration. This paper reports on a physical model devised for generating negative deceleration on the vehicle, presents a mathematical study conducted based on this model, and examines the possibility of creating an optimal vehicle deceleration wave form. Furthermore, the validity of the vehicle deceleration wave forms obtained from this physical model are verified through a mathematical study and a three-dimensional dummy simulation.

2. Model for the Separation of Vehicle Mass

2.1. Optimal Vehicle Deceleration Wave Form

In the past the authors had mathematically studied the vehicle deceleration wave form that minimizes the maximum occupant deceleration value using a two-mass model like that shown in Fig.1. Here, the authors introduced a transient function concept and obtained mathematical solutions for

the optimal vehicle deceleration wave form⁽¹⁾. The transient function is the optimal occupant deceleration wave form that results in a complete ride-down condition during a certain short control time after the crash starts. Solutions of the function are not unique, and a corresponding basic optimal vehicle deceleration wave form type exists for each of the three basic types of transient functions.

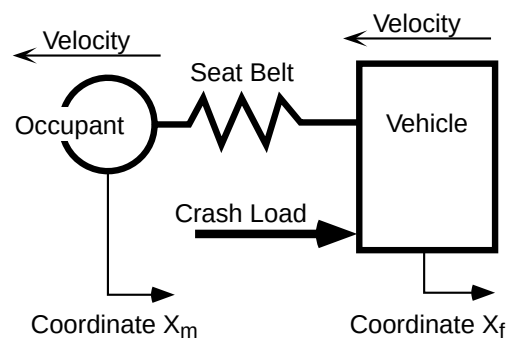


Fig.1 One-dimensional two-mass model

These wave forms are shown in Fig.2, and have in common a three-part structure consisting of high initial deceleration, low or negative middle deceleration, and then constant deceleration later on.

When considering these wave forms as the target vehicle deceleration wave forms for an actual vehicle, creating the deceleration wave form for the middle period of a crash becomes an issue. Vehicle deceleration in a crash is generally produced by the vehicle deformation load (crash load) applied to the vehicle mass. However, the direction of the crash load is limited to the direction opposite that of the velocity, and the deceleration tends to increase as deformation progresses. For this reason, it was impossible

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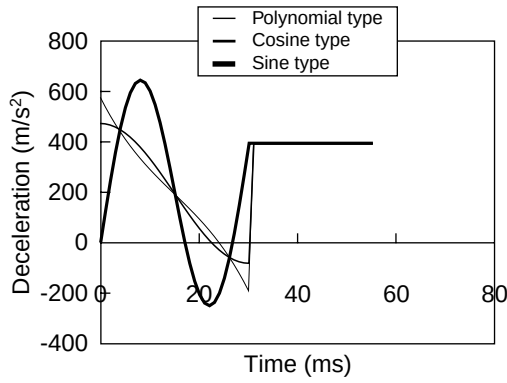


Fig.2 Wave forms of the mathematical solutions

to produce stable low or negative deceleration with conventional vehicle structures during the middle period of a crash. Therefore, the authors devised a new physical model as a means of solving this problem.

2.2 Model for the Separation of Vehicle Mass

Negative vehicle deceleration can be created by applying a crash load to the vehicle in the direction opposite the normal direction. This requires a new mass, but this new mass can be created inside the vehicle by separating the vehicle mass.

Fig.3 shows a model with the vehicle mass separated. Here, the occupant is treated as mass m and the seat belt as a spring with spring constant k . The vehicle is separated into two parts, with the part to which the seat belt is linked expressed by mass M_B and called the binding. Similarly, the remaining vehicle portion is called the frame and expressed by M_f . All masses have an initial velocity of V_0 .

The initial high deceleration and subsequent negative deceleration are required only with the binding. The coordinate system consists of the occupant coordinate X_m , and binding coordinate X_B , and the frame coordinate X_f , and the crash start time is $t = 0$. At this point the binding and frame are relatively separated only by the control gap S_0 . After the crash starts, the respective crash loads F_f and F_B act separately on the frame and binding, and these parts move independently of each other. If the vehicle is designed so that the binding deceleration is larger than the frame deceleration at this time, the gap decreases from S_0 and the

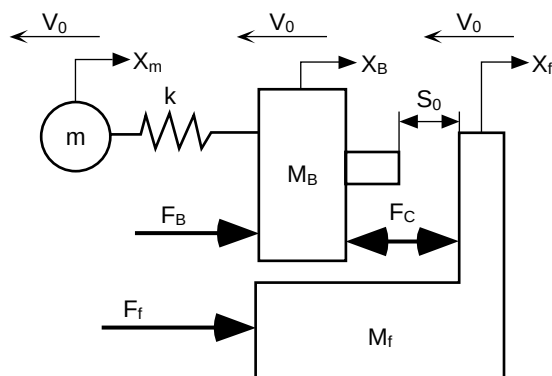


Fig.3 Model for the separation of vehicle mass

two parts eventually contact each other. This contact time is labeled t_{c1} , and the time from 0 to t_{c1} is called the first control time. After contact, a load F_C is produced between the binding and the frame. Here, F_C acts in the negative deceleration (acceleration) direction relative to the binding, so if F_C is sufficiently large, negative deceleration is created on the binding. The model assumes F_f , F_B and F_C to be constant values, and assumes a completely plastic crash. Therefore, the load F_C is eliminated when the binding and the frame reach the same velocity. This time is labeled t_{c2} , and the time from t_{c1} to t_{c2} is called the second control time. After t_{c2} , the binding and frame decelerate as a single unit.

However, while it is clear that negative deceleration can be obtained from this model, it is not known whether the optimal vehicle deceleration wave form can be obtained. Therefore, a mathematical study is conducted next to determine the possibility of realizing the optimal vehicle deceleration wave form.

3. Mathematical Study of Model for the Separation of Vehicle Mass

When a fixed load is applied to the binding as an input, the output occupant deceleration wave form clearly shows the same form as a cosine type transient function, and this also appears in the solution for equation (19) noted hereafter. In addition, the motion equations for this model differ for the three time regions of the first control time, the second control time, and thereafter. Therefore, individual cosine type occupant deceleration wave forms appear in the first and second control times, but when these are linked if the occupant deceleration wave form for the entire control time satisfies the transient function conditions, namely starting from the origin, a tangential gradient of 0 at the origin and a complete ride-down condition at t_{c2} , then this wave form is a single transient function which combines cosine type deceleration wave forms.

Based on this thinking, the time regions are related by solving the equation for each control time with the crash load and control gap as unknown constants and t_{c1} and t_{c2} as independent variables, and using the occupant and binding conditions at the end of the first control time t_{c1} as the initial conditions for the second control time equation. Then, the optimal crash load and optimal control gap are calculated by applying the transient function conditions to the obtained occupant deceleration equation.

When t_{c1} and t_{c2} are set arbitrarily, if these exist as finite values, then they also determine the vehicle deceleration. This is the vehicle deceleration that corresponds to the transient function, or in other words the optimal vehicle deceleration wave form.

3.1. Equations of Motion and Condition

First, the motion equations for the first control time are as follows, with the time differential expressed as $(\cdot)$.

$$\ddot{X}_m = -\omega^2(X_m - X_B) \quad (1)$$

$$\ddot{X}_B = \alpha\omega^2(X_m - X_B) + g_B \quad (2)$$

$$\ddot{X}_f = g_f \quad (3)$$

Provided that,

$$\omega = \sqrt{\frac{k}{m}}, \alpha = \frac{m}{M_B}, g_B = \frac{F_B}{M_B}, g_f = \frac{F_f}{M_f} \quad (4)$$

The initial conditions for these are as follows.

$$\begin{aligned} X_m(0) &= X_B(0) = 0, X_f(0) = S_0, \\ \dot{X}_m(0) &= \dot{X}_B(0) = \dot{X}_f(0) = -V_0 \end{aligned} \quad (5)$$

Also, t_{c1} is the time at which the binding and frame contact each other, so the condition for t_{c1} is as follows.

$$X_B(t_{c1}) = X_f(t_{c1}) \quad (6)$$

Next, the motion equations for the second control time are as follows.

$$\ddot{X}_m = -\omega^2(X_m - X_B) \quad (7)$$

$$\ddot{X}_B = \alpha\omega^2(X_m - X_B) + g_B - g_C \quad (8)$$

$$\ddot{X}_f = g_f + \alpha_B g_C \quad (9)$$

Provided that,

$$g_C = \frac{F_C}{M_B}, \quad \alpha_B = \frac{M_B}{M_f} \quad (10)$$

t_{c2} is the time at which the binding and frame reach the same velocity, so the condition for t_{c2} is:

$$\dot{X}_B(t_{c2}) = \dot{X}_f(t_{c2}) \quad (11)$$

In addition, the transient function conditions at the origin are automatically satisfied by the initial conditions. The remaining conditions, that is to say the conditions for the occupant to reach a complete ride-down condition at t_{c2} , are that the occupant deceleration is C, with C being the target occupant deceleration setting value, and that the occupant and the binding are traveling at the same velocity. These conditions are expressed as follows.

$$\ddot{X}_m(t_{c2}) = C \quad (12)$$

$$\dot{X}_m(t_{c2}) = \dot{X}_B(t_{c2}) \quad (13)$$

Then, the condition equation to maintain the complete ride-down condition after the control time is that the deceleration for the entire vehicle and the occupant deceleration are the same value, or in other words:

$$\frac{F_f + F_B}{M_f + M_B + m} = C \quad (14)$$

3.2. Solutions to the Equations

These equations can be solved by various methods, but this study solves the equations by introducing the relative coordinate as follows.

$$X_m - X_B = X_r \quad (15)$$

This equation was then used to convert the simultaneous equations (1)(2) and (7)(8) into the following single-variable equations.

$$\ddot{X}_r + (1 + \alpha)\omega^2 X_r = -g_B \quad (16)$$

$$\ddot{X}_r + (1 + \alpha)\omega^2 X_r = -g_B + g_C \quad (17)$$

Based on the initial conditions (5), the initial conditions for X_r are as follows.

$$X_r(0) = 0, \quad \dot{X}_r(0) = 0 \quad (18)$$

Solving equation (16) based on equation (18), the solution during the first control time regarding to X_r as follows.

$$X_r = -\frac{g_B}{\beta^2}(1 - \cos\beta t) \quad (19)$$

Provided that,

$$\beta = \omega\sqrt{1 + \alpha} \quad (20)$$

In addition, solving equation (17) with the $X_r(t_{c1})$ and $\dot{X}_r(t_{c1})$ obtained from equation (19), the solution for the second control time is as follows.

$$X_r = -\frac{g_B - g_C}{\beta^2} - \frac{g_C}{\beta^2}\cos\beta(t - t_{c1}) + \frac{g_B}{\beta^2}\cos\beta t \quad (21)$$

On the other hand, the ride-down condition equations (12) and (13) are converted as follows by equation (15).

$$X_r(t_{c2}) = -\frac{C}{\omega^2}, \quad \dot{X}_r(t_{c2}) = 0 \quad (22)$$

Applying these to equation (21) yields the following.

$$g_B = (1 + \alpha)C \frac{\sin\beta(t_{c2} - t_{c1})}{\sin\beta(t_{c2} - t_{c1}) - \sin\beta t_{c2} + \sin\beta t_{c1}} \quad (23)$$

$$g_C = (1 + \alpha)C \frac{\sin\beta t_{c2}}{\sin\beta(t_{c2} - t_{c1}) - \sin\beta t_{c2} + \sin\beta t_{c1}} \quad (24)$$

Then, applying these to equations (6) and (11),

$$g_f = C \frac{\sin\beta(t_{c2} - t_{c1}) - K(1 - \frac{t_{c1}}{t_{c2}})\sin\beta t_{c2}}{\sin\beta(t_{c2} - t_{c1}) - \sin\beta t_{c2} + \sin\beta t_{c1}} \quad (25)$$

Provided that,

$$K = 1 + \alpha_B + \alpha \alpha_B \quad (26)$$

Based on the above equations (23) to (25), the appropriate crash load is calculated by the following equations.

These equations clearly show that the values are finite. Therefore, it is possible to obtain the optimal vehicle deceleration wave form from the vehicle mass separation model presented in this paper.

$$F_f = C \frac{M_f \sin \beta (t_{c2} - t_{c1}) - (M_f + M_B + m)(1 - t_{c1}/t_{c2}) \sin \beta t_{c2}}{\sin \beta (t_{c2} - t_{c1}) - \sin \beta t_{c2} + \sin \beta t_{c1}} \quad (27)$$

$$F_B = C \frac{(M_B + m) \sin \beta (t_{c2} - t_{c1})}{\sin \beta (t_{c2} - t_{c1}) - \sin \beta t_{c2} + \sin \beta t_{c1}} \quad (28)$$

$$F_C = C \frac{(M_B + m) \sin \beta t_{c2}}{\sin \beta (t_{c2} - t_{c1}) - \sin \beta t_{c2} + \sin \beta t_{c1}} \quad (29)$$

Note that as a condition for the F_f obtained from equation (27) here to be a positive value, the limitation on the relationship between t_{c1} and t_{c2} is derived approximately as follows.

$$t_{c2} > \frac{-t_{c1} + \sqrt{K t_{c1}^2 + \frac{3(K-1)^2}{\beta^2}}}{K-1} \quad (30)$$

However, this limitation need to be considered only when t_{c1} is set extremely small within the range of $t_{c1} < \frac{1}{\beta} \sqrt{\frac{3(K-1)}{K}}$. In addition, the setting range for t_{c1} and t_{c2} is $0 < t_{c1} < t_{c2} < \pi/\beta$ so that F_B and F_C are positive values.

The optimal control gap value is obtained as follows by calculating $X_B(t_{c1})$ and $X_f(t_{c1})$, and substituting these into equation (6).

$$S_0 = C \frac{\frac{\alpha}{\beta^2} (1 - \cos \beta t_{c1}) \sin \beta (t_{c2} - t_{c1}) + \frac{t_{c1}^2}{2} K (1 - \frac{t_{c1}}{t_{c2}}) \sin \beta t_{c2}}{\sin \beta (t_{c2} - t_{c1}) - \sin \beta t_{c2} + \sin \beta t_{c1}} \quad (31)$$

Finally, substituting equation (27) and (28) into condition equation (14) shows that this equation can not be satisfied for the period after the control time except the case of $t_{c1} = t_{c2}$, which has no physical meaning. This means that the appropriate crash load within the control time is always insufficient for the required crash load after the control time. Therefore, one or both of F_f and F_B must be changed from the values in equations (27) and (28) at t_{c2} to values that satisfy equation 14. In this study, F_f was changed.

Based on the above analysis results, the deceleration wave forms given by equations (1) to (3) and (7) to (9) for the occupant m , binding M_B , and frame M_f are shown in Fig.4. This example sets $m = 33$ kg, $M_B = 40$ kg, $M_f = 500$ kg, $k \approx 16$ kgf/mm, $C = 40G$, $t_{c1} = 12$ ms, and $t_{c2} = 24$ ms.

Note that the crash load values obtained by equations (27) to (29) at this time are $F_f \approx 8.8$ tons (until t_{c2}) and 20.3 tons (after t_{c2}), $F_B \approx 2.7$ tons, and $F_C \approx 2.4$ tons, and the control gap is $S_0 \approx 32$ mm.

4. Verification through Simulation

The binding deceleration wave form shown in Fig.4 was input to a dummy simulation model to mathematically confirm the validity of the wave form. The model used the ATB program, and applied a three-point seat belt as the standard binding condition. Load limiters and air bags were not applied.

Fig.5 shows the input binding deceleration wave form, the deceleration response of the dummy's chest (dummy

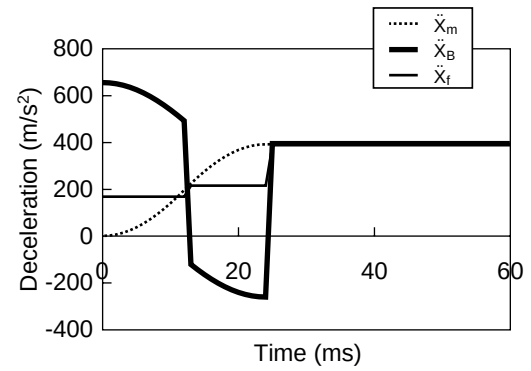


Fig.4 Theoretical vehicle and occupant deceleration wave form from the vehicle mass separation model

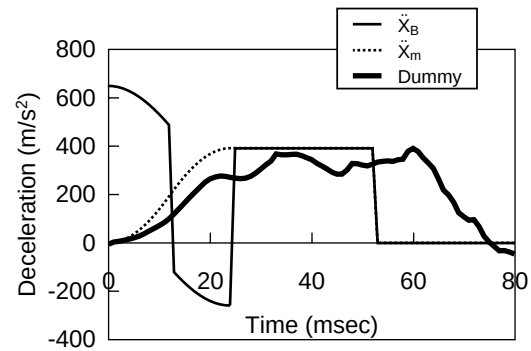


Fig.5 Vehicle and dummy chest deceleration in a three dimensional simulation

coordinates), and the corresponding mathematically obtained occupant deceleration wave form.

This figure shows that although slightly delayed, the graph of dummy chest deceleration matches closely with the calculated graph, and forms a fairly flat portion between 30 and 60 ms.

The slight delay in the dummy graph relative to the calculated graph is thought mainly to occur because the mass corresponding to m increases slightly during the course of the crash due to the effects of the arm and head portions, and because the spring constant of the seat belt in the simulation is adjusted so that elongation is nonlinear in small elongation regions to match with reality. In addition, the fluctuation appearing after 20 ms is presumed to be because the dummy forms a complex multi-mass system.

5. Observations

Creating negative acceleration is impossible with a model that treats the vehicle as a single mass as shown in Fig.1. However, this is possible with a model that separates the vehicle mass. Further, the feasibility of creating an optimal vehicle deceleration wave form using this model was verified both numerically and through simulation.

The studies presented in this paper use a simplified physical model. The applicability of this model to an actual vehicle structure has not yet been studied, and various

technical problems can be expected. Furthermore, verification not only through simulation but also using actual dummies must also be investigated in the future. However, it is significant that this paper has shown the possibility of creating vehicle deceleration wave forms which include a negative deceleration portion using only the crash load due to vehicle mass separation.

6. Conclusions

- (1) A vehicle mass separation model which had not been studied before was devised as a means of creating negative vehicle deceleration.
- (2) It was verified through a mathematical study that the optimal vehicle deceleration wave form can be obtained from this vehicle mass separation model, and a mathematical solution for the optimal vehicle deceleration wave form was obtained using this model.
- (3) The obtained mathematical solution was input to a three-dimensional dummy simulation and the chest deceleration response was obtained. These results verified the validity of the mathematically solved optimal vehicle deceleration wave form with respect to reducing chest deceleration.

Future issues include verifying the validity of this model using actual dummies and investigating the applicability to an actual vehicle structure.

References

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